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CFD Analysis on Course Stability of An Asymmetrical Bridle Towline Model of a Towed Ship

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ABSTRACT

Ship towing system has been widely applied to tow disable ship at sea. However, employing improper towing configuration may lead to towing instability presented in the form of the excessive fishtailing motion. To ensure ship's safety navigation, therefore, a comprehensive assessment on course stability performance of a towed ship is necessarily required. This paper presents the course stability analysis of the towed ship (barge) incorporated with an asymmetrical towing configuration of towline model in calm water. Here, Computational Fluid Dynamic (CFD) has been successfully conducted to achieve the objective. Several towing parameters such as towing angle and towing velocity have been accordingly taken into accounts. The results revealed that the increase of towing angle up to 35o has reduced significantly the sway motion amplitude of barge by 94.6%. However, the increase of towing velocity from 0.655 m/s to 0.728 m/s was insignificant effect to the magnitude of the yaw motion of the barge. It is merely concluded that the increase of the towing angle associated with low towing velocity has remarkably improved the course stability of the barge. These findings are very useful for a better navigational safety guidance of the ship towing system.

1. Introduction

Maritime accidents during ship towing such as ship collision are bounded to occur when there is occurrence of towing instability with large amplitude of slewing and yaw motion. Hence, it is important to assess the course stability of barge dealing with a navigational safety of the towing, Lee *et al.,* [1]. Since the towed ship has not equipped with an active surface [2], a comprehensive towing analysis is necessarily required to ensure a safe navigation of towed ship during towing.

Several researchers have investigated the course stability of towed ship performance incorporated with single and bridle towline model configurations both of numerical by Lee [2], Fitriadhy and Yasukawa [3], Fitriadhy [4] and experimental model test by Zan [5]. Im [6] and Fitriadhy *et al.,* [7] have presented the single towline model in which the prediction of the course stability of barge by considering the hydrodynamic forces acting on the towed barge has been taken into

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account. Bernitsas *et al.,* [8] had analysed the performance of the surge, sway and yaw motions of the towed ship associated with a non-linear elastic rope model. Zan *et al.,* [9] and Fitriadhy and Yasukawa [10] have conducted the CFD and numerical simulations on course stability of the towed ship, where the symmetrical bridle towline model was employed. The results showed that the course stability of barge has improved through a significant attenuation of the sway motion. Furthermore, Zan [5] and Fitriadhy *et al.,* [11] have studied the effect of the asymmetrical bridle towline model; the experimental results showed that the course stability of the towed ship has been significantly improved indicated by the sufficient reduction of the sway motion of towed ship as compared to single and symmetrical bridle towline. It became obvious that a reliable Computational Fluid Dynamic (CFD) analysis has become necessary purposed at attaining more accurate predictions of the course stability of the towed ship incorporated with the asymmetrical bridle towline model.

Therefore, this paper presents CFD analysis on course stability of a towed ship incorporated with an asymmetrical bridle towline model in calm water condition. This approach provides a better accurate result as compared to numerical and analytical methods. Here, CFD simulation using Flow3D software has been successfully conducted. Several parameters such as towing angle and towing velocity of the barge have been considered in the simulation, in which the course stability performance of the barge incorporated with the asymmetrical bridle towline configuration has been appropriately discussed.

2. Governing Equation

General moving object (GMO) allow the object to move independently. The motion can be either translational or rotational motion or both motions. The moving object have six degrees of freedom (6DOF) motion with the center of gravity, G as its origin. The coordinates axis for the body system is parallel to the to the space system at t=0. The coordinate transformation between space system (x,y,z) and body system (x', y', z') is

$$\overrightarrow{x_s} = [R] \cdot \overrightarrow{x_b} + \overrightarrow{x_G} \tag{1}$$

Where $\overrightarrow{x_s}$ and $\overrightarrow{x_b}$ are position vectors of a point in space and body systems, respectively, $\overrightarrow{x_G}$ is position vector of the mass center in space system, and $[R]$ is an orthogonal transformation tensor,

$$[R] = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{bmatrix} \tag{2}$$

Where $R_{ij}, R_{jk} = \delta_{ik}$ and $\delta_{ik}$is the Kronecker δ symbol. The inverse and transposed of the [R] are identical. For a space vector A, the transformation between the space and body systems is

$$\overrightarrow{A_s} = [R] \cdot \overrightarrow{A_b} \tag{3}$$

Where $\overrightarrow{A_s}$ and $\overrightarrow{A_b}$ denote the A expressions in space and body systems, respectively. [R] is calculated by solving

$$\frac{d[R]}{dt} = [\Omega] \cdot [R] \tag{4}$$

Where

$$[\Omega] = \begin{bmatrix} 0 & -\Omega_z & \Omega_y \\ \Omega_z & 0 & -\Omega_x \\ -\Omega_y & \Omega_x & 0 \end{bmatrix} \tag{5}$$

and Ω_x, Ω_y and Ω_z are the x-, y- and z-components of the angular velocity of the object in space system, respectively.

FLOW-3D solves Navier-Stokes type equations embedded with various turbulence models. This simulation used the RNG turbulence model since it consider the low Reynold number effects [12-14]. Besides, it can clarify the low intensity of turbulence flow exactly. This CFD simulation applies the Renormalization-Group (RNG) as the turbulence model in the analysis. This type of turbulence model is more suitable compared to k-ε. It is more accurate to present the low intensity turbulence flows and flows with stronger shear regions. The equation of kinematic turbulent viscosity for the turbulence model transport is

$$v_T = \mathrm{CNU}\frac{k_T^2}{\varepsilon_T} \tag{6}$$

Where, v_T is the kinematic turbulent viscosity of the turbulence model. Eqs. (1) to (6) has been discussed by FLOW-3D user's manual [15] which these equations are applied in the CFD.

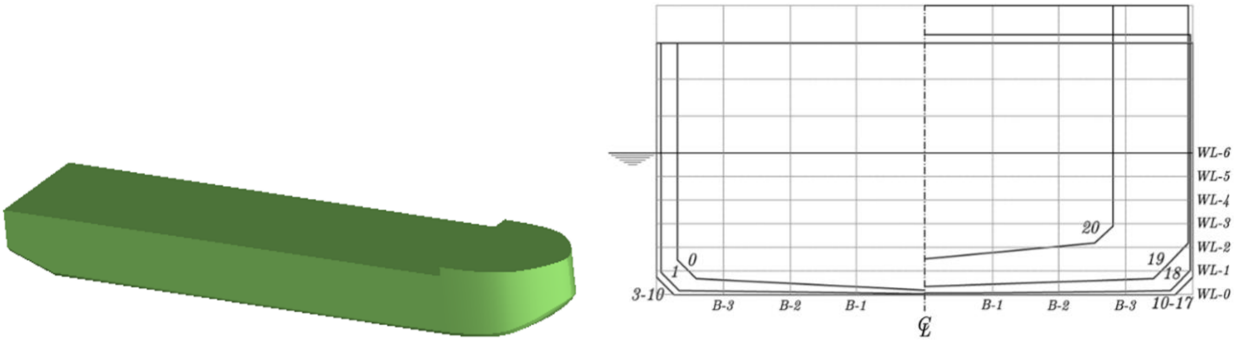
3. Simulation Condition

3.1 Principle Data of Ship

The dimension of the barge is presented in Table 1 while the barge model used in the CFD simulation is shown in Figure 1.

Table 1
Barge dimension

Description	Dimension
Length *l*, (m)	1.221
Breadth *b*, (m)	0.213
Draft *d*, (m)	0.0548
Volume *V*, (m^3)	0.02634
L/B	2.86
Block coefficient, C_b	0.92



a) 3D model b) Barge body plan

Fig. 1. 3D model (a) and body plan (b) of barge

3.2 Simulation Parameter

Figure 2 shows the towing condition of the towed barge. The tug is replaced with the sphere body by using similar characteristics of tug. This is to reduce the computational time during simulation. The simulation parameters used in this analysis are shown in Tables 2 and 3. The towing angle used are 5°, 15°, 25° and 35° at constant velocity 0.509 m/s while the simulation at various towing velocity from 0.509 m/s to 0.728 m/s are simulated for constant towing angle of 25°.

Table 2
Barge towing parameter at various towing angles

Towing angle	Towing velocity (m/s)
5°	0.509
15°	
25°	
35°	

Table 3
Barge towing parameter at various towing velocities

Towline velocity (m/s)	Towing angle
0.509	25°
0.582	
0.655	
0.728	

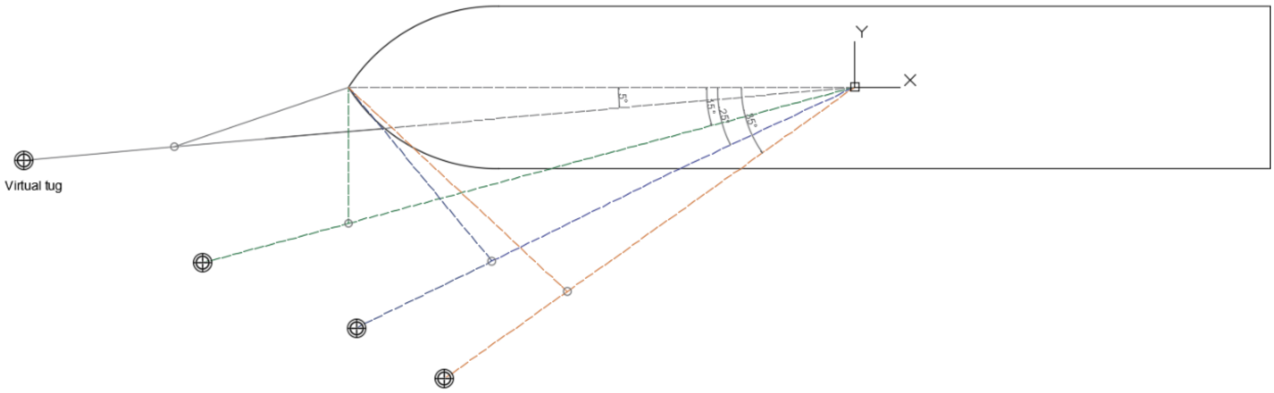


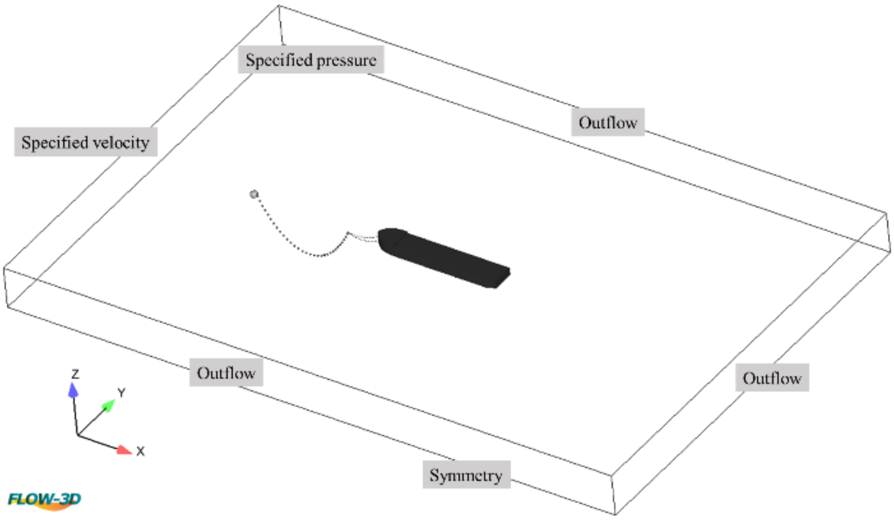
Fig. 2. Simulation condition of barge

3.3 Computational Domain and Meshing Generation

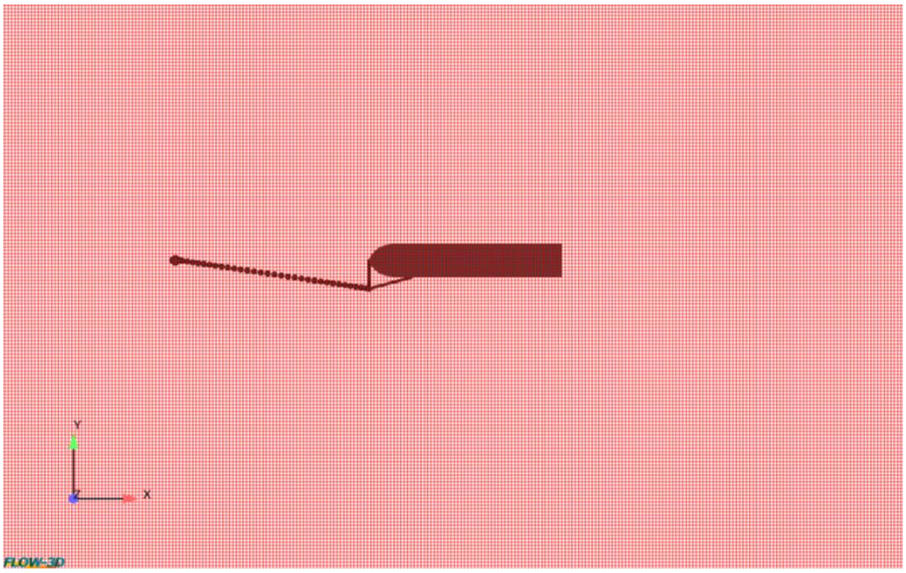
Referring to Figure 3, the boundary conditions are marked in the mesh block. The boundary condition at X-max boundary is assigned by specified velocity so that there is flow of water in the boundary. In the simulation, the barge is coupled through a towline to a virtual tug, where a sphere model has been employed as the virtual tug. In the CFD simulation, the barge is set as coupled motion incorporated with 3 degree of freedom i.e., surge, sway and yaw motions. Here, the towing velocity is set to be constant of 0.509 m/s. The towline is set as mooring line characteristic with spring coefficient of 7.347 kg/s^2.

The computational domain of the barge associated with the number of meshing cells in the CFD. Here, the authors employed 1 million cells meshing. X-min, Y-max and Y-min are defined as the outflow boundary to absorb the wave motion which will reduce the reflection from the boundary while Z-min using symmetry boundary which it applies zero-gradient condition at the boundary and

Z-max using specified pressure to create a uniform pressure in the boundary. The boundary conditions for this simulation are as shown in Table 4.



(a) Boundary condition



(b) Meshing generation

Fig. 3. (a) Boundary condition, and (b) Meshing of barge

Table 4
Boundary conditions

Boundary	Mesh block
X_{min}	Specified Velocity
X_{max}	Outflow
Y_{min}	Outflow
Y_{max}	Outflow
Z_{min}	Symmetry
Z_{max}	Specified pressure

The CFD simulation has been successfully conducted at marine technology simulation laboratory. In average, the total simulation time for each condition was about 70-80 hours (4 parallel computations) using HP Z820 workstation PC with processor Intel (R) Xeon (R) CPU ES-2690 v2 @ 3.00 GHz (2 processors) associated with the installed memory of 32.0 GB and 64-bit Operating System.

4. Results and Discussion

4.1 Single Towline Configuration

Figure 4 shows the characteristics of the sway and yaw motions of the barge associated with the single towline model, where the towing angle is 0°. The results revealed that the sway and yaw motions were steadily oscillated, where their amplitude motions are 0.31m and 0.30 rad/s, respectively. These rigorous motions resulted in significant effect to the magnitude of the towline tension (1.36 N). It is merely concluded that the performance of the course stability of the barge has been degraded presented in the form of her excessive fishtailing motion. The visualization of the hydrodynamic characteristic of the barge is displayed in Figure 5. Here, it is seen that the increase of heading angle has resulted in the increment of the barge resistance indicated by high wave crest (red colour) at the barge's bow. This phenomenon has led to the increase of towline tension of barge. Furthermore, the current results will be finally compared with the asymmetrical bridle towline model, which is completely discussed in sub-section 4.2.

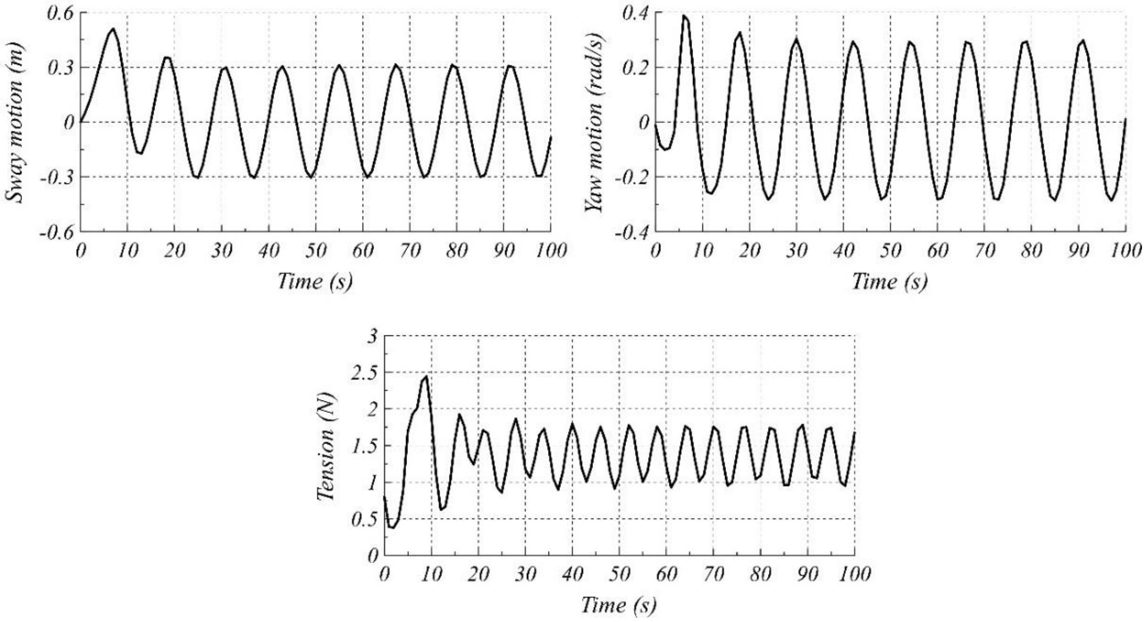


Fig. 4. Characteristic of sway, yaw motions and towline tension at towing angle, α = 0°

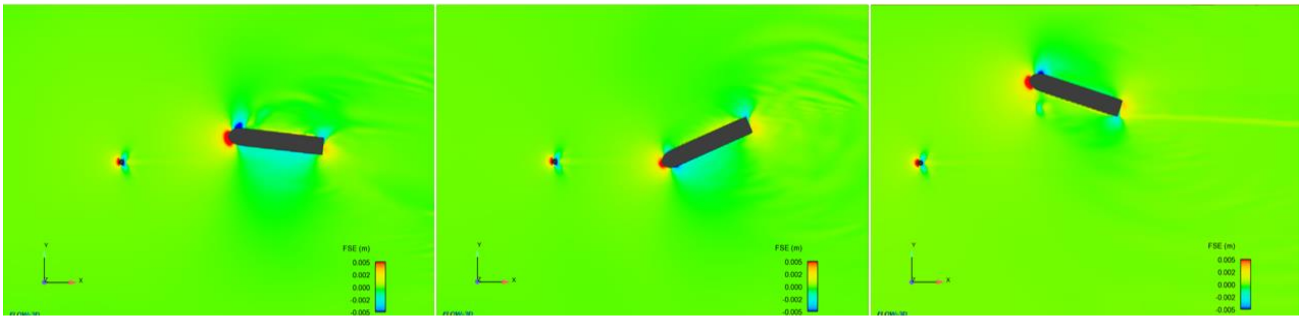
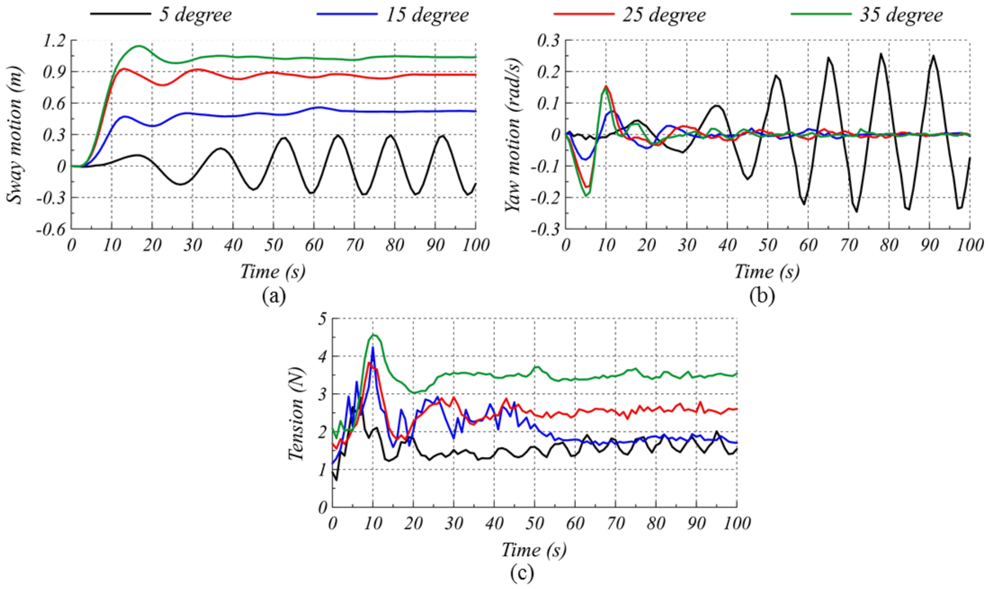


Fig. 5. CFD visualization of asymmetrical towing simulation at towing angle, α= 0°

4.2 Effect of Towing Angle on Course Stability of Barge

The effect of the towing angle on course stability incorporated with the asymmetrical bridle towline model is displayed in Figure 6. The subsequent increase of the towing angle has reduced the sway motion amplitude of barge. Here, the maximum sway motion amplitude has reached up to 0.02 m at the towing angle 35°. As well stated by Zan [5] and Fitriadhy *et al.,* [16],this towline configuration resulted in significant reduction of the sway motion as compared to the single towline model above. This means that the sway motion amplitude has reduced by 93.5 %. In general, the sway motion amplitude has gradually decreased as the towing angle increases from 5° up to 35°, which proportionally improve the course stability of barge. Besides, the increase of towing angle from 5° to 35° shows reduction of slewing motion by 94.5 % as seen in Figure 6 (b).

In addition, the results of towline tension (Figure 6 (c)) have proportionally increased as the towing angle increased from 5° to 35°, where the towing angle at 35° has the highest average towline tension by 3.41 N. The highest percentage increment of towline tension by 35.96% occurred as the towing angle increased from 25° to 35° (see Table 5). This trend is similar to what was found by Zan [5]. It should be noted here that the rapid increase of towline tension at time 10s occurred due to the rapid increase in the slewing motion [11]. In addition, the further increase of towing angle has resulted in higher wave crest (red colour) at the barge's bow as shown in Figure 7. This reason can be explained by the fact that the increase of pressure and resistance acted on the barge which consequently increased the towline tension during towing. Besides, the difference between the bow and stern pressure is created by the isolation of the flow and hull's rear section [16].



(a) (b) (c)

Fig. 6. Characteristics of sway motion (a), yaw motion (b) and towline tension (c) of barge at various towing angles

Table 5
Magnitude of average towline tension at various towing angle

Towing angle	Towline tension (N)	Percentage increment (%)
5°	1.58	-
15°	2.09	32.2
25°	2.51	19.66
35°	3.41	35.96

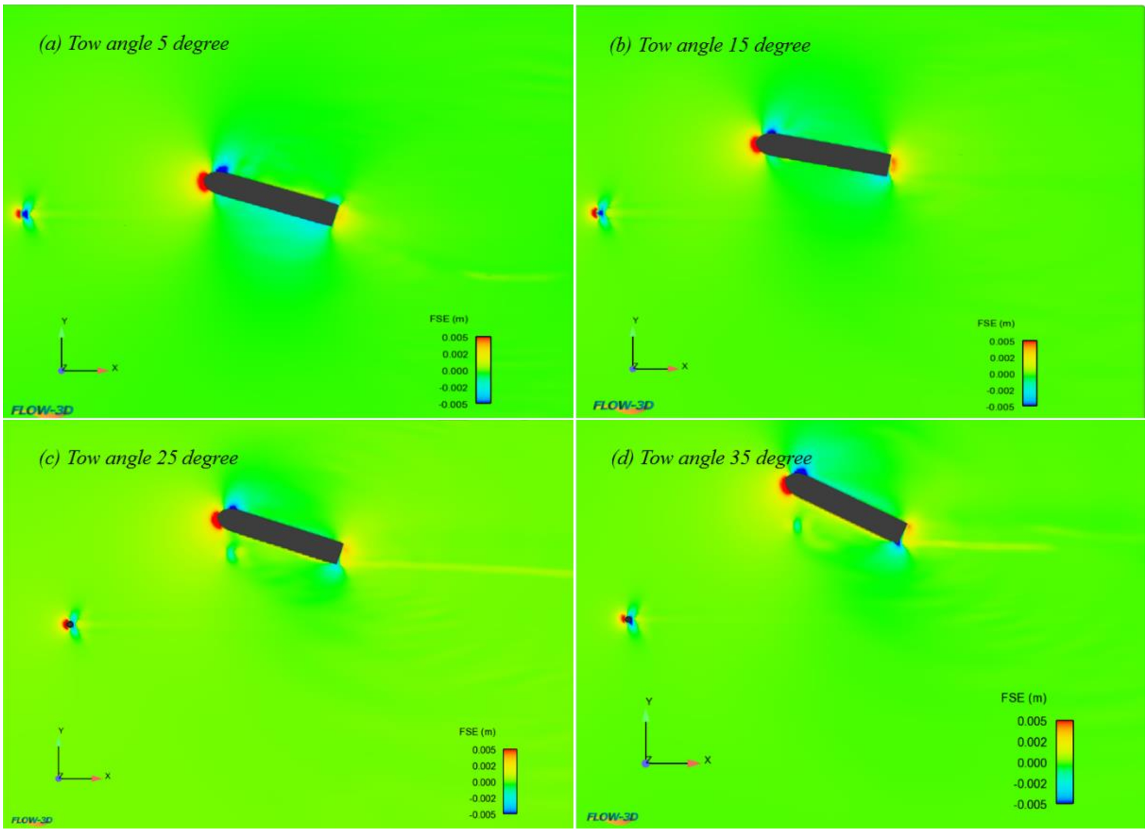


Fig. 7. CFD visualization of asymmetrical towing simulation at various towing angles

4.3 Effect of Towing Velocity on Course Stability of Barge

Figure 8 displays the characteristics of the sway, yaw motions of barge associated with its dynamic towline tension. The results showed that the sway motion has been steadily drifted to starboard as the towing velocity increased from 0.509 m/s up to 0.728 m/s. In average, the amplitude of these oscillation motions has reduced significantly from 0.045 m to 0.003 m. Regardless of the towing velocity increased, however, the towing velocity was insignificant effect to the magnitude of the yaw motions. Meanwhile, the towline tension has reached from 2.51 N up to 4.88 N. It should be noted here that the highest percentage increment of towline tension by 26.40 % occurred as the towing velocity increased from 0.582 to 0.655 (see Table 6). Referring Figure 9 (d), the results were reasonable since the wave elevation (red color) at the bow and stern of barge was higher value as compared to other towing velocity increment. In general, the increase of the towline tension occurred due to the sudden sway motion especially at time 10s.

Table 6
Magnitude of average towline tension at various towing velocities

Towing velocity (m/s)	Towline tension (N)	Percentage increment (%)
0.509	2.51	-
0.582	3.16	26.10
0.655	3.99	26.40
0.728	4.88	22.27

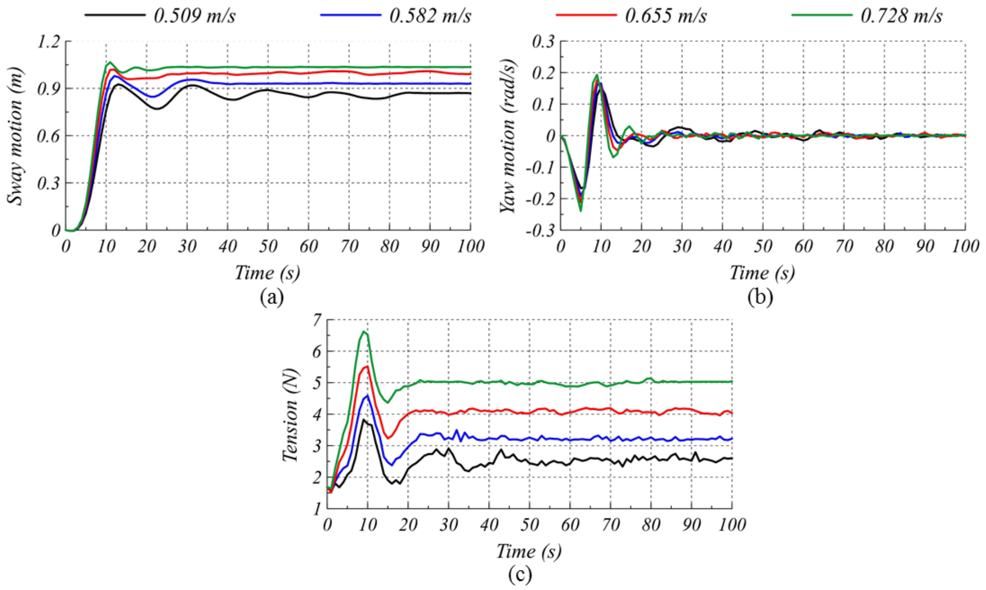


Fig. 8. Characteristics of sway motion (a), yaw motion (b) and towline tension (c) of barge at various towing velocities

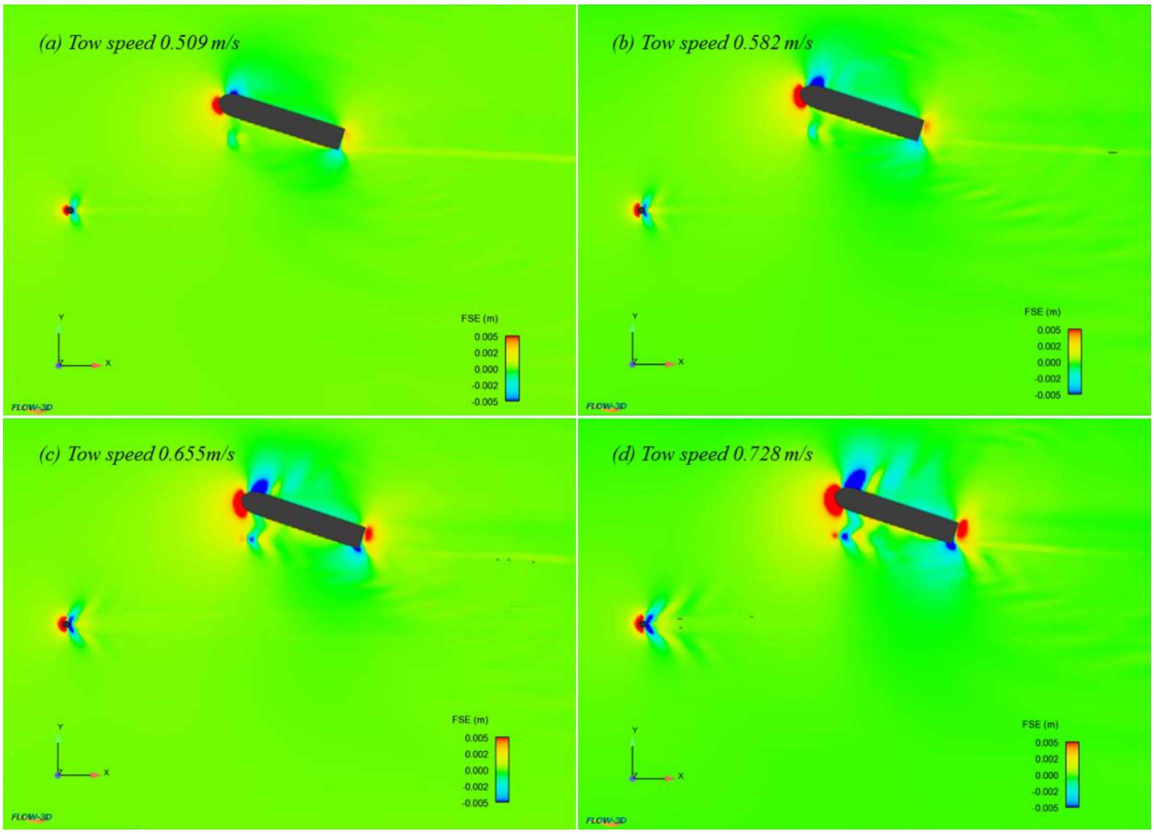


Fig. 9. CFD visualization of asymmetrical towing simulation at various towing velocities

5. Conclusion

The CFD investigation on the effect of course stability of barge using the asymmetrical bridle towline model has been successfully performed. The characteristics of the sway and yaw motions have been assessed accordingly at various towing angles and towing velocities. The conclusion results are drawn as follows:

i. Generally, the subsequent increase of towing angle has resulted in sufficient reduction of the sway motion amplitude of barge. This means that the course stability of the barge has gradually improved. However, the towline tension has proportionally increased, where the maximum increment by 3.41 N occurred at towing angle 35°.
ii. The increase of towing velocity from 0.509 m/s to 0.728 m/s deals with the sufficient attenuation of the sway oscillation motion amplitude by 93.36%. In contrast, the maximum average towline tension by 4.88 N occurred at towing velocity 0.728 m/s. The possible reason for this may occur due to the increase of resistance that can be seen at higher wave elevation at the barge's bow and stern.
iii. In general, the yaw motion of the barge keeps relatively constant, regardless of the increase of the towing velocity.

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