Journal of Engineering Science and Technology
ICIST2024, Vol. 20, No. 5 (2025) 67 - 79

MANOEUVRING SIMULATIONS ON THE DESIGN OF THREE RUDDER-SHAPED LIKE (RSL) BODIES FOR LOW DRAG USV MODEL

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Abstract

This paper presents an investigation into manoeuvring prediction simulation program to assess the effects of hydrodynamic derivatives for single, and three-rudder shaped like (RSL) hulls model. The study was conducted by simulating the manoeuvring mathematical model with values of hydrodynamic derivatives of a three-RSL hulls (model A) and comparing them with the values of hydrodynamic derivatives of single-RSL hull (model B) of a vessel during a turning circle test. Development of the manoeuvring time domain simulation programme by using MATLAB-Simulink software was included this study. The hydrodynamic derivatives and coefficients were obtained from a model test by performing various harmonic tests through a planar motion mechanism (PMM) at Universiti Teknologi Malaysia's Marine Technology Centre towing tank. By simulating the manoeuvring mathematical model and comparing with values of hydrodynamic derivatives, it was found that the tactical diameter and advance ability of the vessel during turning was not the same with International Maritime Organisation (IMO) criteria. The simulation for turning circle trajectory model B was 0.65 times smaller than simulation model A in turning circle size. It showed that by using the values of hydrodynamic derivatives on a single-RSL and then combining their values into one unit to become three-RSL (model B), gave much smaller turning circle size trajectory as compared to the size of the model. Two types of three-RSL hull mathematical manoeuvring models were simulated and successfully demonstrated. In addition, these manoeuvring prediction simulations were proposed for use in the future study on manoeuvring characteristics simulation for three-RSL hull to comply with the IMO criteria.

Keywords: Manoeuvring, MATLAB Simulink, Rudder shaped-like.

1. Introduction

The new design of floating platform by using three hulls with a self-manoeuvring system as Unmanned Surface Vehicle (USV) and capable of collecting the same data as a hydrography boat is needed. This new platform provides moderate speed with long endurance and is kept in station at the one reference point for ocean measurement activities such as recording wave data, meteorological data, current data, sea surface data, and other oceanographic measurements with improved capabilities of resistance and seakeeping [1]

Investigations into the resistance of three hulls or trimaran had proven that such hull forms had lower resistance at high speeds as compared to catamarans and mono hull of similar displacement [2]. In recent years, the term trimaran was associated with a vessel made of three hulls with a larger central main hull and two smaller side hulls called the outriggers. Another term for a vessel that is made of three hulls is tricore but it is different from the trimaran because it is a vessel made of three identical hulls of the same shape [3]. The study of rudder-shaped like (RSL) is similar to the tricore to increase the speed of a vessel with corresponding reduction in required power.

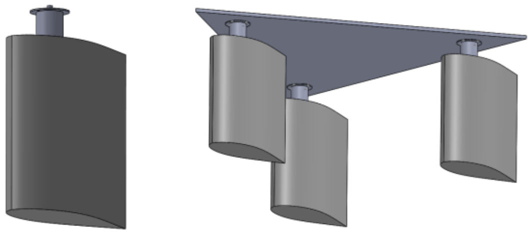
At the moment, studies on related manoeuvring of monohull vessel which followed the standard International Maritime Organisation (IMO) criteria were many, while few studies were done on multihull manoeuvring which were mainly related to the three-hull ship. References of resistance and seakeeping of the three-hull especially in the trimaran are many, but few on manoeuvrability, and thus it has drawn many researchers' attention because one of the most important performances, manoeuvrability, is closely related to the economy and safety of ships.

Therefore, this study is to investigate the manoeuvring characteristics of three RSL hull configuration systems by using a simulation program. This allows the study to determine the vessel by following the standard IMO criteria at an acceptable level. Other than that, the configuration of the hulls is very important in order to optimise their performance [4]. This RSL design uses three RSL bodies in columns with NACA 0012 profile hull form for low-drag determination.

2. Hull Form and Three Hull Configurations

The basic concept of this RSL model platform of this design is the combination of three identical hulls (tricore) with NACA 0012 profiles as shown in Fig. 1. This model operates at low speed. In fact, the three hulls for trimaran types are usually faced with high resistance at low speed due to large wetted surface area, which are affected by the high percentage of frictional resistance [5]. The use of National Advisory Committee for Aeronautics (NACA) profile shape provides the model with low-drag characteristic, with minimum power requirements needed in manoeuvring and station-keeping. Table 1 shows particulars of the RSL model.

This concept is used to accomplish the design requirements related to the low drag and minimum power in operation. The autonomous system needs to be developed by using specific programming as core of the self-manoeuvring vehicle [6]. A motor thruster system will be put at the bottom of each hull as a propulsion system. This means that the motor thruster functions as a propulsion system as well as a steering system.



(a) (b)

Fig. 1. Model design RSL (a) single-RSL hull model and (b) three-RSL hull model.

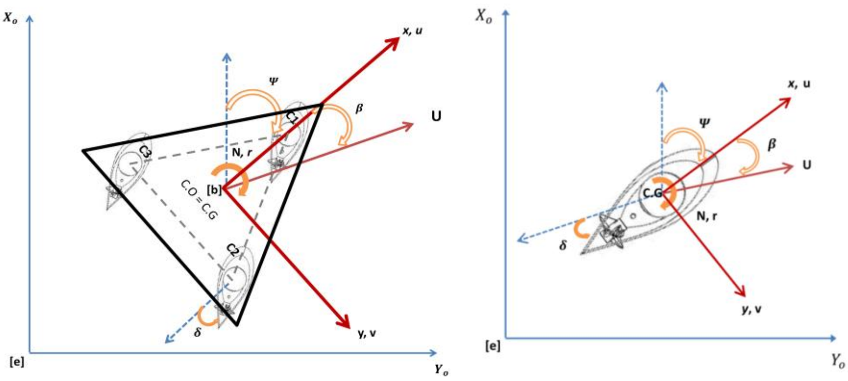
Table 1. Main particulars of single and three-RSL hull of model.

Main Particulars	Single RSL	Three RSL
Length, *l* (m)	0.300	0.730
Beam, *b* (m)	0.120	0.500
Height, *h* (m)	0.325	0.325
Draft, *d* (m)	0.265	0.265
Wetted Surface Area, *S* (m^2)	0.437	1.311
Weight, m (kg)	4.22	18.24
Mass moment of inertia, I'_{zz} (kgm^2)	0.31	1.424
Added mass, m'_x or $X'_{\dot{u}}$	-2.80	-4.68

3. Mathematical Model

In order to simulate the vessel motion, two types of equation model for a three-RSL hull vessel were introduced by H. Yasukawa and Y. Yoshimura [7] one unit of trimaran to become model A and K. S. Varyani et al. [8] method to measure hydrodynamic forces and moments of each hull unit from trimaran become model B.

The mathematical model for two types of equation model manoeuvring motion can be described by the following equation of motion, through the coordinate system in Fig. 2.



(a) (b)

Fig. 2. Co-ordinate systems of (a) three-RSL platform and (b) single-RSL hull platform.

The equations of motion (model A) of a three-RSL hull design with one unit three-RSL hull platform are described as follows:

$$(m+m_x)\dot{u}_G-(m+m_y)v_G r_G=[X_H]+[X_{P1}+X_{P2}+X_{P3}]+[X_{R1}+X_{R2}+X_{R3}] \quad (1)$$

$$(m+m_y)\dot{v}_G+(m+m_x)u_G r_G=[Y_H]+[Y_{P1}+Y_{P2}+Y_{P3}]+[Y_{R1}+Y_{R2}+Y_{R3}] \quad (2)$$

$$(I_{zz}+J_{zz})\dot{r}_G=[N_H]+[N_{P1}+N_{P2}+N_{P3}]+[N_{R1}+N_{R2}+N_{R3}] \quad (3)$$

The second type equations of motion (model B) of a three-RSL hull design with each hull unit from the three-RSL hull platform are described as follows:

$$(m+m_x)\dot{u}_G-(m+m_y)v_G r_G=[X_{H1}+X_{H2}+X_{H3}]+[X_{P1}+X_{P2}+X_{P3}]+[X_{R1}+X_{R2}+X_{R3}] \quad (4)$$

$$(m+m_y)\dot{v}_G+(m+m_x)u_G r_G=[Y_{H1}+Y_{H2}+Y_{H3}]+[Y_{P1}+Y_{P2}+Y_{P3}]+[Y_{R1}+Y_{R2}+Y_{R3}] \quad (5)$$

$$(I_{zz}+J_{zz})\dot{r}_G=[N_{H1}+N_{H2}+N_{H3}]+[N_{P1}+N_{P2}+N_{P3}]+[N_{R1}+N_{R2}+N_{R3}] \quad (6)$$

The left hand-side of Eq. (1) to Eq. (6) represent the inertial terms. The right hand-side represents the hydrodynamic and external forces and moments that act on the ship. The subscripts *H*, *P*, and *R* symbolise ship hull, propeller, and rudder respectively according to the concept of manoeuvring mathematical group (MMG) [9].

3.1. Forces and Moment Acting on Hull

The forces and moments for hull measured according to the previous study in experiment can be expressed by the following equation [10]. The coupling mathematical model in the horizontal plane can be deduced by considering surge, sway, and yaw motions as below:

$$X_H=(0.5\rho L d U^2)(X'_u u) \quad (7)$$

$$Y_H=(0.5\rho L d U^2)(Y'_v v+Y'_r r+Y'_{NL}) \quad (8)$$

$$N_H=(0.5\rho L^2 d U^2)(N'_v v+N'_r r+N'_{NL}) \quad (9)$$

where $X'_u u$ is non-dimensional of ship resistance. ρ, L and d_m are water density, ship length and draft, respectively. $X'_u u$ is ship resistance. $Y'_v v, Y'_r r, N'_v v$ and $N'_r r$ are sum of linear hydrodynamic forces due to the RSL plane motions. Meanwhile Y'_{NL} and N'_{NL} are sum of nonlinear hydrodynamic forces in cubic model obtained by [9].

$$Y'_{NL}=Y'_{rv} rv+Y'_{vvv} v^3+Y'_{rrr} r^3 \quad (10)$$

$$N'_{NL}=N'_{rv} rv+N'_{vvv} v^3+N'_{rrr} r^3 \quad (11)$$

3.2. Forces and Moments Induced Propeller and Rudder

The forces and moments induced by propeller can be expressed by the following formulae [11].

$$X_P=(1-t_P)\rho K_T D_P^4 n^2 \quad (12)$$

$$Y_P = X_P \sin\delta \tag{13}$$

$$N_P = Y_P\ (xp) \tag{14}$$

The rudder forces are expressed as follows:

$$X_R = -F_N\ sin\ \delta \tag{15}$$

$$Y_R = X_R\ cos\ \delta \tag{16}$$

$$N_R = Y_R\ (xr) \tag{17}$$

While F_N is normal force of rudder in Eq. (15) and expressed as follow:

$$F_N = \frac{\rho}{2} A_R f_\alpha U_R^2 \sin\alpha_R \tag{18}$$

While f_α, in the Eq. (18) is the lift coefficient of rudder known as Fujii's prediction formula [7]:

$$f_\alpha = \frac{6.13\Lambda}{2.25} + \Lambda \tag{19}$$

And U_R is rudder inflow velocity and α_R is the rudder inflow angle respectively also in Eq. (18), represented in non-dimensional as follows:

$$U_R = \sqrt{{u_R}^2 + {v_R}^2} \tag{20}$$

$$\alpha_R = \delta - tan^{-1}\left(\frac{-v_R}{u_R}\right) \simeq \delta - \left(\frac{-v_R}{u_R}\right) \tag{21}$$

4. Manoeuvring Test Following the IMO Regulation

The International Maritime Organisation (IMO) is agency responsible for the safety and security of shipping and prevention of marine pollution by ships. The IMO Maritime Safety Committee adopted Resolution MSC.137(76) "Standards for Ship Manoeuvrability"; [12]. The ship will have to achieve to ensure acceptable manoeuvring properties for a minimum criterion performance following the IMO Standards for Ship Manoeuvrability, in which these criteria are listed in Table 2.

Table 2. IMO criteria standards for ship manoeuvrability [13].

Item	Criteria	Test
Initial turning Ability	Distance ship run before 2nd rudder execution < 2.5L	10°/10° Z-test
Turning ability	Advance < 4.5L Tactical diameter < 5.0L	Turning test with max. Rudder angle (35°)

These current IMO criteria in Table 2 were proposed into the IMO standards of ship manoeuvrability. The IMO criteria, such as turning circle test, initial turning ability test, are listed and discussed below.

The turning circle test was performed at the test speed by applying the maximum design rudder angle permissible or with 35° rudder angle to starboard and port [14]. These tests were to obtain the essential information of the tactical diameter and advance manoeuvre criteria is as shown in Fig. 3. Table 2 shows standards for the advance criteria which should not exceed four and half times of ship lengths (L) and tactical diameter criteria should not exceed five times of ship lengths in the turning circle manoeuvre for turning ability.

The initial turning ability test was done by applying the 10° rudder angle to port or starboard of ship. Following criteria of the initial turning ability as shown in Table 2, the time of the ship heading was changed to 10° from the original heading of ship, which should not move more than two and half time of ship lengths.

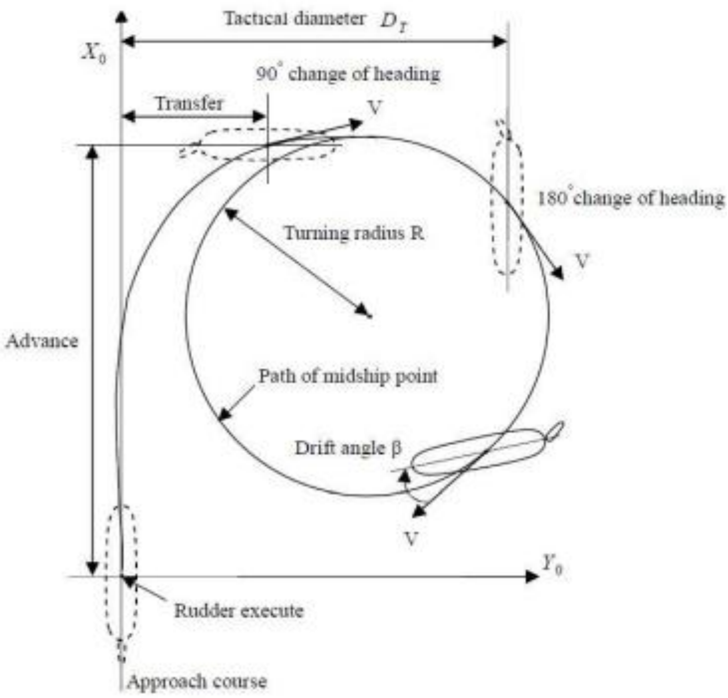


Fig. 3. Definitions used in the turning circle test. [15].

5. Manoeuvring Simulations Program

5.1. Time domain simulation

Time domain simulation program for a three-RSL hull vessel manoeuvring was developed in MATLAB-Simulink software. The simulation program, which was structured in modular form, having interaction with various elements of the module, was described as individual block (hull, thruster, and rudder). The equations of motions were then solved by numerical integration in time domain simulation by using an ordinary differential equation (ODE) solver with variable time steps integration to avoid errors in some critical condition [16]. The software developed followed the International Towing Tank Conference (ITTC) recommended procedures [17].

The MATLAB-Simulink software was used to simulate numerical simulations of manoeuvre motion in turning circle as a comparison to the three-RSL hull mathematical manoeuvring motion model. The time domain simulation program on MATLAB-Simulink was developed based on both mathematical model A and mathematical model B of a three-RSL hull vessel manoeuvring in calm water condition.

5.2. Simulation equation

Equation in the system of motion used in the simulation were three degree of freedom (DOF) and the model was based on the concept of modular manoeuvring model, whereby each element of the three-RSL vessel (hull, thruster and rudder) was represented by a self-contained and discrete module shown in the following surge, sway force and yaw moment equations.

$$m(\dot{u} - vr) = X \tag{22}$$

$$m(\dot{v} + ur) = Y \tag{23}$$

$$I_{zz}\dot{r} = N \tag{24}$$

The equations were rearranged in order to the set of acceleration. The set of accelerations that needed to be integrated to obtain velocities and finally the following described displacements:

$$\dot{u} = \frac{X}{m} + vr \tag{25}$$

$$\dot{v} = \frac{Y}{m} - ur \tag{26}$$

$$\dot{r} = N/I_{zz} \tag{27}$$

The above set of equations could be integrated by using the ODE solver as below:

$$u = \int \dot{u}dt \text{ and } x = \int u\, dt \tag{28}$$

$$v = \int \dot{v}dt \text{ and } y = \int v\, dt \tag{29}$$

$$r = \int \dot{u}dt \text{ and } \Psi = \int r\, dt \tag{30}$$

5.3. Simulations results

In this research the forces and moments for the RSL hull determine the hull derivatives for swaying and yawing motions obtained through captive model test carried out in a towing tank by using PMM [7, 8, 10] as shown in Table 3, Tables 4 and 5. Meanwhile, the surging damping coefficient prediction for the RSL hull was obtained through the model resistance test in the towing tank as shown in Table 6. The equations proposed by Hooft and Pieffers (1988) [18] were used to estimate the added mass coefficient in the longitudinal direction ($X_{\dot{u}}$).

Table 3. The non-dimensional velocity dependent derivatives of a single-RSL hull and three-RSL hull models by pure sway test.

Model	$Y'_{v'}$	Y'_{vvv}	$N'_{v'}$	N'_{vvv}	$Y'_{\dot{v}'}$	$N'_{\dot{v}'}$
Single RSL	-0.059	-2.154	0.239	1.679	-0.749	0.485
Three RSL	-1.449	-2.058	1.588	0.912	-19.026	4.617

Table 4. The non-dimensional velocity dependent derivatives of a single-RSL hull and three-RSL hull models by pure yaw test.

Model	$Y'_{r'}$	Y'_{rrr}	$N'_{r'}$	N'_{rrr}	$Y'_{\dot{r}'}$	$N'_{\dot{r}'}$
Single RSL	9.420	308.360	-0.353	-23.372	2.680	-4.733
Three RSL	21.041	629.730	-3.562	-431.320	177.600	-17.327

Table 5. The non-dimensional angular velocity dependent derivatives of a single-RSL hull and three-RSL hull models by coupling angular velocity with transverse velocity.

Model	$Y'_{r'v'}$	$N'_{r'v'}$
Single RSL	19.057	10.329
Three RSL	51.076	186.11

Table 6. The non-dimensional velocity dependent derivatives of a single-RSL hull and a three-RSL hull models.

Model	$X'_{u'}$
Single RSL	-0.087
Three RSL	-0.122

In the simulation model, prediction of forces and moments induced by thruster was obtained by following azimuthing pod drives by Ayaz et al. (2005) model [11]. The propeller blade was identified based on a bladed Kaplan type propeller with 19A ducted (Ka 4-70) and the propeller blade characteristic data was obtained from the propeller open water test [19] as shown in Table 7. Finally, the force and moment of rudder were predicted by using Kijima formulae [20-23] via rudder parameter, as shown in Table 8.

Table 7. Thruster propeller parameter.

Parameter	Value
Number of propellers, N	1
Propeller Blade Number, Z	4
Blade Area Ratio	0.550
Propeller Diameter. D (m)	0.06
Pitch Ratio (P/D)	1.4
Trust deduction, t	0.07
a_0	0.5705
a_1	-0.0382
a_2	-0.3578

Table 8. Rudder parameter

Parameter	Value
Rudder area (A_R) m^2	0.080
Span (d_m) m	0.325
Draft Fin (d_r) m	0.265
Breadth (b_r) m	0.120
Chord (L) m	0.300
Aspect ratio (Λ) m	0.883
Projectile Area (A_x) m^2	0.032

Figure 4 and Table 9 show that the comparison results of 35^o angle turning trajectory of the three-RSL hull of model A and model B with constant speed. Based on the simulation result, the turning circle of model A as compared to model B for manoeuvre ability of the vessel during turning was not the same in scale size but have the same pattern of turning circle. The simulation for turning circle trajectory model B was 0.65 times smaller than simulation model A in turning circle size. It showed that by using the values of hydrodynamic derivative on a single-RSL and then combining their values into one unit to be three-RSL (model B) gave much smaller for turning circle size trajectory proportion to size of the model. This was due to the influence of interaction effects between the three hulls and hydrodynamic derivative effects were different for each type of configuration for the body hull to one unit system needed to be considered [24]. It was also found that the configuration of the outrigger or the side hull brought the effect of turning circle of the trimaran vessel with respect to distance from the side hull.

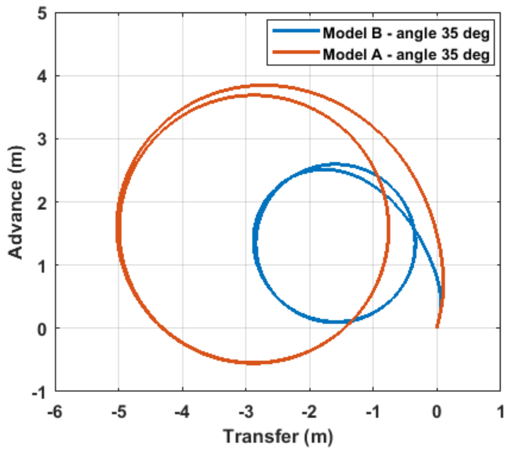


Fig. 4. Comparison of model A and model B of turning circle at angle 35° with speed n-10 rps.

Table 9. Turning circle test three-RSL model for IMO standard ability.

Turning ability (Index)	Criteria	Speed (n-10)	
		Model A	Model B
Tactical diameters (D_T)	<5.0L-Below 3.65 m	5 m	2.9 m
Advances (A_D)	<4.5L-Below 3.29 m	3.7 m	2.6 m
Transfer		2.9 m	1.7 m

Finally, this section also shows the comparison of simulation model with test model on turning circle manoeuvre. The test model conducted with the testing design model is as shown in Fig. 5. Figure 6 and Table 10 shows the result of simulation for turning circle manoeuvre of the model A and model B with the test model. It showed that the test model had similar size turning circle with model A but moving more to negative y- axis as compared to model A and model B. This result showed that, the model A simulation had similar pattern to the test model in turning circle manoeuvre as compared to model B.

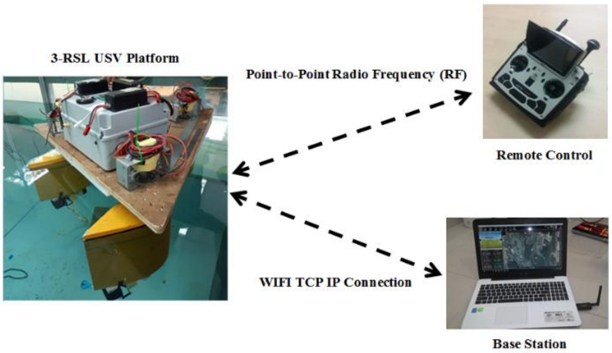


Fig. 5. Three-RSL USV model test design.

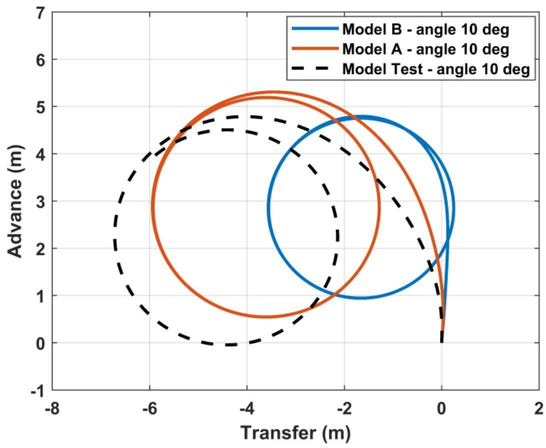


Fig. 6. Comparison of model A, model B and test model of turning circle at angle 10° with speed n-10 rps.

Table 10. Turning circle test three-RSL model for IMO standard ability.

Turning ability (Index)	Criteria	Speed (n-10) Model A	Model B	Model Test
Tactical diameters (D_T)	<5.0L-Below 3.65 m	6 m	3.5 m	7 m
Advances (A_D)	<4.5L-Below 3.29 m	5.3 m	4.8 m	4.8 m
Transfer		3.5 m	1.5 m	4.5 m
Diameter size		4.7 m	3.8 m	4.5 m

6. Conclusions

The MATLAB-Simulink software was used to simulate numerical simulations of motion manoeuvre in turning circle. Two types of three-RSL hull mathematical manoeuvring models were simulated and successfully demonstrated. The time domain simulation program on MATLAB-Simulink were developed based on mathematical model A and mathematical model B of three-RSL hull manoeuvring in calm water condition by using input of both types of hydrodynamic derivatives values, such as resistance, thruster propeller parameter and rudder parameter.

Results of the turning trajectory of the three-RSL of model A and model B showed that the turning trajectory in tactical diameter size for model A was approximately on average 1.65 times bigger than model B. Based on the simulation result, the turning circle of the three-RSL hull vessel became larger because the hydrodynamic derivatives value of the hull for model A more than model B. It was also found that the value of hydrodynamic derivative of three-RSL on the unit hull effected on the manoeuvring performances in turning circle criterion. The main cause was the difference in hydrodynamic force directly proportional to yaw of angular velocity caused by the side hulls. The configuration of side hull brought the effect of turning circle of the trimaran vessel with respect to distance from side hull to the main hull. This was because the effect on hydrodynamic derivative value was different for each configuration type of the body hull to one unit system of the hull configuration. In addition, these simulation programs were proposed for use in the future study on manoeuvring characteristics simulation for three-RSL hull to comply with the IMO criteria.

Nomenclatures

a_0, a_1, a_2	Constants for propeller open characteristics.
A_R	Rudder area, m^2.
D_P	Propeller diameter, m.
f_α	The lift coefficient of rudder and as the function of rudder aspect ratio Λ.
F_N	Dimensionless rudder normal force.
I_{zz}	Moment of inertia of vessel.
J_P	Propeller advance coefficient. [$J_P = U_P/nD_P$]
J_{zz}	Added moment of inertia in z- axis.
K_T	Coefficient of thrust propeller force. [$K_T = a_0 + a_1 J_P + a_2 J_P^2$]
m	Mass of vessel.
m_x, m_y	Added mass in x- axis and y- axis.
n	Propeller revolution in rev/s.
N_H , N_P, N_R	Moments action at z-axis on hull, thruster, and rudder.
$\dot{r}_G$	Angular acceleration at centre of gravity in z- axis.
r_G	Angular velocity at centre of gravity in z- axis.
t_P	Coefficient of thrust reduction in forward moving, [(R/T) 1].
$\dot{u}_G$	Acceleration at centre of gravity in x- axis.
u_G	Velocities at centre of gravity in x- axis.
$\dot{v}_G$	Acceleration at centre of gravity in y- axis.
U_P	Propeller speed, rps.
v_G	Velocities at the centre of gravity in y- axis.
xp	Distance from centre of thruster to centre of vessel body at longitudinal direction, m.
xr	Distance from centre of rudder to centre of vessel body at longitudinal direction, m.
X_H , X_P, X_R	Forces action at x- axis on hull, thruster, and rudder.
Y_H , Y_P, Y_R	Forces action at y- axis on hull, thruster, and rudder.

Greek Symbols

Λ	Rudder aspect ratio
β	Angle of drift at centre of gravity [β = - sin -1 (v/U)]
δ	Thruster angle/ rudder angle
ρ	Water density, kg/m^3.

Abbreviations

DOF	Degree of Freedom
IMO	International Maritime Organisation
IP	Internet Protocol
ITTC	International Towing Tank Conference
MATLAB	Matrix Laboratory
MMG	Manoeuvring Mathematical Group
NACA	National Advisory Committee for Aeronautics
ODE	Ordinary Differential Equation
PMM	Planar Motion Mechanism
RF	Radio Frequency
RSL	Rudder Shaped Like
TCP	Transmission Control Protocol
USV	Unmanned Surface Vehicle

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