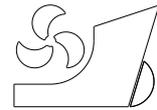


*Sajad Hajizadeh*  
*Mohammad Saeed Seif*  
*Hamid Mehdigholi*



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## EVALUATION OF PLANING CRAFT MANEUVERABILITY USING MATHEMATICAL MODELLING

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Professional paper

### Summary

Ship transportation is increasing globally as is the risk of collision especially in congested areas. Numerical modeling method is a major simulation method to predict ship maneuverability. Ship maneuvering in calm water is an important topic to avoid collisions and leads to safe navigation. Therefore, reliable ship maneuvering simulations are required for incident analysis and prevention. In recent time within the research community orientated towards ship hydrodynamics an increasing attention has been paid to simultaneous solution of the planing ship maneuvering problem. The maneuverability of planing craft has been the subject of many research projects during the last few decades. To assess the maneuverability of planing craft at an early design stage, reliable simulation models are required. Traditionally, these tools have used empiric descriptions of the forces and moments on the planing craft's hull. Ship maneuvering calculations, horizontal plane motion control and development of maneuvering simulators need a mathematical description of ship maneuvering. In recent years, different mathematical models have been suggested for maneuvering of displacement vessels. They are capable of vessel maneuvers estimation with acceptable precision. However, the simulation of planing craft maneuverability by using mathematical model is not common yet and is the subject of future research. Maneuvering of planing craft is influenced greatly by the action of the rudder. Research efforts have been made to include the rudder action in the mathematical models of planing ship maneuvering. This paper presents a mathematical model developed for planing craft maneuvering that includes the rudder forces and moments. Different maneuvers are executed through the mathematical model. Simulations are validated by model tests. Finally, the influence of the rudder angle on the maneuverability of a planing ship is considered. The mathematical model and hydrodynamic coefficients presented in this paper can be applied for the estimation of course control and turning ability of a planing craft in the early stages of design.

Keywords: *maneuvering; modeling; planing ship; rudder;*

### 1. Introduction

Prediction of ship maneuverability is one of the important issues in the study of vessel's hydrodynamics. Vessel's maneuver is inherently nonlinear and unsteady. Due to the limitations of analytical methods, predicting vessel's maneuver has been based on experimental formulation which has been established by the use of a database or model tests.

The experimental data bank method is based on a mathematical model and maneuvering coefficients. These coefficients are either fully empirical or semi empirical - analytical.

In the recent years there have been significant progresses in design and manufacturing of the planing vessels. However, predicting planing vessel's maneuver has been a bottleneck. In the case of semi-experimental methods, results are only applicable to tested models. Analytical study of the planing vessel includes planing, hydrodynamic interactions and also to a lesser degree hydrostatic and wave patterns. The lift force in high speed vessels is due to hydrodynamic displacement of water and the change in the momentum of water under the vessel. However, at low speed, the lift force is acting solely due to the hydrodynamics. As the speed increases the hydrodynamic lift force increases and lifts the vessel out of the water, which itself reduces the hydrostatic force. The dominant equations are nonlinear and somehow complicated, therefore cannot be solved easily.

The very first maneuver modeling goes back to Davidsons who derived the maneuver equations and showed the complicated relation between the turning ability and path keeping in maneuver. Today's theories are based on Davidson's equations [1]. The two main theories for maneuver modeling which are still applicable and popular are the Abkowitz model and the MMG (Maneuvering Models Group, Japan) model. The Abkowitz theory includes prediction of forces acting on the vessel as a function of vessel's characteristic motion and integration of motion equation to find the real path of a maneuvering vessel [2]. With the advances in digital computing, simulations became a great substitution of model testing. With the computer advances, significant changes in applying control theories for maneuvering have occurred [3].

In the recent years, as new high speed vessels entered the market, there have been numerous numerical and experimental studies regarding the vessel's maneuverability. The first experiment was performed on a self-propelled semi-displacement vessel. Roll stability in high speed was the main concern and several spray rails were tested on 1.8m and 3.26 m models. It was shown that the loss of roll stability in high speed may result in directional instabilities or broaching [4]. Experimental techniques were studied in vessels maneuvering tests and the qualities necessary for a good maneuvering and control in high speed were investigated. Several parameters affecting the performances of a high speed vessel including deadrise angle, longitudinal center of gravity, vertical center of gravity and trim control fins were investigated [5].

In order to study the behavior of a planing vessel in calm water, restrained hydrodynamic model tests on two models of planing catamarans were performed in the towing tank of Delft University of Technology. Tests included the measuring three indexes of force and moment as a function of pitch, heave, roll, drift and model speed. Furthermore, by model tests, the added mass and damping force of a planing vessel, the rudder and propeller forces were measured [6]. Six non-linear degrees of freedom of the vessel's motion can be expressed by the use of data from model tests. Then the time dependent equations of the high speed vessel's motion can be coded and its dynamic instability and maneuvering can be studied. In the present paper, using two models, several restrained tests in which forces and moments were measured along all six degrees of freedom were performed. All these tests can provide a little knowledge about the hydrodynamics of planing vessels [6].

In order to have a better understanding of forces and moments acting on a planing vessel while maneuvering in horizontal plane, the oscillating motion of the high speed vessel was studied. While performing these tests, the model was completely restrained and was just under maneuvering forces (pure sway, pure yaw, and yaw with drift). Forces and moments were measured along each degree of freedom and simultaneously the vessel's draft, trim angle, model's forward speed, sway speed and yaw's speed were changed systematically. Based on the measured forces and moments, a mathematical model was developed using

analysis and linear regression with varying coefficients as the input. Then the developed mathematical model was applied to simulating software, which was developed in advance to predict the six degrees of freedom behavior of a planing vessel. Hydrodynamic terms were exerted in the software through added mass coefficients to include the dependence of forces on vessel forward speed [7].

In a planing vessel, running attitude (usually consisting of draft, trim and heel angle) changes as the vessel maneuvers. However, in a displacement vessel this change of running attitude and its effects on the maneuver can be ignored. In these vessels, the changes in running attitude are so small that in several special hulls they are ignored. Predicting high speed vessels maneuver is harder than in case of other vessels. Therefore, to accurately simulate the high speed vessels maneuverability, a maneuvering model which includes motion characteristics (trim angle, heel angle...) is needed. In previous researches, the influences of maneuvering motions on the motion characteristics and vice versa were investigated. The results of the mentioned researches have shown that some maneuvering motions of a high speed vessel affect the motion characteristic of the vessel and on the other hand, some of the motion characteristics have a great influence on the hydrodynamic coefficients of the high speed vessel. Therefore, in predicting maneuverability of a high speed vessel, these tips should be considered [8].

Jahanbakhsh et al. developed NUMELS code which can simulate six degrees of freedom for a fluid-structure interaction in two phase fluid. NUMELS software was developed for simulating 3D, time dependent, two phase, viscous fluid coupled with rigid body motion. They simulated a planing catamaran's maneuver. They studied the turning diameter of a planing catamaran at different angles of thrust [9].

Javanmardi et al. studied the influences of all three longitudinal configurations of demi-hulls on maneuverability of a trimaran. In order to simulate hydrodynamics, they used NUMELS software. They showed that longitudinal positions of the body sides have a significant influence on maneuverability of the trimarans [10]. Mathematical equations for maneuvering models are derived from equations of viscous flows. In these mathematical models, special attention was paid to the backward or sideward maneuvering [11].

In [12] hydrodynamic maneuvering coefficients were derived using system identifications like the advanced Kalman filter method based on the experimental data, analytical tests, and computational fluid dynamics. The authors investigated the accuracy of each method in the calculation of the hydrodynamic maneuvering coefficients.

In [13] by using CFD based on the data from experimental test of planar motion mechanism, the maneuverability of the vessel was investigated in the pre-design phase and maneuvering parameters like turning radius and zigzag test were studied [13].

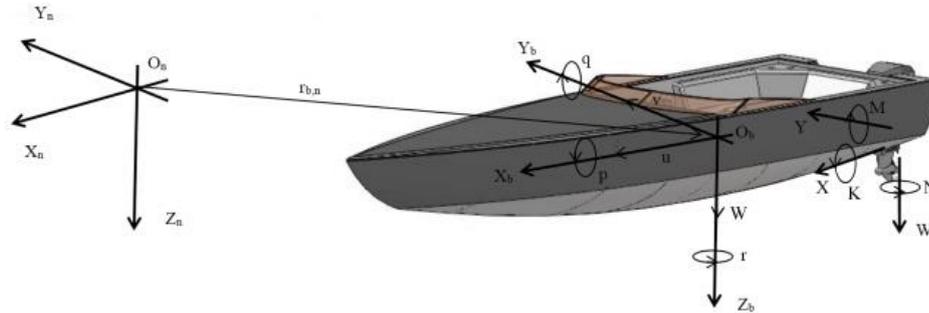
Previous researches did not consider through modeling of a high speed planing vessel and influence of individual hydrodynamic parameters of a high speed vessel on its maneuvering ability. The influence of the rudder on maneuvering was not previously investigated in mathematical modeling. It should be noted that the rudder action can influence the maneuverability of a high speed craft severely. In the present paper, a comprehensive model of a high speed vessel which can investigate the influence of the rudder on the maneuverability of the high speed vessel was developed. Finally, in order to check the accuracy of the presented method, the results of the presented numerical method were compared to the published results of the experiments performed with the model of a high speed vessel.

## 1. High speed vessel maneuvering equations

In the analysis of maneuvering and seakeeping characteristics of conventional (displacement) vessels, it is assumed that the wetted surface of the vessel is always constant. However, in high speed vessels the wetted surface, draft and trim angle change rapidly as the forward speed increases. Therefore [14]:

- 1- All the hydrodynamic coefficients are strongly time dependent, even though simplifying assumptions are taken into account.
- 2- Longitudinal and transverse motions can influence longitudinal and vertical forces, as they change the trim and heave angle which can affect the wetted surface of the vessel.
- 3- In waves, the wetted surface continuously changes and in a rough sea, some sections of the vessel might even get out of the water. In other word, due to the dynamic lift, coefficients in maneuvering equations of a high speed vessel should be carefully calculated.

The equations of motion for analyzing a high speed vessel's motion are derived regarding a coordinate system fixed at the vessel's center of gravity [14]:



**Figure 1** Fixed and moving coordinates

As shown in Fig.1,  $u$  is linear velocity of surge motion,  $v$  is linear velocity of sway motion,  $w$  is linear velocity of heave motion,  $p$  is angular velocity of roll motion,  $q$  is angular velocity of pitch motion,  $r$  is angular velocity of yaw motion,  $X$  represents forces exerted on the vessel in direction of the surge motion,  $Y$  is force exerted on the vessel in direction of the sway motion and  $Z$  is the force in direction of the heave motion,  $K$  is moment of the roll motion,  $M$  is moment of the pitch motion and  $N$  is the moment of the yaw motion. Basic equations of motion in six degrees of freedom are as follows:

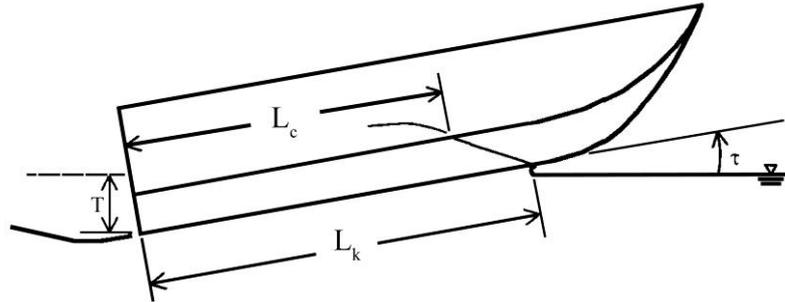
$$\begin{aligned}
 X &= m(\dot{u} + wq_a - vr_a) \\
 Y &= m(\dot{v} + ur_a - wp_a) \\
 Z &= m(\dot{w} + vp_a - uq_a) \\
 K &= \frac{d}{dt}(I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z) - r_a(I_{yy}\omega_y - I_{yz}\omega_z - I_{xy}\omega_x) + q_a(I_{zz}\omega_z - I_{xz}\omega_x - I_{yz}\omega_y) \\
 M &= \frac{d}{dt}(I_{yy}\omega_y - I_{yz}\omega_z - I_{xy}\omega_x) - p_a(I_{zz}\omega_z - I_{xz}\omega_x - I_{yz}\omega_y) + r_a(I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z) \\
 N &= \frac{d}{dt}(I_{zz}\omega_z - I_{xz}\omega_x - I_{yz}\omega_y) - q_a(I_{xx}\omega_x - I_{xy}\omega_y - I_{xz}\omega_z) + p_a(I_{yy}\omega_y - I_{yz}\omega_z - I_{xy}\omega_x)
 \end{aligned} \tag{1}$$

where,  $\omega$  is the vessel's angular velocity with respect to the axes and  $\Omega = (p_a, q_a, r_a)$  is the angular velocity of the axes. It should be noted that the  $a$  subscript is used for parts to avoid any confusion with the regular quantities.

Force in the sway direction and moment in roll and yaw motion are shown in Eq. 2:

$$\begin{aligned}
 Y &= Y_v \dot{v} + Y_{v,v} + Y_{\phi} \ddot{\phi} + Y_{\phi} \dot{\phi} + Y_{\phi} \phi + Y_{\psi} \ddot{\psi} + Y_{\psi} \dot{\psi} \\
 K &= K_v \dot{v} + K_{v,v} + K_{\phi} \ddot{\phi} + K_{\phi} \dot{\phi} + K_{\phi} \phi + K_{\psi} \ddot{\psi} + K_{\psi} \dot{\psi} \\
 N &= N_v \dot{v} + N_{v,v} + N_{\phi} \ddot{\phi} + N_{\phi} \dot{\phi} + N_{\phi} \phi + N_{\psi} \ddot{\psi} + N_{\psi} \dot{\psi}
 \end{aligned}
 \tag{2}$$

In order to find the coefficients used in Eq. 2, a series of experiments on the hull forms with the deadrise angle of 10, 20 and 30 degrees were performed. In the test procedure, the advance velocity, drift angle, roll and trim angle were altered and finally each of the coefficients in Eq. 2 was defined [14]. After defining each parameter given in Table 1, the relations concerning each parameter are defined in Table 2.



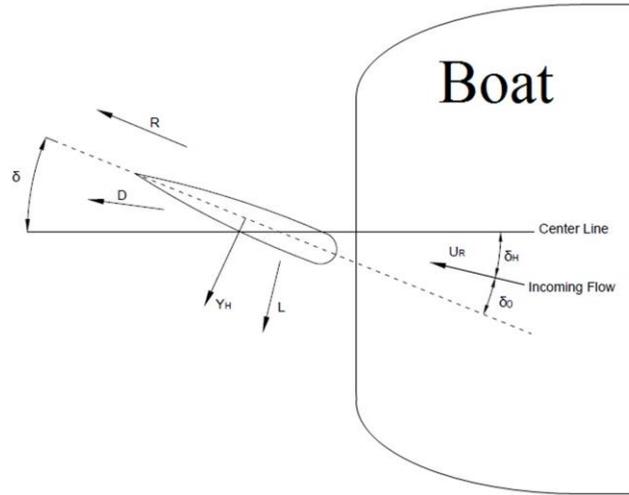
**Figure 2** Definition of mean trim and wetted keel length and chine length in a planing vessel

**Table 1** Definition of parameters used in calculation of the hydrodynamic coefficients

Parameter	Definition
B	Chine mean wet width
$\beta$	Deadrise angle
$\tau$	Trim angle
$L_c$	Chine's wet length
T	Aft draft
$C_v$	Velocity coefficient ( $U/\sqrt{gB}$ )
LCG	Longitudinal center of gravity

## 2. Rudder forces

In the present paper, formulations regarding the forces of the rudder are based on the studies performed by Inoue and Hooft [6]. Dimensions and exact location of the rudder are not yet determined in the initial design stages. However, only a rough approximation of the rudder dimensions and position would be enough to evaluate the vessel maneuverability. It was assumed in the present study that the flow velocity around the rudder was high enough and no separation has occurred. In fact the flow might separate and the present assumptions might somehow affect the accuracy. Furthermore, in the present study the added mass and damping of the rudder were completely ignored. Forces acting on the rudder are shown in Fig. 3. Flow velocity acting on the rudder was locally measured and the apparent angle of attack was calculated.



**Figure 3** Forces exerted on the rudder

**Table 2** Relations concerning the hydrodynamic coefficients of a planing vessel

Coefficient	Formula
$Y_{\dot{v}}$	$-B^2 \rho \tan(\beta) k(\beta) [L_k + 2L_c] / 12$
$K_{\dot{v}}$	0
$N_{\dot{v}}$	$-B^2 \rho \tan(\beta) k(\beta) [L_k^2 + 2L_k L_c + 3L_c^2] / 48$
$Y_{\ddot{\psi}}$	$N_{\dot{v}}$
$K_{\ddot{\psi}}$	0
$N_{\ddot{\psi}}$	$-B^2 \rho \tan(\beta) k(\beta) [L_k^3 + 2L_k^2 L_c + 3L_c^2 L_k + 4L_c^3] / 120$
$Y_{\ddot{\phi}}$	0
$K_{\ddot{\phi}}$	$-0.010237 \rho B^5 \lambda (1 - \sin \beta) + h_1 Y_{\dot{v}}$
$N_{\ddot{\phi}}$	0
$Y_v$	$-0.5 \rho U B^2 [0.6494 \beta^{0.6} T^2 C_v^2]$
$K_v$	$Y_v [-KG + 1.5145B / \beta^{0.342}]$
$N_v$	$Y_v [-LCG + 12.384BT^{0.45} / (\tau + 5.28)]$

The local flow velocity entering the rudder having the height  $h_r$ , the cord length  $c_r$ , the lateral surface  $A_r$  and the effective aspect ratio  $A_e$  can be calculated using Eqs. 3 to 5:

$$u_r = U(1 - w_p) + C_{DU} \Delta u_p \quad (3)$$

$$v_r = C_{db} (v \cos \phi_F + w \sin \phi_F) - C_{dr} \sqrt{x_r^2 + y_r^2} \cdot r + C_{dr} \sqrt{x_r^2 + z_r^2} \cdot q \quad (4)$$

$$U_{rud} = \sqrt{u_r^2 + v_r^2} \quad (5)$$

The effect of velocity increment is calculated using Eq. 6:

$$C_{DU} = 0.7 \frac{D_P}{h_r} \text{ OR } 0.9 \frac{D_P}{h_r} \quad (6)$$

Flow velocity increment:

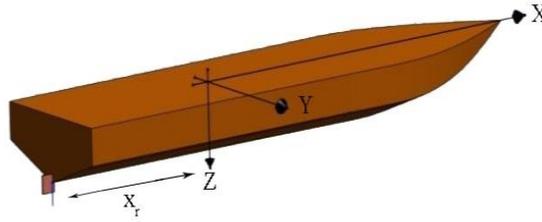
$$\Delta u_p = \sqrt{u_p^2 + \frac{8X_{prop}}{\rho\pi D_p^2}} - u_p \quad (7)$$

Flow unfirming factor:

$$C_{db} = 0.7 \quad (8)$$

$$C_{dr} = 1.0 \quad (9)$$

where  $\phi_r$  is the relative angle between the rudder and the vertical plane and  $z_r, y_r$  and  $x_r$  represent the location of the rudder with respect to the vessel's center of gravity, which is shown in Fig.4.



**Figure 4** Longitudinal distance between the vessel's center of gravity and the rudder

Where  $\delta_e = \delta - \delta_H$  is the rudder's effective angle of attack and can be shown as:

$$\delta_H = \arctan \frac{v_r}{u_r} \quad (10)$$

Using the previous equations, the lateral force can be derived as:

$$L = \frac{1}{2} \rho A_r C_{L\delta} U_{rad}^2 \sin \delta_e \quad (11)$$

In which:

$$C_{L\delta} = \frac{6.13A_e}{A_e + 2.25} \quad (12)$$

Lift flow induces drag force along the entrance of the rudder which can be calculated by:

$$D = \frac{1}{2} \rho A_r C_{Di} U_{rad}^2 \sin \delta_e \quad (13)$$

In which:

$$C_{Di} = \frac{C_{L\delta}^2}{\pi A_e} \quad (14)$$

The drag force acting on the rudder due to the frictional drag can be shown by the Eq. 13:

$$R = \frac{1}{2} \rho S_{wT} C_{TR} (U_{rad}^2 \sin \delta_e)^2 \quad (15)$$

Normal force exerted on the rudder due to the lateral drag coefficient  $C_n = 1.8$  is as follows:

$$Y_N = \frac{1}{2} \rho A_r C_n U_{rad} \sin \delta_e |U_{rad} \sin \delta_e| \quad (16)$$

The following equations define the forces and moments exerted on the rudder:

$$\begin{aligned}
 X_{rud} &= -R \cos \delta - D \cos \delta_H - Y_N \sin \delta - L \sin \delta_H \\
 Y_{rud} &= (-R \sin \delta - D \sin \delta_H + Y_N \cos \delta + (1 + a_h) L \cos \delta_H) \cos \phi_F \\
 Z_{rud} &= (-R \sin \delta - D \sin \delta_H + Y_N \cos \delta + (1 + a_h) L \cos \delta_H) \sin \phi_F \\
 M_{rud} &= X_{rud} \cdot z_r + Z_{rud} \cdot x_r \\
 N_{rud} &= -X_{rud} \cdot y_r + ((Y_N \cos \delta - R \sin \delta - D \sin \delta_H) \cdot x_r \\
 &\quad + (x_r + a_h \cdot x_h) L \cos \delta_H) \cos \phi_F
 \end{aligned} \tag{17}$$

where:

$$a_h \approx 0.672C_B - 0.153 \tag{18}$$

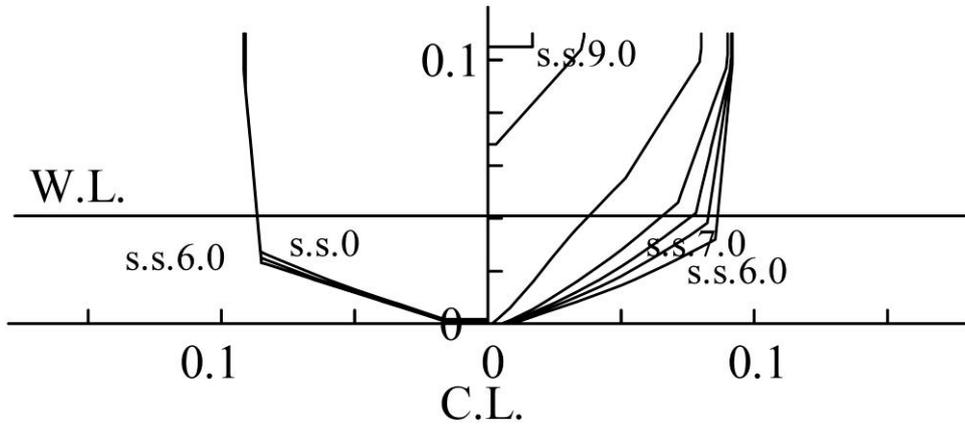
### 3. Model specifications

In order to check the validity of the present numerical method in simulating the maneuver of a planing vessel, a model-scaled planing vessel was considered; the experimental data on its maneuvering are available in publications. The main characteristics of the model are presented in Table 3 and the body lines are shown in Fig. 5.

**Table 3** Characteristic of the model vessel [8]

Parameter	Description	Value
L	Length (m)	0.93
B	Breadth (m)	0.18
T	Draft (m)	0.03
M	Mass (kg)	3.08
$\tau$	Trim (degree)	4
$\beta$	Deadrise (degree)	10
$l_{cg}$	Longitudinal center of gravity measured from stern (m)	0.33

overall length:  $L_{oa}=0.9366$  [m]



**Figure 5** Hull form of the model vessel [8]

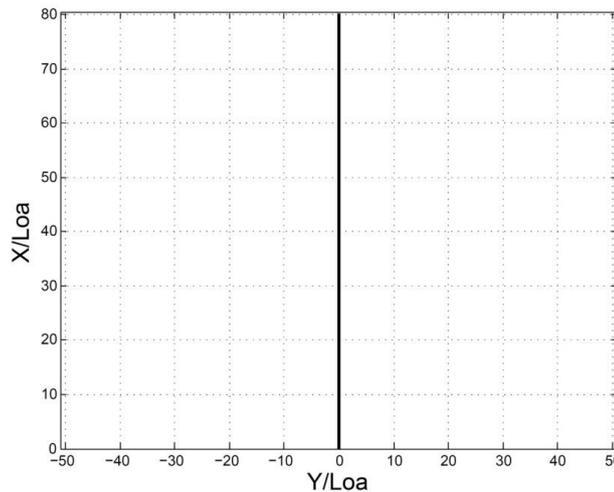
In the following sections, different types of maneuvers will be studied and the behavior of the vessel will be analyzed.

#### 4. Simulation of motion along the straight line

In this maneuvering scenario, as shown in Fig.6 the rudder angle was set to zero. The vessel's speed in the range of planing was set to 5 m/s. Fig. 7 shows the diagram of the vessel's path.



**Figure 6** Straight line maneuvering scenario

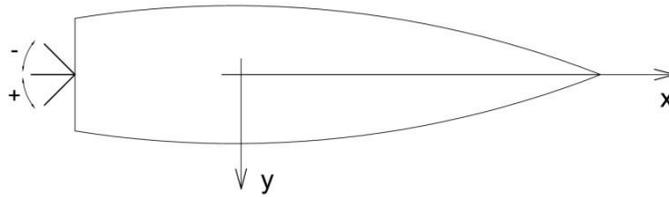


**Figure 7** Vessel's path with its rudder angle set to zero

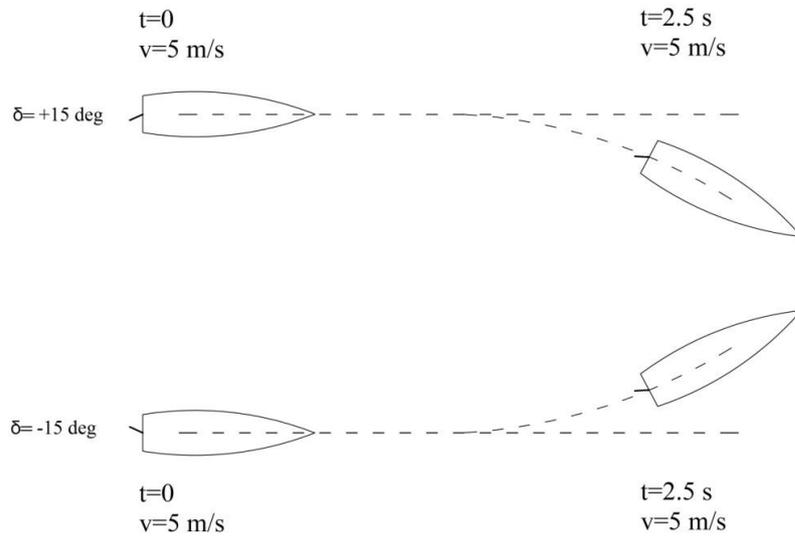
As it has been expected, the longitudinal speed of the vessel is not changing and no lateral speed exists. Therefore, the numerical prediction is in total agreement with what is expected from a real ship.

#### 5. Simulation of the course-changing maneuver

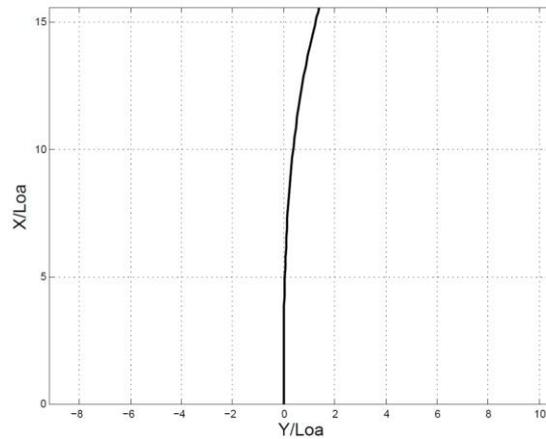
The aim of the course-changing maneuver is to find out the vessel's sensitivity to the rudder angle. In order to perform this maneuver, while the vessel is moving ahead in a straight line, the rudder angle increases to a specific angle, then the rudder angle remains constant. The vessel starts to change its path from the straight line. When the angle between the vessel's new directions with its previous straight line path reaches the value of the rudder's angle, the test finishes and the corresponding time duration gets logged. According to the logged time duration and with the help of the longitudinal motion-time diagram of the vessel, the traveling distance of the vessel can be calculated. In order to perform this maneuver test in the present paper, the initial vessel's speed and its ruder angle was set to 5 meters per second and 15 degrees ( $\delta = \pm 15^\circ$ ), respectively (see Fig.8). The numerical software was run with the initial conditions set as mentioned before. The results of the vessel's traveling path, vessel's yaw diagram vs. time (the angle between the vessel's directions and its old straight line) and the longitudinal path traveled by the vessel vs. time are shown in Figs. 10 to 12, respectively. In the vessel's yaw diagram, the corresponding time that takes the vessel's yaw angle to reach 15 degrees ( $\psi = +15^\circ$ ) was logged, then using the longitudinal displacement diagram of the vessel along the surge motion, its traveled distance was logged. This procedure was repeated for the negative angle of the rudder.



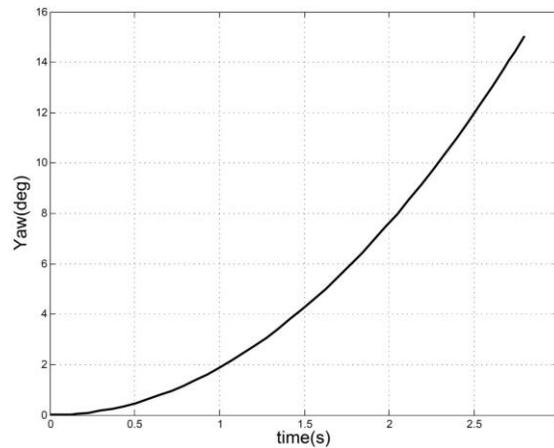
**Figure 8** Top view of the vessel and the rudder angle



**Figure 9** Schematic view of course-changing maneuver of the vessel

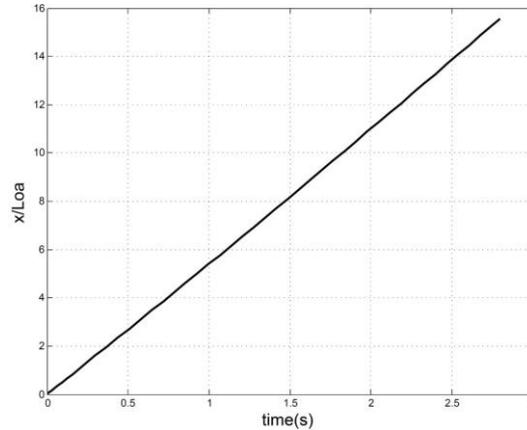


**Figure 10** Vessel's traveling path with the rudder angle of 15 degrees



**Figure 11** Vessel's yaw angle with the rudder angle of 15 degrees

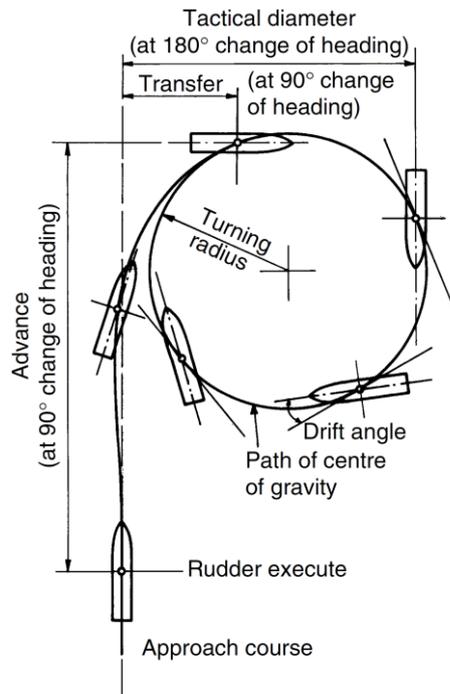
As one can see in Fig. 11, when the rudder angle is set to 15 degrees, it takes 2.7 seconds for the vessel's yaw angle to reach 15 degrees (the angle between the current path and old straight line). In such time duration, the vessel travels about 15 times its own length. This traveled path can be compared to those of the design guidelines, if any existed.



**Figure 12** Vessel's displacement along the surge motion with the rudder angle of 15 degrees

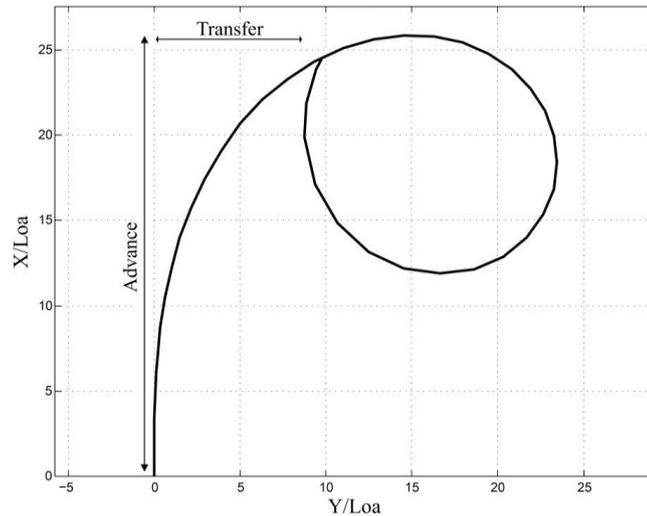
### 6. Simulation of the turning circle maneuver and validation of the results

In some situations (like collision avoidance) it is necessary for a vessel to turn and at the same time keep its stability in maneuvering. Furthermore, the vessel's turning diameter must be in an acceptable range. According to Fig. 13, in the turning circle maneuver, at first the vessel travels in a straight line with a constant speed, then the rudder's angle is deflected to its maximum (usually about 35 degrees) and remains so until the vessel travels a whole circle (at least 540 degrees). Both the portside and starboard turn should be performed. While the vessel is turning, the turning circle must be completed less than 540 degrees, so that the main maneuver parameters and necessary modifications for the deviations caused by sea currents or wind are applied.



**Figure 13** Definitions used in the turning test

For the turning circle test, it is assumed that the vessel is moving ahead at a speed of 2.1 meters per second, which corresponds to a Froude number of 0.7, and reaches its stable condition and there are no environmental factors affecting the vessel. Then the rudder angle increases up to 15 degrees. The simulated turning circle of the vessel is shown in Fig. 14.

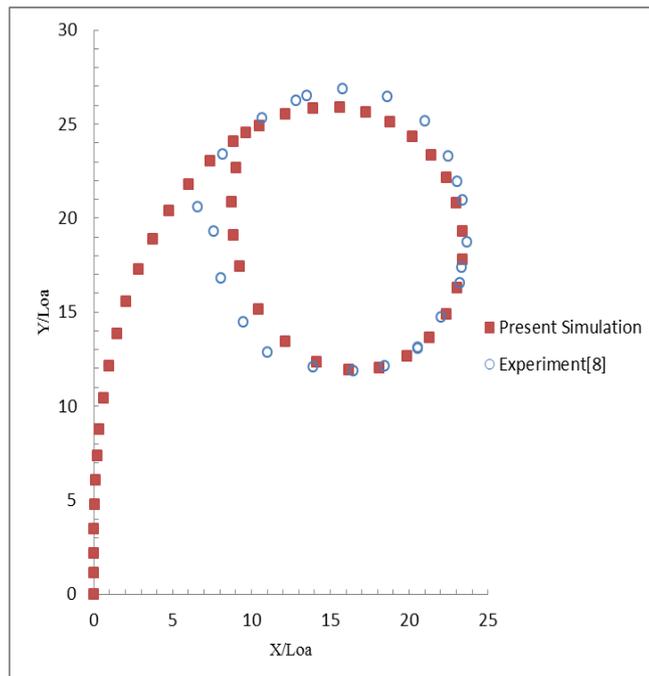


**Figure 14** Turning circle maneuver simulation

It can be seen from the diagram in Fig. 14 that:

- Vessel's advancement is 25 times of its own length.
- Tactical diameter of the turning circle is 15 times of the model length
- Vessel's transfer is about 10 times of its own length

In reference [8] the turning circle maneuver of the considered model with the same scenario used in the present paper was experimentally performed. The results of the present study and those given in reference [8] are shown in Fig. 15.



**Figure 15** Turning circle diagram of the present method and that given in [8]

As one can see there are some differences in the results. The hydrodynamic coefficients used in numerical modeling of the turning circle maneuver were taken from Table 2 and as it was mentioned earlier, those coefficients are only applicable for planing vessels with prismatic hulls. But the hull form used in the model experiments is neither prismatic nor in the planing regime. The experimental data for the rudder were not available. Basically, the experimental results were obtained by captive model tests and no rudder was fitted on the model. Thus, the software was run using some arbitrary, appropriate data for the rudder. It should be noted that the rudder has a great influence on the vessel's maneuverability. Therefore, the existence of such errors was not improbable.

### 7. Rudder influence on planing hull maneuverability

Forces exerted on a vessel while maneuvering in calm water are from different sources. From this viewpoint these forces can be divided into two distinct categories. First, as a vessel maneuvers the angle of attack to incident flow leads to hull hydrodynamic forces as described previously. The other category refers to external forces due to control surfaces such as the rudder. In the case of displacement vessels the rudder forces are small when compared to huge hull forces. But in the case of planing vessels the rudder forces are compared to the main hull forces. Rudder forces are proportional to the square of the inlet velocity. Because of the high inlet flow velocity to the rudder, the forces generated by a lifting surface such as the rudder are extremely high. Thus, the rudder is so more effective in the case of high speed craft.

Some geometric characteristics of the rudder govern the forces produced. As it was mentioned, the flow velocity is the main concern. Angle of attack (rudder angle) and aspect ratio are prominent too according to equations (11) and (12).

In the following text the influence of rudder angle on the planing craft turning circle is investigated. The equations of motion are solved for three rudder angles of 15, 17 and 19 degrees, respectively. Turning circles are as shown in Fig. 16.

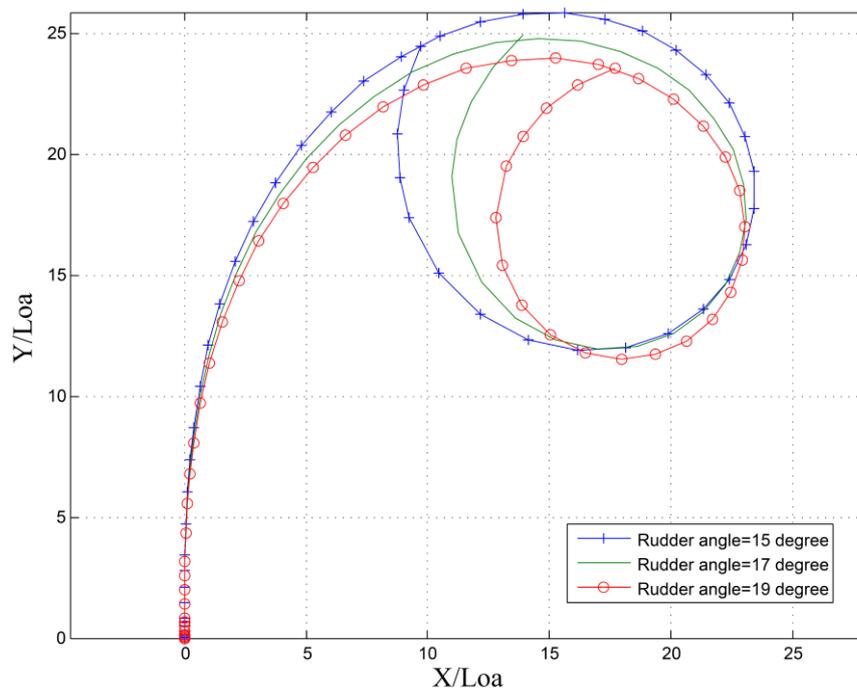


Figure 16 The influence of rudder angle on turning circle

As it is seen the rudder angle does not influence the advance distance of the planing hull so much. However, the tactical diameter reduces slightly as the rudder angle increases. As the rudder angle increases, the generated lift force increases too. On the other hand, the rudder drag would be higher too. Thus, the speed loss due to turning would be greater for high rudder angles.

Rudder geometry and dimensioning are the main concern of designers in the early stages of high speed craft design. One of the main characteristics is the rudder aspect ratio. Rudder lift/drag efficiency for a given angle of attack is strongly influenced by the aspect ratio which has as one definition, the depth or span of the rudder divided by the average chord length as shown in equation (19). Larger aspect ratios with the same area result in more efficient rudders and generate a given amount of lift at lower angles of attack than rudders with lower aspect ratios [15].

$$AR = \frac{T}{C} \tag{19}$$

The simulation is repeated for three rudders of different aspect ratio and the results are presented in Fig. 17. The aspect ratio proves to be an important design parameter. A higher aspect ratio leads to a smaller tactical diameter of the vessel. The aspect ratio is a control parameter in the design stage and ship's maneuverability can be modified by optimization of the rudder aspect ratio.

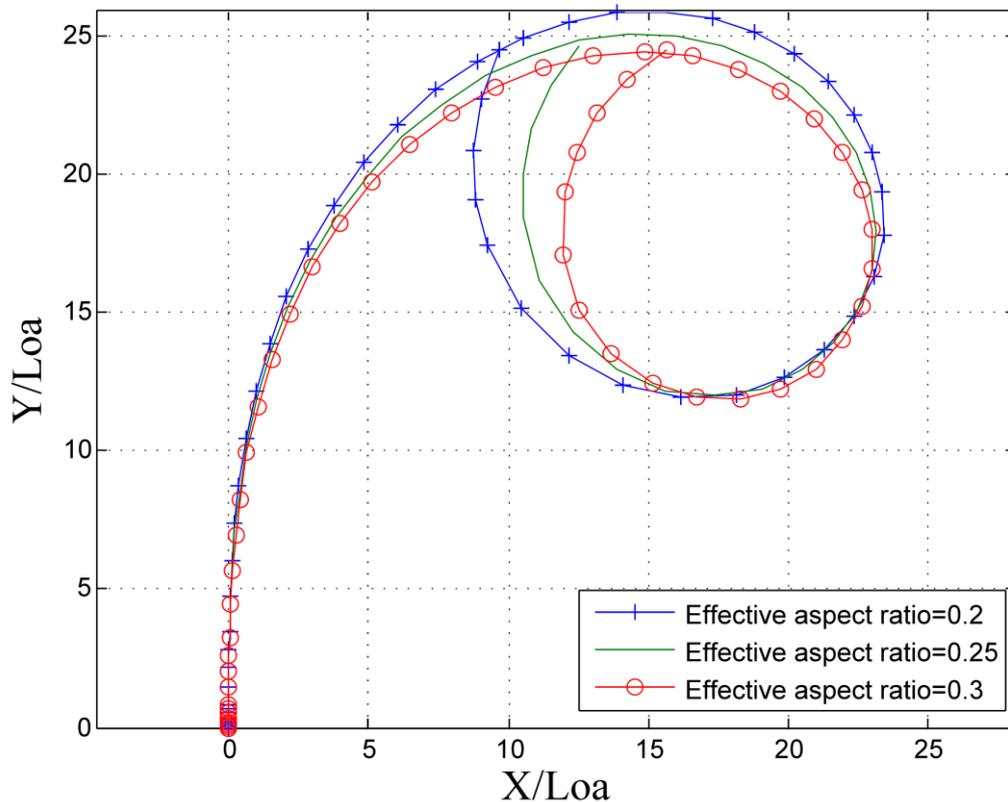


Figure 17 Turning circles for different aspect ratios

## 8. Conclusion

Hydrodynamic phenomena involved in maneuvering of planing vessels cause difficulties in the simulation of their maneuvers using mathematical models. Several parameters affecting the maneuvering of planing vessels are yet to be known and cannot be mathematically modeled. At high speeds, the coupling between the vessel's motion in the horizontal plane and the vessel's motion in the vertical plane and transverse plane is significant and cannot be ignored. Therefore, this study presents a mathematical model in which the influences of the roll angle, the pitch angle and the vertical displacement of the ship are considered in the maneuvering equations of the vessel. The presented method was verified using a planing model for which experimental results were available. The presented method can accurately predict high speed vessel's maneuver and its results are in a good agreement with those given in the references. In the present mathematical method, the influence of the vertical position of the center of gravity, its weight distribution and the deadrise angle were considered as the characteristics of the vessel's motion. The method can investigate the influence of each of these parameters on the behavior of the vessel. Furthermore, a simple mathematical model which can be used for planing vessels and controlling their traveling path is an important issue for which the present paper has formulized its equations. Rudder selection is a main concern in the design of high speed craft. The effect of rudder on vessel maneuverability is studied in this paper. The mathematical model can be used for comparing the influence of different rudder parameters on the turning circle. Although the presented method can be applied to simulate the rudder forces, it should be mentioned that the mathematical model cannot be used to evaluate the interaction of the rudder and the main hull and some special phenomena in the planing speed such as cavitation and ventilation of the rudder. These phenomena can be investigated through computational fluid dynamics, model experiments in a towing tank, and vessel's full scale measurements.

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Submitted: 30.05.2015. Sajad Hajizadeh, Mohammad Saeed Seif, [Seif@sharif.ir](mailto:Seif@sharif.ir),  
Hamid Mehdigholi  
Accepted: 01.02.2016. Department of Mechanical Engineering, Sharif University of Technology,  
Center of Excellence in Hydrodynamics and Dynamics of Marine Vehicles,  
Tehran, Iran