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MANEUVERING PERFORMANCE OF TUGBOAT USING COMPUTATIONAL FLUID DYNAMICS (CFD) APPROACH

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Abstract: Concerning on navigational safety of a ship, comprehensive investigation of manoeuvrability of the ship is prominently required. The turning instability due to improper speed and magnitude of the rudder angle is vulnerable to serious accidents such as collision especially in the confined waters. This paper presents a computational fluid dynamic analyses on manoeuvrability performance of a tug in calm water. Here, the characteristics of the turning ability and zig-zag characteristics of the tug has been assessed due to effect of the various angles of twin-rudder and turning speeds. The results revealed that the increase of rudder's angle resulted in subsequent reduction of her advance diameter from 144 m, 108 m, 96 m to 92 m. While for zig zag manoeuvre, the first overshoot angle is 0.6° and 1.08° for 10°/10° and 20°/20° rudder's angle respectively. The first overshoot and second overshoot angle are within the IMO criteria which is below 20° and 25°. However, the increase of turning speed from 7 knots to 9 knots has been proportional with the increase of the turning diameter (advance diameter) from 70 m to 105.2 m. Basically, the turning performances of the tug manoeuvring with the turning speed of 7 to 9 knots incorporated with rudder's angle 20°, 25°, 30° and 35° have been complied with IMO manoeuvring standards. This preliminary analysis contributes very valuable findings at early ship design stage to provide a safety of the navigational guidance for turning ability of the tug.

Keywords: CFD, Manoeuvring, zig-zag, rudder's angle; turning speed

Introduction

Manoeuvrability is defined as the inherent ability of a vessel to change its course or path. Mistakes in speed control and turning velocity of the vessel while using engines and tugs may lead to instability and cause damages or accidents such as collision. Understanding the factor of manoeuvrability of a vessel is extremely important to a designer or a seafarer, along with other aspects such as structural design, machinery, propulsion, stability and seakeeping. Some numerical and experimental investigations on predicting of ship's manoeuvring performances have been established. Moreover, the increase in computer capabilities incorporated with less time consuming and cheaper cost; the use of numerical program methods to predict the manoeuvrability of ship at the initial ship design stage has become possible. Several authors have conducted free-running tests via Computational Fluid Dynamics (CFD) approach for different hulls, such as Hirano *et al.* (1980) and Ueno *et al.* (2003). Moreover, turning tests in both regular and irregular waves were performed by Yasukawa (2006) with the ITTC standard S-175 container ship model.

This paper presents a Computational Fluid Dynamic (CFD) simulation used to predict the manoeuvrability of a tugboat in calm water. Here, the commercial CFD called FLOW-3D is used to analyse the turning performance of ship with various angular velocity and speed. The computational domain with adequate numbers of grid meshes specifically for the rudder has been carefully determined. This motion analysis is carried out in a three degrees-of-freedom of horizontal plane motions i.e., surge, sway and yaw motions. The effects of the varying rudder angle (δ) and ship forward speed (U) on the manoeuvring performance of tugboat are taken into account. The results are comprehensively discussed to point out the advance and tactical diameter of manoeuvring fulfil the critical standards of IMO.

Methods and Materials

Principle Dimensions

The principle dimensions of the tugboat and twin-rudder that are applied in this simulation are presented in Table 1 and Table 2. The tugboat coupled with twin-rudder is design using MAXSURF and CATIA V5 as shown in Figure 1.

Table 1: Principle dimensions of tugboat

Descriptions	Model	Full scale
Length L, (m)	0.8	40
Breadth B, (m)	0.178	9.0
Draft d, (m)	0.044	2.2
Volume V, (m3)	0.0003	494.7
L/B	4.44	4.44
Block coefficient Cb	0.62	0.63

Table 2: Principle dimensions of rudder

Descriptions	Model	Full scale
Length L, (m)	0.04	0.2
Draft d, (m)	0.04	0.2
Thickness, (m)	0.004	0.02

Figure 1: Geometry of tugboat with rudder

Parametric Studies

In the current CFD simulation, there are three parametric studies have been considered as summarized in Table 3 and Table 4.

Table 3: Rudder's angle for zig zag manoeuvre

Rudder's angle	Forward speed (knot)
10°/10°	7
20°/20°	

Table 4: Various rudder's angles and forward speeds

Rudder's angle (°)	Forward speed (knot)		
	7	8	9
20	√	-	-
25	√	-	-
30	√	-	-
35	√	√	√

Computational Domain and Boundary Conditions

The domain is set up to fit the moving tug to manoeuvre at various speeds and rudder's angle. The mesh generation is set up with nested block. Referring to the main mesh block, the boundary of X_{min} is assigned as velocity; while the X_{max} is defined as outflow, which is purposed to absorb water flow from X_{min} boundary. The boundary for Y_{min}, Y_{max}, Z_{min} and Z_{max} are assigned as symmetries to minimize the effects of friction loss and surface tension (Fitriadhy *et al.,* 2019). This is similar to all conditions of nested mesh block. The detailed boundary conditions are completely presented in Table 5.

Table 5: Boundary conditions

Boundary	Main Mesh Block	Nested Mesh Block (Tugboat)	Nested Mesh Block (Rudder)
Xmin	Velocity (V)	Symmetry	Symmetry
Xmax	Outflow (O)	Symmetry	Symmetry
Ymin	Symmetry (S)	Symmetry	Symmetry
Ymax	Symmetry (S)	Symmetry	Symmetry
Zmin	Symmetry (S)	Symmetry	Symmetry
Zmax	Specified Pressure (P)	Symmetry	Symmetry

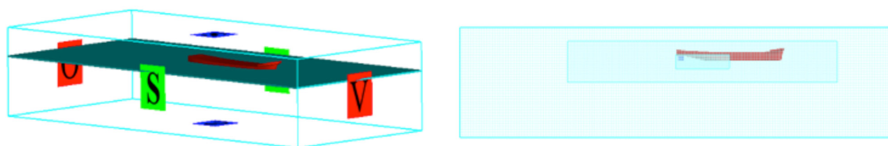


Figure 2: Boundary condition (left) and mesh generation (right)

Meshing for fixed point rotation consists of 3 mesh blocks as clearly shown in Figure 2 (right). In order to increase the quality of meshing, the nested block is highly required. The gridlines of main mesh block and nested block need to align using 2:1 ratio. In this CFD simulation, the main mesh block applied 1 m cell size with 64,000 total number of cells, the tugboat's nested block applied 0.2 m cell size with 72,000 total number of cells, and rudder's nested block applied 0.25 m cell size with 32,000 total number of cells. However, the meshing for zig zag and turning manoeuvre cases only consists of 1 main mesh block; where the cell size is 0.8 m with 3.15 million and 4.03 million total number of cells, respectively.

Here, the mesh independent study is necessary for examining the adequate number of meshes needed in order to ensure the accuracy of computational results. The result of the mesh independent study shows the total number of cells was about 1,161,750 in case C has been selected for all computation due to stadiness computation results with less computational time as presented in Table 6.

Table 6: Mesh independence of study

Case	Total number of cells	Angular velocity (rad/s)
A	969,400	0.038768
B	988,800	0.038697
C	1,161,750	0.038870
D	1,577,440	0.039000

Results and Discussion

The CFD simulations have been successfully carried out to predict the effect of various rudder's angle and operational speed towards manoeuvrability of the tugboat. The yaw motion of tugboat associated various rudder's angle are discussed accordingly in the Sub-sections 3.1 ~ 3.3.

Effect of rudder's angle to the zig zag manoeuvrability of tugboat

The zig-zag manoeuvres were carried out for purpose of yaw checking ability which represent the inherent effectiveness of the rudder in making changes of ship's heading. Initially, the rudder's angle is set to change from 10° port to 10° starboard (10°/10°) with a forward of 7 knots. As measured in the 10°/10° zig-zag simulation, the first overshoot angle is seen to be relatively small by 0.6°. This means that the result complied with IMO criteria for manoeuvring, in which the first overshoot angle should not exceed 10◦ if L/U ≤ 10 sec, where L is ship's length in meter and U is the forward speed in meter/sec. For the second overshoot angle is obtained about 0.6°◦, which also complied with IMO criteria i.e., it should not exceed by L/U ≤ 25 sec. In addition, the yaw checking time for the first and second overshoot angle are 1.9 sec and 2.2 sec, respectively. In the case of 20°/20° zig-zag simulation, it shows that the first overshoot angle also complied with IMO criteria which is 1.08°. Furthermore, its yaw checking times is 3.1 sec. In general, 10°/10°and 20°/20° zig-zag manoeuvrability of tugboat are acceptable with IMO manoeuvring standards.

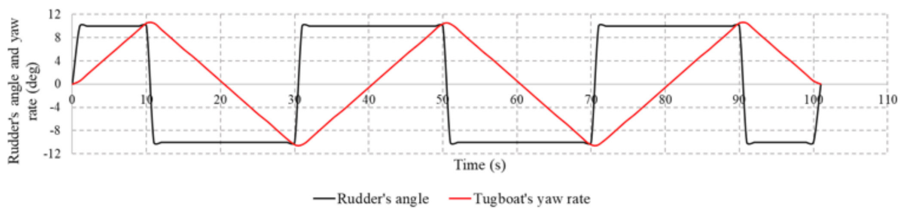


Figure 3: Zig zag graph of tugboat manoeuvre at rudder's angle 10°/10°

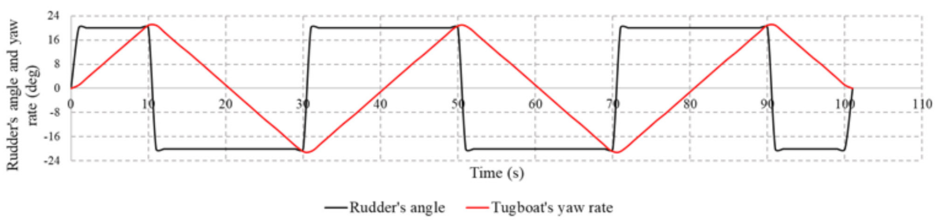
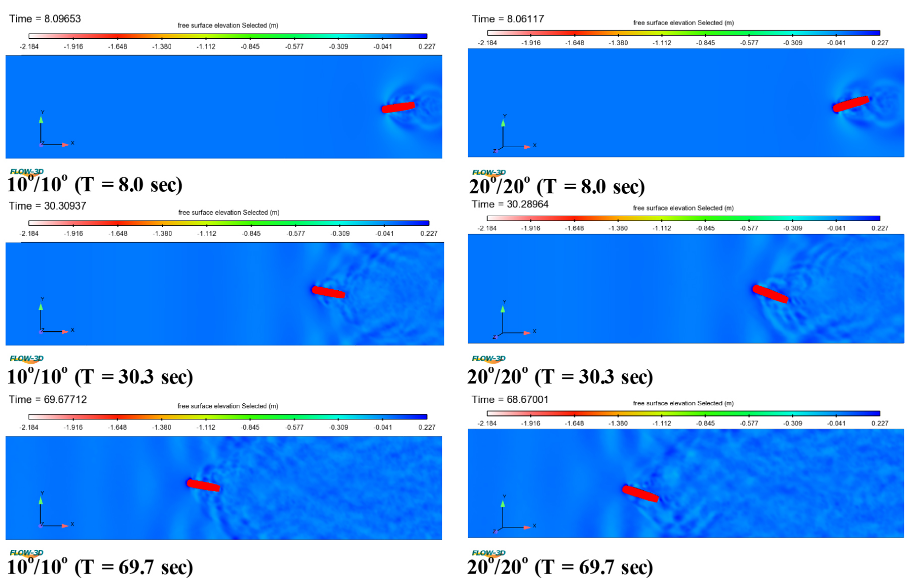
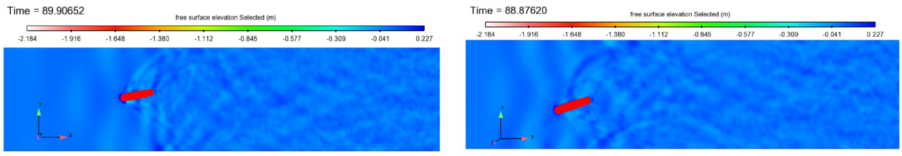


Figure 4: Zig zag graph of tugboat manoeuvre at rudder's angle 20°/20°





10°/10° (T = 89.9 sec) **20°/20° (T = 89.9 sec)**

Figure 5: Free surface elevation of zig zag manoeuvre for 10°/10° (left) and 20°/20° (right) rudder's angle

Table 7: IMO criteria with zig zag manoeuvre

Rudder's angle	First overshoot angle (°)	IMO criteria	Second overshoot angle (°)	IMO criteria
10°/10°	0.6°<20°	comply	0.6°<25°	comply
20°/20°	1.08°<20°	comply	-	-

Effect of rudder's angle to the turning manoeuvrability of tugboat

The turning performance of tugboat was examined through nonlinear analysis, Figure 5. Based on the simulation results, tugboat complies with the IMO criteria both for its advance and tactical diameters except for the rudder's angle δ= 15° (tactical diameter value) as completely summarized in Table 8. The subsequent increase of δ from 20° to 25° and 35° led to reduce the advance diameter of tugboat by 7% and 11%, respectively. The similar tendencies showed that the tactical diameter also significantly reduced about 20% and 41%, respectively. It can be inferred that the increase of δ has more considerable effect to the magnitude of the tactical diameter than advance diameter of tugboat.

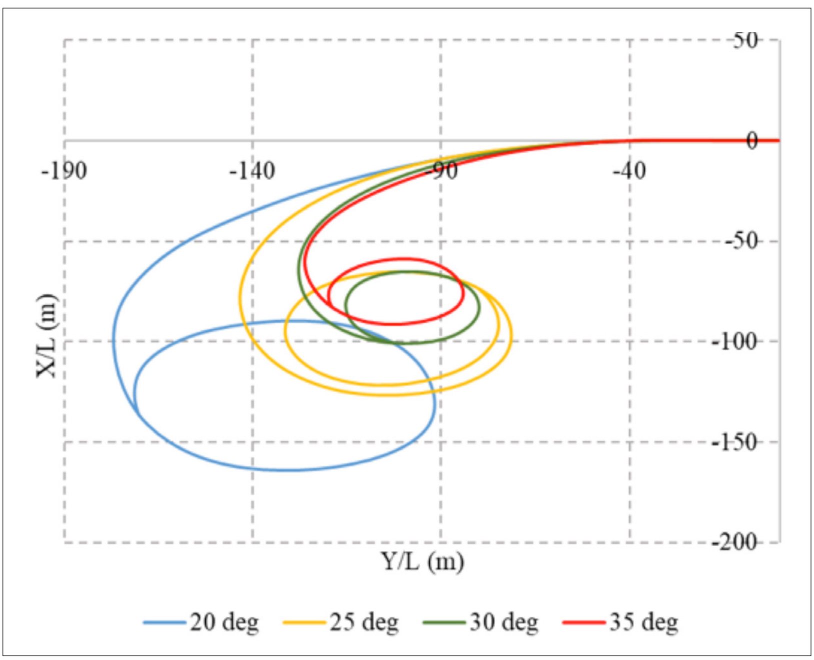


Figure 5: Graph of turning diameter at various rudder's angles

Table 8: IMO criteria with turning manoeuvre at various rudder's angles

Rudder's angle (°)	Advance diameter (m)	IMO criteria	Tactical diameter (m)	IMO criteria
20	3.6L<4.5L	OK	4.5L<5L	OK
25	2.7L<4.5L	OK	3.2L<5L	OK
30	2.4L<4.5L	OK	2.5L<5L	OK
35	2.3L<4.5L	OK	2.3L<5L	OK

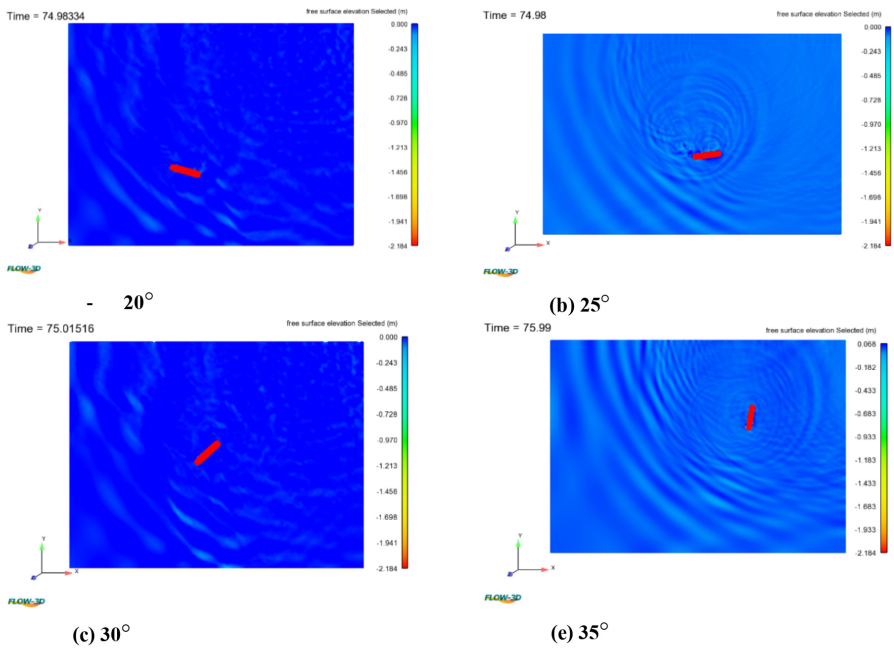


Figure 7: Free surface elevation of complete turning circle at rudder's angle (a) 20°, (b) 25°, (c) 30° and (d) 35°

Effect of Forward Speed to the Manoeuvrability of Tugboat

Increase of forward speed from 7 knots to 9 knots significantly decreased the turning diameter of ship. Higher forward speed with large angular velocity during manoeuvring will reduce the stability of the ship.

Figure 7: Graph of turning diameter at various forward speed

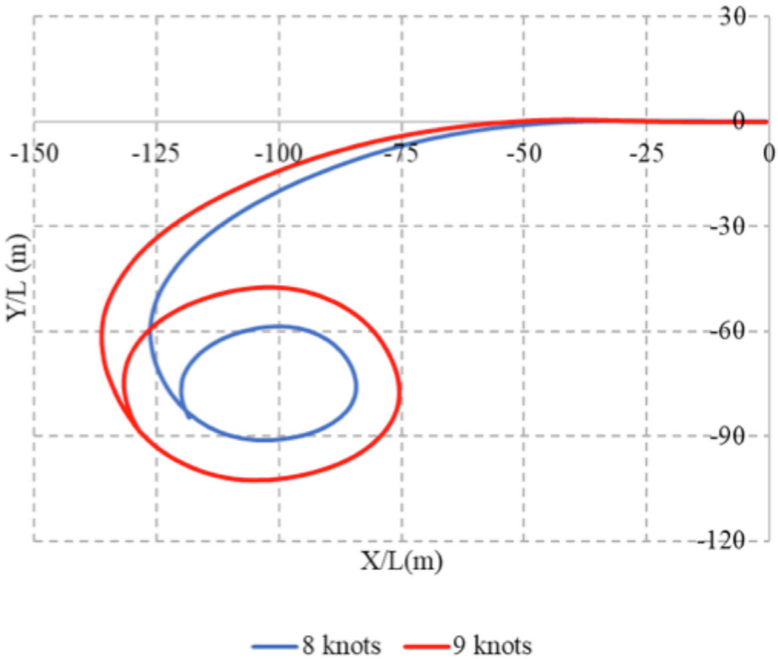
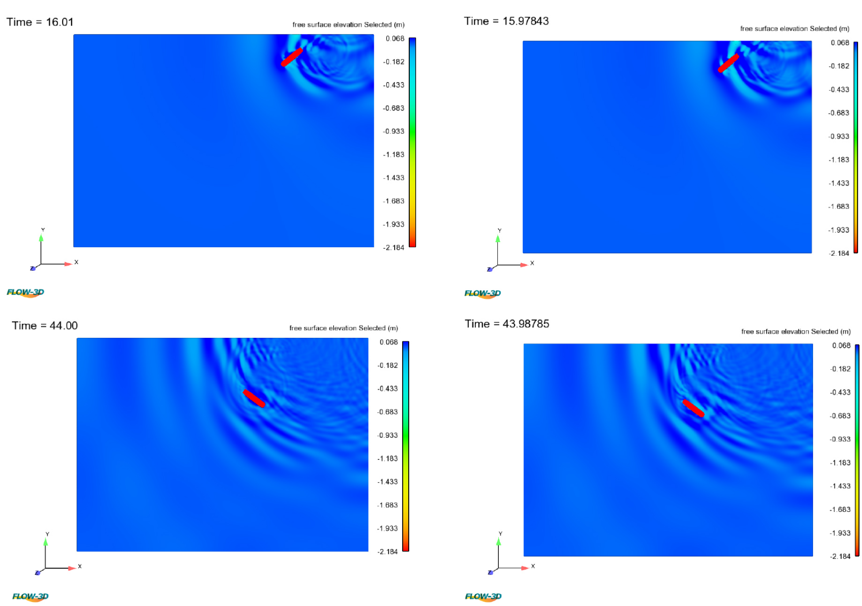


Table 9: IMO criteria with turning maneuver at various forward speed

Forward speed (knot)	Advance diameter (m)	IMO criteria	Tactical diameter (m)	IMO criteria
8	1.75L<4.5L	OK	2.27L<5L	OK
9	2.63L<4.5L	OK	2.54L<5L	OK



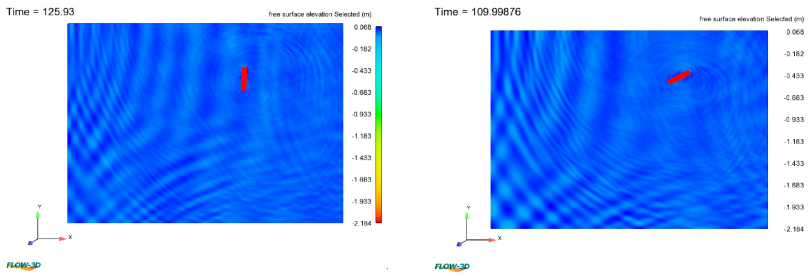


Figure 9: Free surface elevation of complete turning circle at 8 knots (left) and 9 knots (right)

Conclusion

The Computational Fluid Dynamics (CFD) analysis on manoeuvrability of a tugboat was successfully performed using the Flow 3D version 11.2 software. The effects of various rudder's angle and various operational speed have been appropriately investigated. Based on nonlinear analyses, several conclusions of manoeuvring prediction for tugboat manoeuvre can be drawn as follows;

- The advance diameter with the rudder's angle of 15°does not comply with the IMO criteria.
- The advance and tactical diameters with the rudder's angle of 25°and 35°comply with the IMO criteria.
- The zig-zag manoeuvring simulation showed that the first and second overshoot angles of 10°/10°and 20°/20° are acceptable with the IMO criteria.

In nutshell, the manoeuvring performance of a ship will be strongly influenced by its rudder(s). Prior to ship construction, a methodology to evaluate the manoeuvring characteristics of tugboat is established with several different parameters to be considered namely forward speed and angular velocity by using FLOW3D free-running model approach. Increased of ship rudder's angle generally decreased the turning diameter of manoeuvring. While increased of forward speed during operation will increased the turning diameter of ship. Proper parameters during turning will increase the effectiveness of ship manoeuvring to avoid undesired accident.

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