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PREDICTION OF MANOEUVRING BEHAVIOUR OF AN OFFSHORE SUPPLY VESSEL BY USING SIMULATION PROGRAM

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ABSTRACT

Manoeuvring ability of Offshore Supply Vessel (OSV) is a very critical aspect. An early prediction of vessel behaviour will definitely help to improve upon the design. The regular methods available for manoeuvring prediction such as free running model test, captive model test etc., are found to be expensive and time consuming. As an alternative, the current approach tries a numerical simulation method with parameters determined from a database. This study presents the manoeuvring prediction of an OSV which includes the development of time domain simulation program by using Matlab Simulink software. Three degrees of freedom were considered and applying the Newtonian laws, the equations of motion were framed. Further, forces on hull, forces and moments induced by propeller and rudder were also taken into reckoning. Results were obtained with inputs of vessel speeds, engine revolutions etc. Validation of the prediction results was also carried out by comparing the results with full-scale sea trial data. The prediction results show a good agreement with the sea trial data. Applying approximate numerical formula for manoeuvring prediction is seen to be a reliable and economic prediction tool at early design stages of such vessels.

Keywords: Manoeuvring prediction, Manoeuvring characteristics, Offshore Supply Vessel

1. INTRODUCTION

Manoeuvring characteristic of an Offshore Supply Vessel (OSV) is a very important aspect as her mission of operation demands high manoeuvrability in order to make sure that it can be operated in various situations and locations. In harbour and offshore operations and tow and tug activities the risk of collision and grounding are high for such vessels. A successful manoeuvring is interpreted as the ability of the ship to go anywhere, from straight ahead without any rudder action to tight turning with significant rudder action.

In general, low speed vessels with high block coefficient such as OSVs are known to have bad manoeuvring characteristic because of the full hull form with small length to beam ration [1]. The ship particulars of OSV are shown in Table 1.

In December 2002, International Maritime Organization (IMO) has adopted the Resolution MSC.137 (76), Standards for Ship Manoeuvrability. These standards were developed to ensure safe operation of ships at sea. In order to comply with the IMO manoeuvring standards, the ability to predict the manoeuvrability of OSV at the design stage is important. The fact that it is too late to effect design changes after the vessel has been built makes such predictions imperative. The complexity in analysing manoeuvrability characteristics is due to many variables.

Table 1: Ship particulars

Particulars	Vessel
LOA	60.8 m
LBP	54.0 m
B	14.8 m
D	5.7 m
T	4.6 m
Displacement	2373 tonnes
Speed	12.5 knots
Block coefficient	0.705
Prismatic coefficient	0.72

Firstly, the area and shape of the rudder may be mentioned. The flow around the rudder is affected by a combination of variables such as the eddy currents created by ship's motion and the propeller races.

Being located partially or as a whole, the rudder experiences basic hydrodynamic phenomena of stall, cavitation and aeration. During the stall, separation occurs resulting in reduction of normal flow pressures. These factors are difficult to predict as they are governed by different laws of similitude and further affected by the ship's turning actions. Secondly, the steering action of the ship itself is affected by many factors. The hull section just forward of the propeller affects the directional stability. Larger the area of this section, greater is the resistance to turning. In the case of OSVs, where greater manoeuvrability is desired, these areas are reduced. Factors beyond the control of design could be the depth of water, number of propellers, relative position of rudders and propellers. Lastly, the forces on the ship while the turning occurs affect the manoeuvrability. The initial turning phase causes an inward heeling which may change to outward heel due to heeling moments caused by the forces. During the final steady turning phase, the position of the rudder is important in correct the heel and the ship-keeping as well.

While measuring the manoeuvring performance of vessels, the regular tests would be on turning circles, pull-back manoeuvres, zig-zag manoeuvres, changing of vessel's heading, and turning / stopping / direct-reverse tests. IMO standards provide criteria on the ship turning ability, yaw checking ability, course keeping ability and stopping ability. Of the several methods available to assess the manoeuvring criteria of a vessel, sea trial and free running model tests are the straightforward methods which are regularly employed. However these methods are expensive.

Simulation methods could also be used to analyze manoeuvring criteria either by incorporating the hydrodynamic coefficients obtained from captive model tests or empirical formulae. The captive model test often incurs heavy expenditure in equipment, testing time and cost. In practice, both time and costs are limited in the early design stages and so the execution of extensive model test on every ship is practically not achievable. As an alternative, nowadays, the numerical simulation method with parameters determined from a database is the principal approach employed. Further, the reliability and accuracy of numerical simulation are required to be validated with full-scale sea trial data. The establishment of cheaper and accurate manoeuvring prediction tools based on numerical approach is essentially important in order to comply with IMO manoeuvring standards.

This study describes a manoeuvring prediction study based on numerical simulation method which did not require a series of model tank tests. The objective of this study is to predict manoeuvring performance of an Offshore Supply Vessel (OSV) by using numerical approach simulation program and then validate the simulation results with the full-scale sea trial data.

2. IMO MANOEUVRING STANDARDS

The problem of ship manoeuvrability has considerably grown in the last decade, both for merchant and naval ships. With regards to merchant ships, The Interim Standards of Ship Manoeuvrability A.751 (18) was adopted finally as IMO Resolution MSC.137 (76), Standards for Ship Manoeuvrability in 76th MSC of IMO in December 2002. IMO established minimum manoeuvrability standards to ensure safety of all seagoing ships.

The current IMO standards for ship manoeuvrability contain four distinct criteria: turning ability, initial turning ability, stopping ability, yaw-checking and course-keeping abilities. These criteria are listed in Table 2 while the manoeuvring indices are shown in Figure 1.

Table 2: IMO Evaluation criteria in final standards for ship manoeuvrability [2]

Ability	Test	Criteria
Turning ability	Turning test with max. Rudder angle (35°.)	Advance <4.5 *L* Tactical Diameter <5.0 *L*
Initial turning Ability	10°/10° Z-test	Distance ship run before 2nd rudder execution < 2.5*L*
Stopping ability	Stopping test with full astern	Track reach < 15*L*
Course-keeping and Yaw-checking ability	10°/10° Z-test	1st Overshoot <10° (*L/U*<10s) <(5+0.5 *L/U*) (10s<*L/U*<30s) <20° (30s<*L/U*)
		2nd Overshoot <25° (*L/U*<10s) <(17.5+0.75(*L/U*)) °(10s<*L/U*<30s) <40° (30s<*L/U*)
	20°/20° Z-test	1st Overshoot. <25°

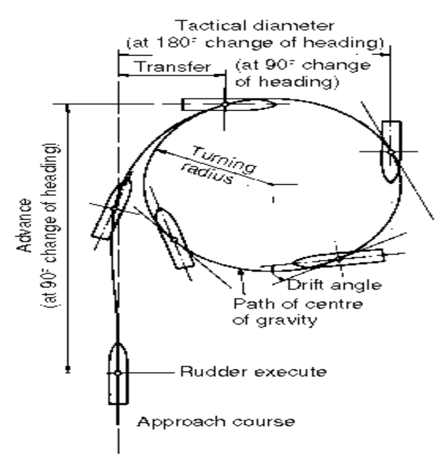

Figure 1: Manoeuvring Characteristic Indices for Turning Ability [3]

3. MATHEMATICAL MODEL

The mathematical model for manoeuvring motion can be structured from the equations of motion with reference to the co-ordinate system, whose origin is the ship's centre of gravity as shown in Figure 2.

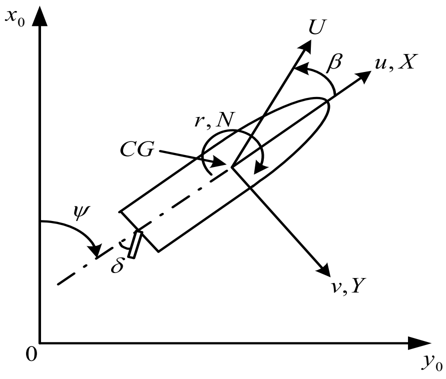

Figure 2: Co-ordinate System [4]

As shown in Figure 2, (U) is the actual ship velocity that can be resolved into advance velocity (u) and transversal velocity (v). The ship has also a rotation velocity with respect to the z-axis. This axis is normal to the XY plane and passes through the ship centre of gravity ($C.G$). (β) is the angle between U and the x-axis and it is called drift angle. (Ψ) is the ship heading angle and (δ) is the rudder angle.

In this study, manoeuvrability will be approached as a bi-dimensional phenomenon. Two reference systems will be used, one of them fixed (X_o, Y_o) and the other moving with the ship, with its origin at the centre of gravity. Yaw motion is supposed to occur around this point. In the moving reference, X-axis is positive forward and Y is positive starboard. For both systems, moving and fixed, angles are positive in the clockwise sense.

3.1 Equations of Motion

Once the reference systems have been defined, the ship is considered as a solid with three degrees of freedom: surge, sway and yaw. In accordance with these three degrees of freedom, the Newton's Second Law equation is applied to the moving reference system of Figure 2 for each motion [4]. Interrelating both axes and differentiating the Newtonian equations of motion, the dynamical model which governs the motion of the ship, can be simply written as follows:

$$\left\{(m'+m'_x)\left(\frac{L}{U}\right)\left(\frac{\dot{U}}{U}\cos\beta - \dot{\beta}\sin\beta\right) + (m'+m'_y)r'\sin\beta\right\} = X'$$

$$\left\{-(m'+m'_y)\left(\frac{L}{U}\right)\left(\frac{\dot{U}}{U}\sin\beta - \dot{\beta}\cos\beta\right) + (m'+m'_x)r'\cos\beta\right\} = Y'$$

$$\left\{(I'_{zz}+J'_{zz})\left(\frac{L}{U}\right)^2\left(\frac{\dot{U}}{L}r' + \frac{U}{L}\dot{r}'\right)\right\} = N' \qquad (1)$$

where: X', Y': Dimensionless Surge and Sway force acting on a ship, N': Dimensionless Yaw moment acting on a ship, m', m'_x m'_y: Dimensionless mass of ship, and added mass in x- and y-directions, I'_{zz}: Dimensionless moment of inertia of ship in z-axis, J'_{zz}: Dimensionless added moment of inertia of ship in z-axis, β : Drift angle at the center of gravity C.G. [$\beta = - \sin^{-1}(v/U)$], r' : Dimensionless Turning rate [$r = d\psi/dt$], L, T, U : Ship Length, Ship Draught and Ship Speed respectively.

The superscript {'} in the equations refers to the non-dimensional quantities.

The left hand-side of equations (1) represents the inertial terms. The right hand-side represents the external forces and moments that act on the ship. These forces and moments can be described separately into the following components from the viewpoint of the physical meaning. The subscripts "$_H$", "$_P$", and "$_R$" symbolize ship hull, propeller, and rudder respectively according to the concept of MMG [5] [6].

$$X' = X'_H + X'_R + X'_P$$
$$Y' = Y'_H + Y'_R \qquad (2)$$
$$N' = N'_H + N'_R$$

3.2 Forces and Moments Acting on Hull

X'_H, Y'_H and N'_H are approximated by the following polynomials in terms of β and r' at the amidships. The coefficients of the polynomials are called hydrodynamic derivatives. The longitudinal component of hydrodynamic force (X'_H), the lateral force (Y'_H), and yaw moment (N'_H) acting on the ship hull are expressed as follows [4]:

$$X'_H = \{ X'_{\beta r}\, r' \sin\beta + X'_{uu} \cos^2\beta \}$$

$$Y'_H = \{ Y'_\beta\, \beta + Y'_r\, r' + Y'_{\beta\beta}\, \beta|\beta| + Y'_{rr}\, r'|r'| + (Y'_{\beta\beta r}\beta + Y'_{\beta rr} r')\beta r' \}$$

$$N'_H = \{ N'_\beta\, \beta + N'_r\, r' + N'_{\beta\beta}\, \beta|\beta| + N'_{rr}\, r'|r'| + (N'_{\beta\beta r}\beta + N'_{\beta rr} r')\beta r' \} \qquad (3)$$

X'_H is consist of hydrodynamic derivates which expresses the change of ship resistance due to drift angle $\beta = \tan^{-1}(-v/u)$, yaw rate r', and X'_{uu} which is the ship resistance in forward straight motion. Y'_β, Y'_r, ..., $N'_{\beta\beta r}$ are also the hydrodynamic derivatives.

The Kajima formulae are based on the functions of ship length (L), breadth of hull (B), draught (d), block coefficient (CB), form factor (K) and aspect ratio of ship hull k ($k = 2d/L$).These formulae were derived based on a database involving 15 kinds of ships (container, bulk carrier, tanker, general cargo, VLCC, car-ferry etc.) and their 48 loading conditions [7]. The formulae of individual hydrodynamic derivatives for sway and yaw motion can be deduced to following equations:

$$X'_{\beta r} = (-1.66CB + 1.5)m'_y$$
$$X'_{uu} = R_T / (0.5\rho LTU^2)$$
$$Y'_{\beta} = 0.5\pi k + 1.9257(CB/L)\sigma_a,$$
$$Y'_r - (m' + m'_x) = 0.25\pi k + 0.052e'_a - 0.457,$$
$$Y'_{\beta\beta} = -1.199CB\sigma_a + 1.05,$$
$$Y'_{rr} = 0.225(dCB/B)e'_a - 0.12,$$
$$Y'_{\beta rr} = 7.1256\{d(1-CB)/B\},$$
$$Y'_{\beta\beta r} = 10.443[\{d(1-CB)/B\}e'_a]^2 - 9.374\{d(1-CB)/B\}e'_a + 1.227,$$
$$N'_{\beta} = k[(150.668\{d(1-CB)/B\}e'_a K)^2 - 23.819\{d(1-CB)/B\}e'_a K + 1.802],$$
$$N'_r = -0.54k + k^2 - 0.0477e'_a K + 0.0368,$$
$$N'_{rr} = 0.15K - 0.068,$$
$$N'_{\beta\beta} = 43.857\{d(1-CB)/B\}e'_a K)^2 - 3.671\{d(1-CB)/B\}e'_a K + 0.086],$$
$$N'_{\beta rr} = -0.4086CB + 0.27,$$
$$N'_{\beta\beta r} = -0.826\{d(1-CB)/B\}e'_a - 0.026 \quad (4)$$

3.3 Forces & Moments Induced by Propeller

The hydrodynamic forces generated by the propeller are expressed as below [8][9], neglecting lateral force and yaw moment that affects the stopping manoeuvre:

$$X'_P = [C_{tp}(1 - t_P)\, n^2 D_P^4 K_T(J_P)]/0.5\rho LdU^2$$
$$Y'_P = 0$$
$$N'_P = 0$$
$$K_T(J_P) = C_1 + C_2 J_P + C_3 J_P{}^2 \quad (5)$$
$$J_P = U\cos\beta(1 - w_P)/(nD_P)$$

where: t_p: thrust reduction coefficient in straight forward moving, C_{tp}: constant, N: propeller revolution, D_p: propeller diameter, w_p: effective wake fraction coefficient of propeller in straight running, K_T: thrust coefficient of a propeller force, J_p : advance coefficient, C_1, C_2, C_3: constants for propeller open characteristics.

3.4 Forces and Moments Induced by Rudder

The hydrodynamic forces generated by rudder are described below [8] [9], in term of rudder normal force F'_N, rudder angle δ and rudder-to-hull interaction coefficient t_R, a_H and x_H ($= x_H/L$).

$$X'_R = -(1 - t_R)F'_N \sin\delta$$
$$Y'_R = -(1 + a_H)F'_N \cos\delta$$
$$N'_R = -(x_R + a_H x_H)F'_N \cos\delta \quad (6)$$

where: x_R: The distance between the centre of gravity of ship and centre of lateral force, ($x_R = x'_R . L$) & x_R represents the location of rudder ($= -L/2$), x_H : The distance between the centre of gravity of ship and centre of lateral force, ($x_H = x'_H . L$), Δ: Rudder angle, F'_N : Dimensionless rudder normal force, t_R : Coefficient for additional drag, a_H : Ratio of additional lateral force.

4. SIMULATION PROGRAM

The vessel's swept path was obtained by double integrating the acceleration mathematical equation in surge, sway and yaw as shown in equation (7).

$$x = \int_{t1}^{t2}\int_{t1}^{t2}\left[\left(\frac{X' - (m' + m'_y)r'\sin\beta}{(m' + m'_x)\left(\frac{L}{U}\right)} + \dot{\beta}\sin\beta\right)\frac{U}{\cos\beta}\right]dt \quad (7)$$

Simulation program was written in graphical programming language and compiled using MATLAB Simulink compiler. The programs are developed in three main blocks which are input block, process block and output block.

In input block, the program will read the input data such as rudder angle and hydrodynamic coefficients. These input data will then be used in the module process block to calculate the hull, rudder and propeller forces. The layouts of the process block module are shown in Figure 3. Hull modules are divided into three sub-blocks which are called surge, sway and yaw sub-block. The propeller and rudder forces are also calculated in their respective sub-blocks.

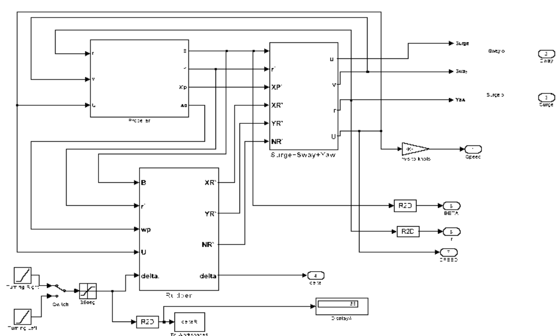

Figure 3: Layout of Process Block

The equation of motion will be double integrated to obtain the translation of motion in x and y directions. Lastly, the output results of ship's path are displayed in graphical form as shown in Figure 4.

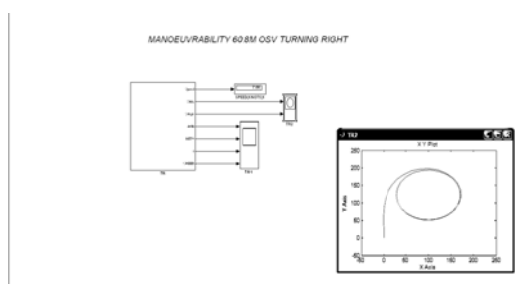

Figure 4: Output result of Ship's Path

5. RESULTS AND DISCUSSION

5.1 Simulation

Simulation for Turning Circle and Zig-Zag manoeuvre was run at constant ship speed of 12.5 knots. The propeller was assumed to be working ahead with constant RPM, neglecting the transient behaviours of the main engine caused by torque limit, governor and so on. The predicted result of Turning Circle to Port and Starboard are plotted in Figures 5 and 6, respectively.

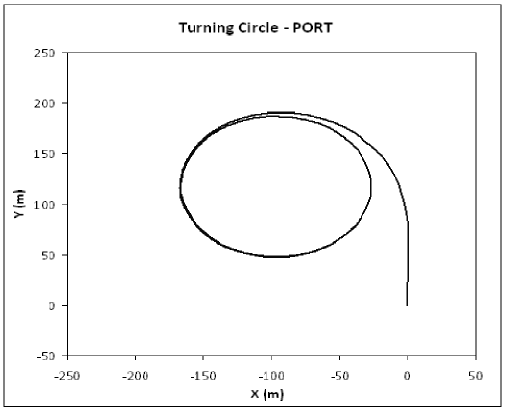

Figure 5: Prediction result of Turning Circle Trajectories to Port

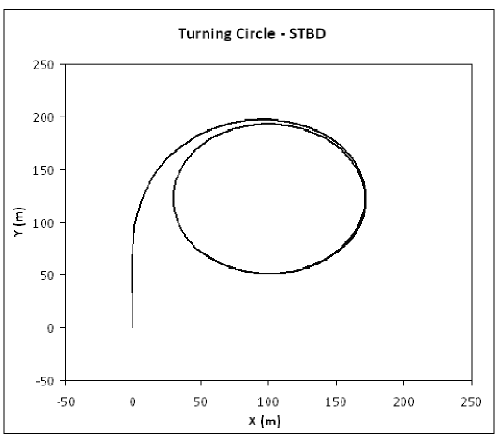

Figure 6: Prediction result of Turning Circle Trajectories to Starboard

Table 3 shows the summary of predicted results for turning circle to port and starboard. The Advance Distance (A_d) and Tactical Diameter (T_d) for Port and Starboard turning are found to satisfy IMO criteria. Turning manoeuvre is carried out to determine the turning ability and the response of the ship to the deflection of rudder at 35^o angle. Thus, the results show that OSV has a good turning ability based on IMO criteria.

On the other hand, the Zig-Zag manoeuvre was carried out for purpose of yaw checking ability which represents the inherent effectiveness of the two rudders in making changes of ship heading. The predicted results of Zig-Zag 10/10 and Zig-Zag 20/20 are recorded in Table 4. It shows that the 1st and 2nd overshoot angle of Zig-Zag 10/10 and Zig-Zag 20/20 meet the IMO criteria. Thus, the OSV had a good yaw checking ability. The details of the predicted time histories simulation for Zig-Zag 10/10 and Zig-Zag 20/20 are plotted in Figures 7 and 8, respectively.

Table 3: Prediction results of Turning Circle

Parameter	Turning (Port)	Turning (Starboard)	IMO Criteria	Result
Advance Distance	3.1 L (188m)	3.2 L (194m)	< 4.5 L	Comply
Tactical Diameter	2.7 L (164m)	2.8 L (169m)	< 5.0 L	Comply

Table 4: Prediction results of Zig-Zag 10/10 and 20/20

Parameter	Zig-Zag 10/10		Zig-Zag 20/20		Result
	Predi.	IMO	Predi	IMO	
1st overshoot (deg)	6.5	10	15.7	25	Comply
2nd overshoot (deg)	10.6	25	23.6	-	Comply

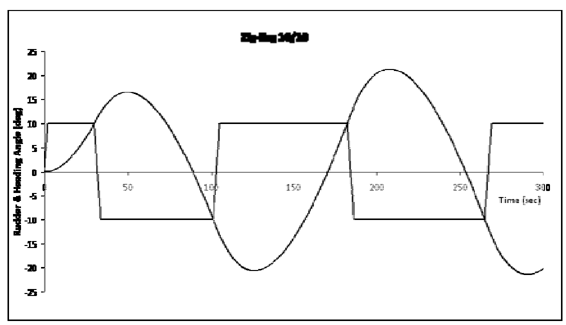

Figure 7: Prediction result of Zig-Zag 10/10

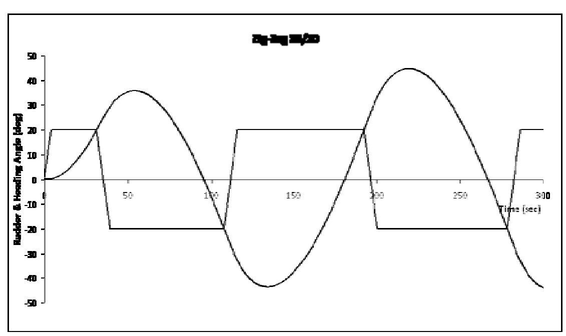

Figure 8: Prediction result of Zig-Zag 20/20

5.2 Validation with Full-Scale Sea Trial

A full-scale manoeuvring sea trial of an OSV was carried out and the ship path data was recorded by using *FURUNO GPS/WAAS Navigator model GP-32*. Ship heading angle are displayed on magnetic compass which are mounted onboard. Sea trial data for Turning Circle to Port and Starboard are recorded in Table 5 and 6 respectively. It shows that the sea trial results are smaller than predicted value for Advance Distance and Tactical Diameter.

The discrepancies between predicted and measured results can be shown in terms of deviation percentage which was calculated as follow:

$$Deviation\ (\%) = \frac{(Prediction - Measurement)}{Measurement}\ X\ 100 \qquad (8)$$

Table 5: Comparison between Prediction and Sea trial results for Turning Circle to Port

Turning (Port)	Prediction	Sea trial	Deviation (%)
Advance Distance (Mtr)	188	174	8.0
Tactical Diameter (Mtr)	164	160	2.5

Table 6: Comparison between Prediction and Sea trial results for Turning Circle to Starboard

Turning (Stbd)	Prediction	Sea trial	Deviation (%)
Advance Distance (Mtr)	194	176	10.2
Tactical Diameter (Mtr)	169	157	7.6

The deviation percentage of Advance Distance and Tactical Diameter for Port Turning Circle was 8.0 % and 2.5 % respectively. Meanwhile the deviation percentage for Advance Distance and Tactical Diameter for Starboard Turning Circle was 10.2 % and 7.6 % respectively. The predicted results for Port Turning Circle are more accurate than the Starboard Turning Circle with the smaller deviation percentage.

6. CONCLUSION

Manoeuvring assessment of an Offshore Supply Vessel had been successfully performed by using numerical simulation method which was developed on Matlab Simulink software. The prediction result shows that manoeuvring characteristic of an OSV meet the requirements stipulated by IMO resolution MSC.137 (76), International Maritime Organization standards for ship manoeuvrability. Validation with full-scale sea trial data gives small deviation to the predicted result. This discrepancy may due to inaccuracy of estimated hydrodynamic derivatives and others external forces which are not taken into account. However, the numerical method developed in this study can be used as a primary tool in order to access OSV manoeuvring characteristic at early design stages. This method may be considered as an economical and reliable manoeuvring prediction method which can estimate manoeuvring characteristic without relying on model tests (captive or free running test). Although the results of prediction tools show a good agreement to the sea trial data, the authors suggest that for future work, the study should be continued with further validation process with other full-scale sea trials data and captive model test data.

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