

Z-Manoeuvring of a Liquefied Natural Gas Carrier with Podded Propulsion System

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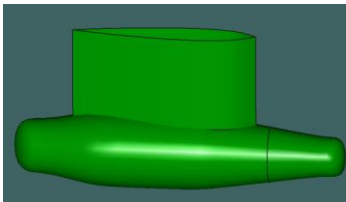
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Graphical abstract



Abstract

The application of pod propulsion has become an important concern in designing a new LNG carrier due to the high maneuverability characteristic. However, podded propulsion LNG carrier is a new concept which is still in the evaluation stage. Practically, the maneuverability of podded propulsion LNG carrier is an uncertainty. Hence, it is essential to assess the ship's maneuvering characteristics. Z-Manoeuvre assessment is one of the recommended tests for maneuverability prediction. This paper discusses on Z-Manoeuvre characteristic of the podded propulsion LNG carrier. A mathematical model for podded propulsion LNG carrier was presented and a simulation program was developed for the Z-Manoeuvre assessment. Finally, simulations were carried out on both conventional propulsion and podded propulsion LNG carriers. The simulation results show that podded propulsion LNG carrier has a better Z-Manoeuvre characteristic.

Keywords: z-manoeuve; podded; LNG carrier; manoeuvring; mathematical model; simulation z-manoeuve; podded; lng carrier; manoeuvring; mathematical model; simulation

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1.0 INTRODUCTION

In recent years, the application of podded propulsion system has become a trend as the system has a high propulsive efficiency and manoeuvrability (Toxopeus and Loeff, 2002). It gives high manoeuvrability because the system able to generate high side forces and yaw moments. The pod allows steering in a complete cycle of 360°, consequently, the propulsor can produce maximum side force and yaw moment at angle $\pm 90^\circ$. This allows the ship to manoeuvre more rapidly and precisely even in a restricted environment. Hence, the ship can turn faster and has a smaller turning diameter at low speed (Van *et al.* 2001). Furthermore, the podded propulsor has no stall limit since it can rotate 360° whereas the conventional propulsor has a stall limit typically around 35° (Toxopeus and Loeff, 2002). This allows podded propulsor to have a better turning ability than conventional propulsor.

Nowadays, it is clearly discern the use of pod propulsion in ship industry. A large number of ships are equipped with the podded propulsors because of the advantages. Same to other vessels, the application of pod propulsion has become an important concern in designing a new LNG carrier. However, podded propulsion LNG carrier is a new concept which is still in the evaluation stage. Practically, the manoeuvrability of podded propulsion LNG carrier is an uncertainty. Hence, it is essential to assess the ship's manoeuvring characteristics. Z-manoeuve

assessment is one of the recommended tests for manoeuvrability prediction. It is used to evaluate the initial turning, yaw-checking and course-keeping abilities.

In this present paper, the authors proposed mathematical model to analyze the Z-manoeuve characteristics of pod propulsion LNG carrier. By applying the mathematical model, a simulation program is developed to predict the Z-manoeuve characteristic. The simulation program was developed using Visual Basic. Z-manoeuve assessment was then conducted on both conventional propulsion and podded propulsion LNG carriers. The simulation results were analyzed to determine whether the podded propulsion LNG carrier has a better Z-manoeuve characteristic.

2.0 MANOEUVRING PREDICTION

The International Maritime Organization (IMO) has endorsed a set of criteria and standards for the ship manoeuvrability in December 2002. The IMO Standards provide a valuable tool for ensuring minimum manoeuvrability characteristics to ensure the safety of ship operation. Ship designer are required to establish an optimum design for the ship hull in order to satisfy the criteria stated in the IMO Standards. Generally, the IMO Standards cover the parameters including course-keeping ability, yaw-checking

ability, turning ability, initial turning ability, overshoot angle and stopping ability.

2.1 Simulation Methods

There are several simulation methods to predict the manoeuvring trajectories. These can be illustrated by the figure below:

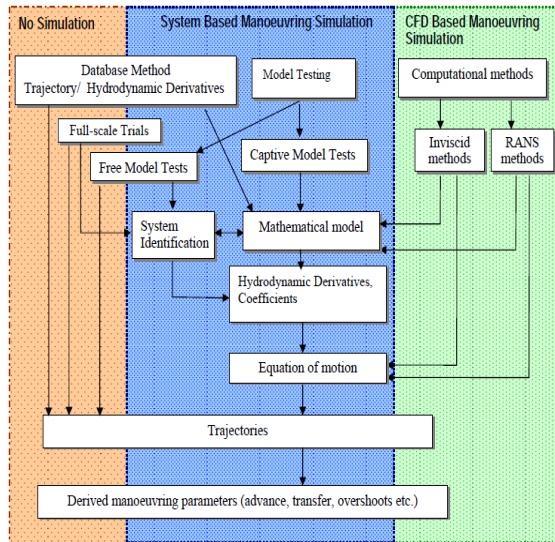


Figure 1 Manoeuvring prediction methods

It can be seen that the methods can be distinguished into three categories which are No Simulation, System Based Manoeuvring Simulation and CFD Based Manoeuvring Simulation. Among these methods, System Based Manoeuvring Simulation is widely used to predict the manoeuvring trajectories. This method can give an accurate manoeuvring prediction and it is inexpensive compared to the free running model test. In this study, Z-manoevre characteristic of podded propulsion LNG carrier is assessed using System Based Manoeuvring Simulation which also known as numerical simulation.

2.2 Existing Mathematical Models

A mathematical model is required before a manoeuvring simulation is carried out. The hydrodynamic phenomena around the ship hull can be described by a suitable mathematical model. MMG model is one of the mathematical models used for the prediction of manoeuvring motion. It is proposed by the Mathematical Modelling Group (MMG) in 1970. MMG model reflects manoeuvring motion based on the expression of hydrodynamic force and moment acting on ship hull, propeller and rudder. All these elements are considered self-contained interactive modules. This model allows its elements to be developed and tested separately. Nowadays, there are different mathematical models and each of them has its own advantages and limitation.

Kijima *et al.* (1990) discussed about the numerical simulation for the ship manoeuvring characteristics prediction at the initial design. He proposed the approximate formula to obtain the hydrodynamic force which later used to reflect the manoeuvring performance considering the changes in ship's hull form, rudder and propeller. The model ships used in his study are 13 conventional ships such as general cargo and oil tanker. From the simulation results, the predicted manoeuvring approximately agrees with the measured results. However, there were some

problems and limitations. Since the formulas were developed based on the conventional ships results, Kijima's model was not suitable for the unconventional ship with different stern shape.

Lee *et al.* (1998) also proposed a model which can be applied on the ships with stern. Planar Motion mechanism (PMM) tests were carried out for 19 models of low-speed blunt ship with stern bulb rudder. Then, regression analysis has been made to predict the hydrodynamic derivatives acting on a ship and hull-propeller-rudder interaction coefficients. Sensitivity study on simulation parameters also carried out to improve the accuracy of prediction. It was discovered that the simulation results obtained by Lee's regression model agree well with the Kijima's and PMM model tests. The prediction method is suitable for the ship with stern bulb. Yet, there are some limitations such as the insufficient in database result in the prediction only suitable for ships with certain principle dimension.

Yoshimura *et al.* (2003) had carried out a study on manoeuvring prediction for fishing vessel in 2003. He explained that Kijima model's trim corrections for the linear hydrodynamic derivatives are insufficient for fishing vessels since they are the large trimmed ships. Thus, modification has been done and the proposed model takes into account of these trim effects. From the simulation generated using the proposed model, the predicted manoeuvring for the fishing vessels agree well with the measured results from the captive model tests. It was a practical tool to investigate the fishing vessel's manoeuvring. However, due to the limitation of database, the developed regression formulas only work for the fishing vessels with certain dimensions.

Kijima and Nakiri (2003) also have done some improvement on the previous study in 1990. They further revised the database formulas so that the mathematical model can be used for different stern hull shape. The formulas were obtained from the study of model tests involving 15 kinds of ship (container ship, cargo ship and etc.) with 48 loading conditions. The new mathematical model takes into account of the forces and moments acting on propeller (in sway and yaw motion). From the simulation with new approximate formulae it was found a close agreement between the predicted and measured results was obtained. The prediction method was able to assess the effect of changes in the stern shape and it can be used on the ships which were not included in the model test database.

Jaswar *et al.* (2011) proposed the integrated ship maneuverability simulation model and then the model was applied analyzed the performance of a Very Large Crude Oil Carrier. In 2012, Jaswar *et al.* continued his research by proposing 3D manoeuvring animation simulation and applied to the VLCC ship. In the same year, he also discussed the effect of stern hull shape on turning circle of ships and zigzag maneuver characteristics of U-V VLCC tankers. He compared the simulation results with the with the experimental one and it showed agreement.

3.0 Z-MANOEUVRE SIMULATION MODEL

3.1 Equation of Motion

The Z-manoevre motion of a ship can be represented as a rigid body with directions in surge, sway, and yaw. The mathematical model for manoeuvring motion of ships can be described by the following equations of motion using the coordinate system as shown in Figure 2.

The non-dimensional force for surging, sway and moment for yaw can be expressed as

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

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

$$N' = (I'_{zz} + i'_{zz}) \left(\frac{L}{U} \right)^2 \left(\frac{\dot{U}}{L} r' - \frac{U}{L} \dot{r}' \cos\beta \right) \quad (1)$$

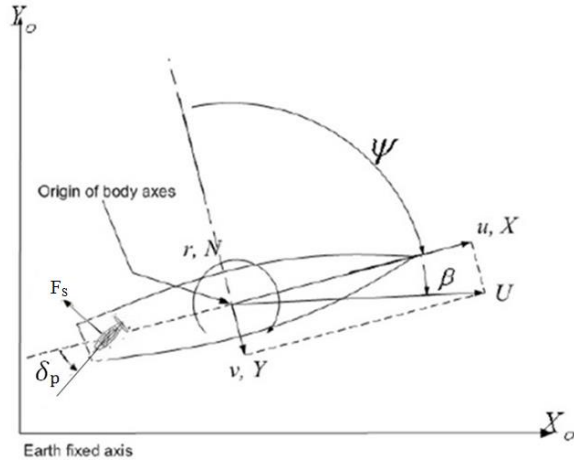


Figure 2 Surge, sway and yaw motion

The non-dimensional quantities are defined as

$$m', m'_x, m'_y = \frac{m, m_x, m_y}{0.5\rho L^2 d}$$

$$I'_{zz}, i'_{zz} = \frac{I_{zz}, i_{zz}}{0.5\rho L^4 d}$$

$$X', Y' = \frac{X, Y}{0.5\rho L U^2 d}$$

$$N' = \frac{N}{0.5\rho L^2 U^2 d}$$

$$r' = \frac{r}{U} L$$

where; L is ship length, D is draft, m is ship mass, m_x and m_y are added mass of ship, I_{zz} and i_{zz} are moment and added moment of inertia of ship, U is ship speed, β is drift angle, r is angular velocity, X' is external surge force acting on ship, Y' is external sway force acting on ship, N' is yaw moment acting on ship, ρ is density of fluid.

The proposed equations for external forces and moments are expressed as:

$$X' = X'_H + X'_P + X'_{POD}$$

$$Y' = Y'_H + Y'_P + Y'_{POD}$$

$$N' = N'_H + N'_P + N'_{POD} \quad (2)$$

where; subscript H indicates hull, subscript P indicates propeller and the subscript POD indicates the pod unit.

3.2 Forces and Moments Acting on Hull

In this study, modifications do not take into account changes in the hull forces and moments. Same as Kijima model, the forces and moments acting on Hull (X'_H, Y'_H , and N'_H) can be expressed as:

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

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

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

where;

$Y'_{\beta\beta}, Y'_{r'r'}, Y'_{\beta\beta r}, Y'_{\beta rr'}, N'_{\beta\beta}, N'_{r'r'}, N'_{\beta\beta r}, N'_{\beta rr'}$ and $N'_{\beta\beta r}$ are the hydrodynamic derivative coefficients. The hydrodynamic derivative coefficients are defined as:

$$Y'_{\beta\beta} = 0.5\pi k + 1.9257 \left(\frac{C_b B}{L} \right) \sigma_a$$

$$Y'_{r'r'} - (m' + m'_x) = 0.25\pi k + 0.052e'_a - 0.457$$

$$Y'_{\beta\beta r} = -1.199C_b \sigma_a + 1.05$$

$$Y'_{r'r'r'} = 0.225 \left(\frac{dC_b}{B} \right) \cdot e'_a - 0.12$$

$$Y'_{\beta\beta rr'} = 10.443 \left(\frac{d(1-C_b)}{B} \cdot e'_a \right)^2 - 9.374 \left(\frac{d(1-C_b)}{B} \cdot e'_a \right) + 1.227$$

$$Y'_{\beta rr'r'} = 7.1256 \left(\frac{d(1-C_b)}{B} \right)$$

$$N'_{\beta\beta} = k \left(15.0668 \left(\frac{d(1-C_b)}{B} \cdot e'_a K_{form} \right)^2 - 23.819 \left(\frac{d(1-C_b)}{B} \cdot e'_a K_{form} \right) + 1.802 \right)$$

$$N'_{r'r'r'} = -0.54k + k^2 - 0.0477e'_a K_{form} + 0.0368$$

$$N'_{\beta\beta r} = 43.857 \left(\frac{d(1-C_b)}{B} \cdot e'_a K_{form} \right)^2 - 3.671 \left(\frac{d(1-C_b)}{B} \cdot e'_a K_{form} \right) + 0.086$$

$$N'_{r'r'r'r'} = 0.15K_{form} - 0.068$$

$$N'_{\beta\beta rr'} = -0.4086C_b + 0.27$$

$$N'_{\beta\beta rr'} = -0.826(d(1-C_b)/B)e'_a - 0.026 \quad (3)$$

where; $k = 2d/L$, e_a and e'_a expressed fullness of aft run, σ_a is the aft sections fullness, K_{form} is the form factor. These parameters can be described as follows:

$$e_a = \frac{L}{B} (1 - C_{pa})$$

$$e'_a = \frac{e_a}{\sqrt{\frac{1}{4} + \frac{1}{B} \frac{d^2}{d^2}}}$$

$$\sigma_a = \frac{1 - C_{wa}}{1 - C_{pa}}$$

$$K_{form} = \left(\frac{1}{e_a} + \frac{1.5}{L} - 0.33 \right) (0.95\sigma_a + 0.40) \quad (4)$$

3.3 Forces and Moments Induced by Propeller

Pod propulsor is different from the conventional propulsion system as it can be steered over 360°. Hence, the thrust produced by the propeller not only acting in the surge direction but also in sway and yaw direction. The proposed equation to determine the propeller forces and moment are shown below:

$$X'_P = \frac{(1 - t_{pod}) n^2 D_p^4 K_T \cos\delta_p}{0.5LdU^2}$$

$$Y'_P = \frac{(1 - t_{pod}) n^2 D_p^4 K_T \sin\delta_p}{0.5LdU^2}$$

$$N'_p = \frac{-x'_{pod}(1 - t_{pod})n^2 D_p^4 K_T \sin \delta_p}{0.5 L d U^2}$$

$$K_T(J_p) = C_1 + C_2 J_p + C_3 J_p^2$$

$$J_p = \frac{(1 - W_p) U \cos \beta}{n D_p} \tag{6}$$

Where; t_{pod} is thrust deduction due to pod suction, n is propeller revolution, D_p is propeller diameter, C_1, C_2, C_3 are constants and W_p is effective wake fraction coefficient. δ_p is pod angle, x'_{pod} is the non-dimensional longitudinal distance between centre of gravity of the ship and centre of pod propulsor

3.4 Forces and Moments Induced by Pod Strut

A pod propulsor not only produce thrust force but also lift force (normal force). The strut of the pod unit intends to act like a conventional rudder as the controlling device. The forces and moments induced by the strut are almost same with the conventional rudder but there are some changes in the equations parameters. The new proposed equations are expressed as:

$$X'_{strut} = -(1 - t_R) F'_S \sin \delta_p$$

$$Y'_{strut} = -(1 + a_{Hpod}) F'_S \cos \delta_p$$

$$N'_{strut} = -(x'_{pod} + a_{Hpod} x'_{Hpod}) F'_S \cos \delta_p \tag{7}$$

where; δ_p is pod angle, t_R is additional drag coefficient, a_{Hpod} is interactive force coefficients among hull and pod, x'_{Hpod} is non-dimensional distance between centre of gravity of the ship and point of action of the normal force, x'_{pod} is non-dimensional longitudinal distance between centre of gravity of the ship and centre of pod unit and F'_S is Strut normal force.

F'_S can be described as follow:

$$F'_S = \left(\frac{A_s}{Ld}\right) C_{NS} U_p^2 \sin \alpha_{pod} \tag{8}$$

where; A_s is strut area, C_{NS} is gradient of the lift coefficient of strut, U_p is effective pod inflow speed and α_{pod} is effective pod inflow angle. The C_{NS} and U_p can be described as below:

$$C_{NS} = \frac{6.13 \Lambda_s}{\Lambda_s + 2.25}$$

$$U_p = \frac{V_{hp}^2 + V_{hp} V_{ps} + C_s V_{ps}^2}{U^2} \tag{9}$$

where; Λ_s is strut aspect ratio, V_{hp} is effective flow due to interaction between hull and pod propeller, V_{ps} is effective flow due to interaction between pod propeller and strut, C_s is strut coefficient. In pod propulsion system, V_{hp} is taken as the advance velocity, V_A . Since the pod is steerable, the inflow velocity is almost not influenced by the ship hull.

3.5 Forces and Moments Induced by Pod Body

Besides the strut effects, there are also effects on pod body due to the side force generated by pod propeller. Equations below are proposed to determine the forces and moments induced by the pod body.

$$X'_{Body} = \frac{-(1 - t_{pod})n^2 D_p^4 K_T \sin \alpha_{pod} \sin \delta_p}{0.5 L d U^2}$$

$$Y'_{Body} = \frac{-(1 + a_{Hpod})n^2 D_p^4 K_T \sin \alpha_{pod} \cos \delta_p}{0.5 L d U^2}$$

$$N'_{Body} = \frac{-(x'_R + a_{Hpod} x'_{Hpod})n^2 D_p^4 K_T \sin \alpha_{pod} \cos \delta_p}{0.5 L d U^2} \tag{10}$$

4.0 Z SIMULATION PROGRAM

A simulation program was developed to assess Z-maneuvre characteristics. In this research, considering the ease-of-use factor, the simulation program is developed based on Visual Basic language. The simulation program consists of two components. The first component is the main body and the second component is the subroutines. The main body will compute the hydrodynamic forces and moments and predict the Z-Manoeuvre characteristic. Meantime, subroutines will handle the calculations to obtain necessary parameters such as propulsion factors, added mass, moment inertia, and so forth. When all the subroutine calculations were done, the program main body will gather all the information to compute the finalized output results. Figure 3 shows the program flowchart and program layout.

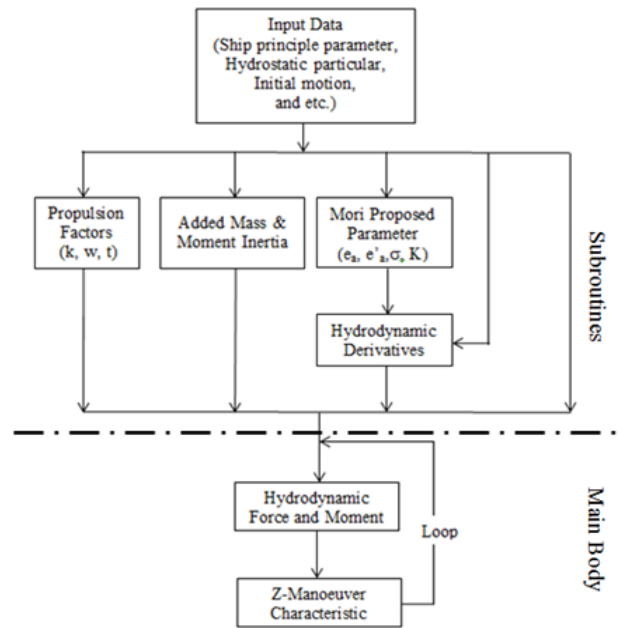


Figure 3 Program flowchart

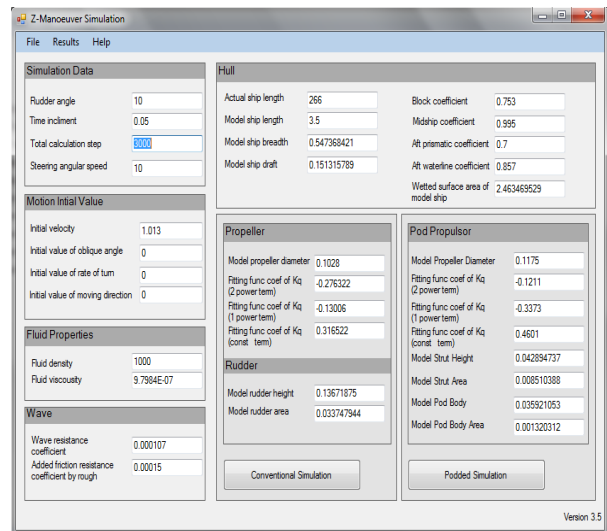


Figure 4 Program flowchart and program layout

5.0 3D MODELLING

3D modelling is carried out to obtain the hull and pod propulsor particulars. The modelling involves hull modelling and pod propulsor modelling. Maxsurf software is used during the modelling process. Hull modelling is able to give necessary parameters such as length of the ship, breadth, depth, block coefficient while pod propulsor modelling in is able to give information such as strut area, strut height and pod diameter. Figure 4 shows the models created in Maxsurf.

Table 1 Hull parameters

| Item | Value |
|---------------------------------------|----------|
| Length Overa All (m) | 280.00 |
| Length Between Perpendicular (m) | 266.00 |
| Beam (m) | 41.60 |
| Depth (m) | 25.45 |
| Draught (m) | 11.30 |
| Prismatic coefficient (Cp) | 0.734 |
| Block coefficient (Cb) | 0.726 |
| Midship section area coefficient (Cm) | 0.989 |
| Waterplane area coefficient (Cwp) | 0.801 |
| Wetted Area (m ²) | 14000.00 |
| Displacement (m ³) | 94715.00 |

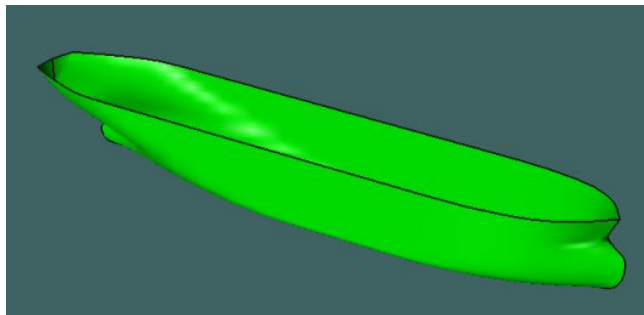


Figure 5 3D hull model

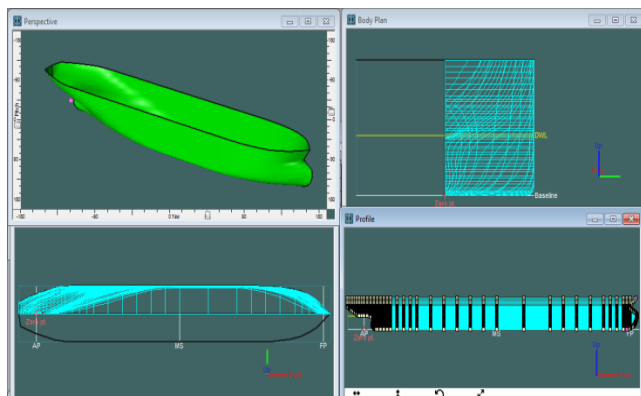


Figure 6 Body plan, sheer plan and water line of hull model

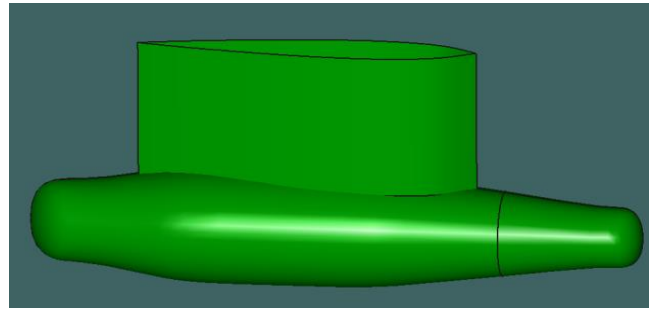


Figure 7 3D Pod Propulsor Model

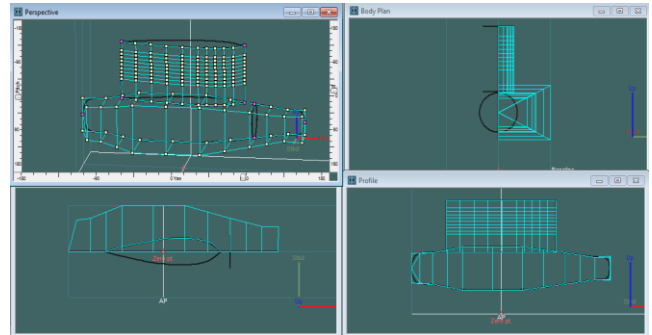


Figure 8 Body plan, sheer plan and water line of pod propulsor model

6.0 RESULTS AND DISCUSSION

6.1 Simulation Results

The aim of this research is to determine whether the podded propulsion LNG carrier has better Z-Manoeuvre characteristic than conventional propulsion LNG carrier. Thus, simulations were carried out on both conventional propulsion and podded propulsion LNG carriers. Figure 9 and Figure 10 illustrate the results of 10°/10° Z-Manoeuvre and 20°/20° Z-Manoeuvre.

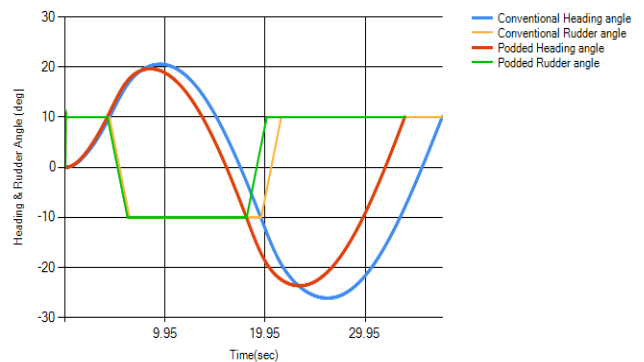


Figure 9 Comparison Result of 10°/10° Z-Manoeuvre

The overshoot angles of simulations are recorded in Table 2. It can be seen that podded propulsion LNG carrier has smaller overshoot angles in both 10°/10° and 20°/20° Z-Manoeuvre. This indicates the podded propulsion LNG carrier has better course-keeping and yaw-checking abilities.

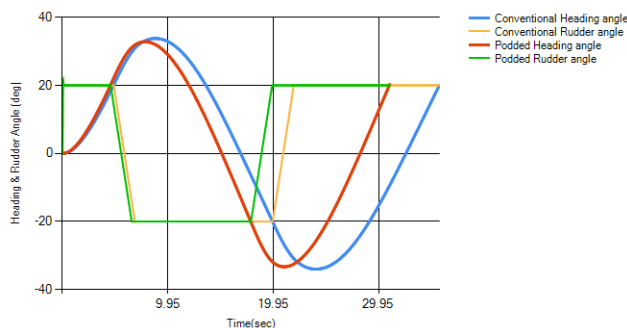


Figure 10 Comparison result of 20°/20° Z-Manoeuvre

Table 2 Overshoot angles comparison

| Z-Manoeuvre | Overshoot(degree) | Conventional | Podded |
|---------------------|-------------------|--------------|--------|
| 10°/10° Z-Manoeuvre | 1st | 10.6 | 9.7 |
| | 2nd | 16.1 | 13.6 |
| 20°/20° Z-Manoeuvre | 1st | 23.8 | 22.8 |
| | 2nd | 24.1 | 23.3 |

6.2 Discussion

From the simulation results discussed in previous section, it can be seen that podded propulsion LNG carrier has better Z-Manoeuvre characteristic than conventional propulsion LNG carrier. This can be explained by following factors:

- Pod propulsion system is able to generate thrust not only in surge direction but also in sway and yaw direction. The generated thrust in sway and yaw direction allows the LNG carrier to turn more quickly at a given pod angle.
- Effective inflow velocity from the hull to the propeller using pod propulsor is higher than conventional propulsion system. The strut component allows the inflow becomes more streamlined and this leads to more uniform wake behind the ship. Thus, the reduction of inflow velocity is relatively small.

7.0 CONCLUSIONS

Based on the results of this research, the following conclusions are drawn:

- The proposed mathematical model simulates the use of pod propulsor and the forces and moments due to pod propulsor are taken into consideration.
- Simulation program for Z-manoevr assessment was developed. The proposed mathematical model was applied to the program and the simulation results are sufficient for Z-manoevr analysis.
- Z-manoevr assessment was done on podded propulsion LNG carrier. Simulation result shows that podded propulsion LNG carrier has smaller overshoot angles compared to the conventional propulsion LNG carrier. Hence, podded propulsion LNG carrier has a better Z-manoevr characteristic.

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