Safe Operation of Tugs within Close Proximity to the Forward and Aft Regions of Ships

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Abstract *— When tugs are used for ship assist manoeuvers, hydrodynamic interaction effects between them can adversely affect the safety and handling of the tug. During such manoeuvers, tugs need to frequently change their location and drift angle with respect to the ship in order to provide the required assistance. Such variations can adversely affect the tug's hydrodynamic interaction forces and moments, thus making it vulnerable to collisions or run-overs.*

In order to safely and effectively operate tugs in these situations, it is essential that the operators are aware of the adverse interaction effects under different operating conditions and locations, enabling them to take necessary precautions and corrective actions to mitigate the dangers. To date, however, most of the data available in the public domain are limited to an 'ideal' tug assist situation, where the tug is operating parallel to the ship. This study discusses the hydrodynamic interaction effects on tugs operating at drift angles ranging from zero to 90 degrees relative to the ship, when located around the forward and aft regions of the ship and at progressively increasing lateral separation between the vessels. The study was conducted using Computational Fluid Dynamics (CFD) simulation models which were validated against experimental measurements obtained at the Australian Maritime College model test basin.

The non-dimensionalised interaction effects were used to create Hydrodynamic Interaction Region Plots (HIRP) to identify the variation of the coefficients with respect to the tug drift angle and the relative distance between the vessels. The results demonstrate that the safest approach to the ship with the least interaction effects is at a tug drift angle of less than 15 degrees. In addition, once the tug reaches the desired position relative to the ship, it is advisable to maintain a parallel course with the ship to avoid substantial longitudinal forces and yaw moments that can adversely affect the tug's manoeuvrability.

Keywords — **ship – tug interaction, forward and aft regions, HIRP, tug safety**

Nomenclature

C_N	Yaw moment coefficient
C_X	Surge force coefficient
C_Y	Sway force coefficient
F_r	Froude Number, Tug; $\frac{u}{\sqrt{gL_t}}$
g	Acceleration due to gravity (9.81m/s^2)
HIRP	Hydrodynamic Interaction Region Plot
L_s	Waterline length of the tanker (m)
L_t	Waterline length of the tug (m)
N	Yaw moment acting on tug (Nm)
u	Fluid flow velocity (m/s)
X	Longitudinal force acting on tug (N)
Y	Lateral force acting on tug (N)
δx	Longitudinal distance between hulls (m)
δy	Lateral distance between hulls (m)
Δx	Non-dimensionalised longitudinal distance between vessels
Δy	Non-dimensionalised transverse distance between vessels
ρ	Density of water (kg/m^3)
∇_s	Volumetric displacement of the tanker (m^3)
∇_t	Volumetric displacement of the tug (m^3)

I. INTRODUCTION

When a large ship is manoeuvred in restricted waters at low speeds, it is usually required to have an assisting tug or tugs in order to maintain its course and berthing safely. However, when a tug operates in close proximity to a larger ship, the hydrodynamic interaction effects induced on the tug could lead to danger such as collision between the vessels or the tug being run-over by the ship (Hensen, 2012). Hence, it is essential to understand the hydrodynamic interaction behaviour between the vessels to enable the tug and ship operators to take the required action to avoid such dangers. There are a number of published work addressing interaction effects between vessels operating in close proximity that investigate and provide information on (Sutulo et al., 2012):

- the qualitative behaviour of the hydrodynamic interaction effects;
- estimation of maximum loads, safe distances and velocities during vessel overtaking and encounter situations;

- the mooring line loads on a berthed vessel due to passing vessels;
- navigational accidents of vessels operating in close proximity;
- manoeuvring standards for tug and ship operators; and
- algorithms for ship handling simulators.

To date, most studies on the interaction behaviour available in the public domain (Newton, 1960, Vantorre et al., 2002, Pinkster and Bhawsinka, 2013, Lindberg et al., 2012, Zou and Larsson, 2013, Tuck and Newman, 1974, Lataire et al., 2009, Taylor, 1909) have investigated ships that are similar in size. There is a limited number of studies (Dand, 1975, Simonsen et al., 2011, Geerts et al., 2011, Fonfach et al., 2011, Sutulo et al., 2012) that focus on the interaction behaviour of a tug (which is significantly smaller in size and thus more susceptible to the interaction effects) operating in close proximity to a large ship. However, most of these studies used either a tug operating at one specific location alongside the ship (e.g. the midship region) or only at one tug drift angle relative to the ship (usually with the ship and tug operating in parallel). Thus, the predicted results of the interaction effects were specific to certain locations and operating conditions, and thus do not provide a comprehensive view of the overall behaviour of the tug during such manoeuvres.

Previous work published by the authors (Jayarathne et al., 2017b, Jayarathne et al., 2017a, Jayarathne et al., 2016, Jayarathne et al., 2014) attempts to address these gaps by providing interaction information on a tug operating at various locations and angles of attack relative to a large ship. These studies were aimed at developing comprehensive Hydrodynamic Interaction Region Plots (HIRP) to assist tug operators to identify safe operating envelopes for their tugs during ship-assist manoeuvres. In Jayarathne et al. (2016), the authors presented HIRPs for tugs operating around the midship region of a large ship at various lateral separations. However, as explained by Hensen (2003), the forward and aft regions of ships are the most critical areas for the tugs to operate and thus need careful attention. This study extends the previously presented HIRPs to include the forward and aft regions to provide a more comprehensive set of interaction effect data to assist tug operators during ship assist manoeuvres.

II. CASE STUDY

The study utilised a MARAD F-series tanker and a typical stern drive tug hull, which were used previously by the authors (Jayarathne et al., 2016), with the hull geometries reproduced in Figure 1. Throughout the analysis, the tug was located on the port side of the tanker. Two different tug operating speeds: 3 knots (Tug length based Froude number, $F_r = 0.09$) and 6 knots ($F_r = 0.18$), were investigated in this study. These speeds represent the minimum and maximum tug operational speeds during usual ship assist manoeuvres (Hensen, 2003). The coordinate systems used for the study are given in Figure 2. The global coordinate system was used to obtain the tug's longitudinal and lateral forces, while the yaw moment was measured on the tug local coordinate system.

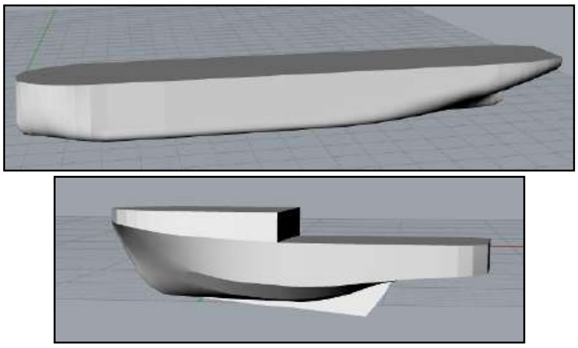


Figure 1: 3D Hull forms: (Top) MARAD-F Series Tanker (Bottom) Typical stern drive Tug. [*Not to scale*]

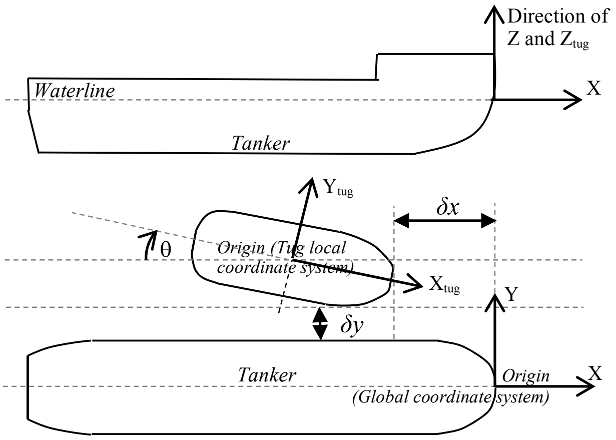


Figure 2: Local (tug) and global coordinates systems, and vessel locations. [*Not to scale*]

The forces, moment, and the longitudinal and lateral distance between the two vessels were non-dimensionalised using Eqs. 1 to 5 respectively (Fonfach, 2010, Simonsen et al., 2011, Jayarathne et al., 2017a, Jayarathne et al., 2016).

$$C_X = \frac{2X}{u^2 \nabla_t^{1/3} \nabla_s^{1/3} \rho} \quad \text{(Eq.1)}$$

$$C_Y = \frac{2Y}{u^2 \nabla_t^{1/3} \nabla_s^{1/3} \rho} \quad \text{(Eq.2)}$$

$$C_N = \frac{2N}{u^2 \nabla_t^{1/3} \nabla_s^{1/3} L_t \rho} \quad \text{(Eq.3)}$$

$$\Delta x = \frac{\delta x}{L_s} \quad \text{(Eq.4)}$$

$$\Delta y = \frac{\delta y}{B_s} \quad \text{(Eq.5)}$$

with all symbols defined in the nomenclature.

The analysis was conducted using Computational Fluid Dynamics (CFD) simulations utilising the computational mesh presented in Jayarathne et al. (2016). The CFD mesh at model scale was validated using the results from the captive model tests conducted in the model test basin at the Australian Maritime College (AMC) (Figure 3).

Figure 3: Experimental setup to measure the interaction effects between vessels in AMC's Model Test Basin

The mesh model was then extended to full-scale conditions with a scale factor of 1:50 based on the Froude scaling technique, with a final mesh domain of 13.2 million shown in Figure 4. The full-scale CFD mesh (Jayarathne et al., 2016) was used to investigate the interaction effects induced on the tug operating within the forward region (i.e. Δx = -0.10) and the aft region (i.e. Δx = -0.75) alongside the tanker at three different lateral separations and seven different drift angles, as outlined in Table 1.

Figure 4: The final full scale 13.2 million CFD mesh model of the tug and ship.

The commercial CFD code, Star-CCM+® was used to investigate the test scenarios outlined in Table 1 via Reynolds Averaged Navier-Stokes (RANS)-based simulations with the Shear Stress Transport (SST) turbulence model. The computational domain used in the Star-CCM+® simulations is shown in Figure 5.

Table 1. Cases investigated for the tug operating at forward (Δx = -0.10) and aft (Δx = -0.75) regions alongside the tanker.

Drift Angle between hulls	Distance between hulls		
	δy = 1 m Δy = 0.03	δy = 18.225 m Δy = 0.5	δy = 36.45 m Δy = 1.0
0 Degree	✓	✓	✓
15 Degrees	✓	✓	✓
30 Degrees	✓	✓	✓
45 Degrees	✓	✓	✓
60 Degrees	✓	✓	✓
75 Degrees	✓	✓	✓
90 Degrees	✓	✓	✓

The free surface in the CFD simulation was modelled as an Euler Multiphase using the volume of fluid (VOF) technique. Verification and validation studies of the simulation model were previously presented by the authors in (Jayarathne et al., 2017a, Jayarathne et al., 2017b) showing good agreement between the interaction coefficients for the model scale CFD and model scale EFD results, and full-scale CFD results based on Froude scaling. The difference of the coefficients was less than the experimental uncertainties of 7%, 9.4%, and 7% for the longitudinal force, lateral force, and yaw moment respectively. The model scale and full-scale predictions of the interaction effect coefficients were in good agreement (within 8%) thus providing confidence in the CFD model to be extended to the full-scale conditions of this study.

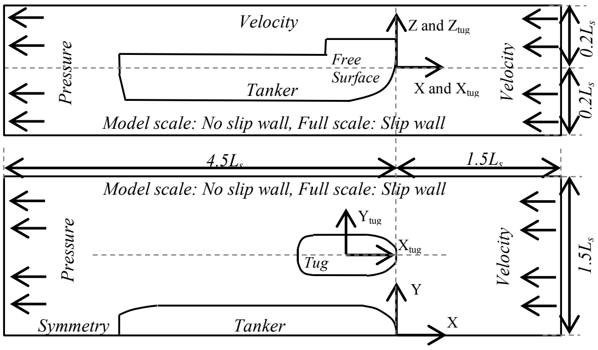


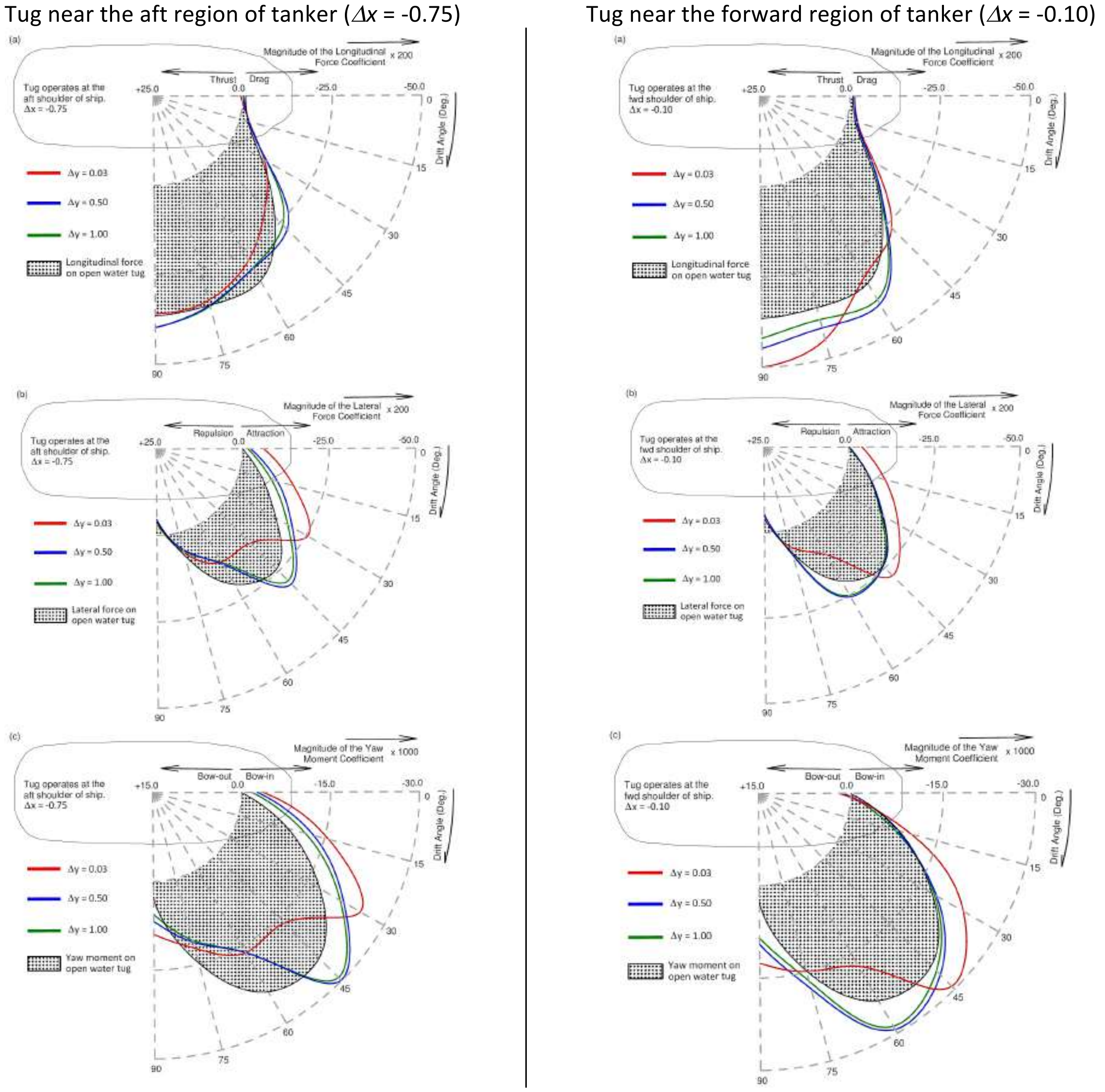
Figure 5: Computational domain used in Star-CCM+® simulations. [*Not to scale*]

III. HIRP RESULTS

The coefficients of the interaction effects when the tug is positioned alongside the tanker at the different drift angles and lateral and longitudinal locations as given in Table 1 are presented below. It includes a comparison of the forces and moments obtained by simulating the tug in open-water and in close proximity to the tanker to identify the significance of the tanker's presence on the tug's manoeuvrability. Figure 6 illustrates the HIRPs of the tug operating around the aft and forward regions of the tanker.

From Figure 6 it is seen that when the tug is at the aft region of the tanker (Δx = -0.75), its longitudinal force is similar to the open-water tug until a drift angle of 15 degrees for all three lateral separations. The same behaviour is observed when the tug is at the forward region of the tanker, i.e. Δx = -0.10. When the drift angle increases above 15 degrees, there is a deviation of the longitudinal force from that for the open-water tug and the maximum force is seen at a drift angle of 90 degrees for both the aft and forward regions. It is also observed that this variation is greater for the forward region. Therefore tug operators should expect a greater change in tug resistance when manoeuvring within the forward region of the larger vessel.

Considering the lateral force on the tug with respect to the drift angle in the aft region of the tanker, the suction force peaked at 30 degrees for Δy = 0.03 and 45 degrees for Δy = 0.50 and 1.00; decreasing steeply thereafter as the drift angle increases.


Tug near the aft region of tanker (Δx = -0.75)

Tug near the forward region of tanker (Δx = -0.10)

Figure 6: Hydrodynamic Interaction Region Plots (HIRP) showing the forces and moments on the open-water tug, and on an interacting tug operating at the aft and forward regions of the tanker. a) Magnitude of the longitudinal force coefficient; b) Magnitude of the lateral force coefficient; c) Magnitude of the yaw moment coefficient.

The yaw moment follows the same trend of the lateral force with respect to drift angle. Therefore, tug operators should avoid being close to the critical drift angles between 30 and 75 degrees due to the difficulty in predicting the variation of the forces due to the interaction, as this increases the chances of the vessel reacting contrary to the commands given. From zero to 15 degrees and 75 to 90 degrees, the lateral force and yaw moment for the interacting tug follow a pattern similar to the open-water tug, thus making it easier for tug operators to predict the variation of the forces and moments due to the interaction. However, it should be remembered that between the drift angles of 75 and 90 degrees, the tug experiences the maximum longitudinal force which can affect its position keeping ability. Therefore, the tug should maintain a drift angle of less than 15 degrees near the aft region of the tanker to minimise adverse interaction effects.

When observing lateral force and yaw moment on the tug with respect to drift angle in the forward region of the tanker, the interaction behaviour follows a similar trend to the aft region. The exception is that the suction force and yaw moment peak at 45 degrees for Δy = 0.03 and 60 degrees for Δy = 0.05 and 0.10. It can this be summarises that when a tug is operating around the forward or aft regions of a larger ship, tug operators can avoid excessive lateral forces and moments due to the interaction if they maintained a drift angle less than 15 degrees.

IV. FLOW VISUALISATION

Figure 7 illustrates CFD pressure contours on the tug hull at a drift angle of 45 degrees around the aft region of the tanker and at 60 degrees around the forward region of the tanker. These represent locations where critical changes in forces and moment are observed in the HIRPs (see Figure 6). Hull pressure contours of the open-water tug are also presented to highlight the interaction effects due the differences in the pressure field.

As seen in the figure, when the tug is at the stern region of the tanker (Δx = -0.75) and the lateral separation is the smallest (Δy = 0.03), the pressure on the tug's leeward side is more than that of the open-water tug. This is due to the tug operating around the aft region of the tanker resulting in a comparatively higher pressure due to the pressure recovery in that region. This high pressure decreases the longitudinal and lateral suction forces acting on the tug in comparison to that in an open-water condition. In addition, at Δy = 0.03, the pressure distribution along the tug's length is less than on the open-water tug. This in turn reduces the bow-in yaw moment on the tug. In contrast to the Δy = 0.03 separation, at Δy = 0.50 and 1.00 the hull pressure is less on the leeward side. Therefore, at these lateral separations, the forces and moment become larger than what is experienced in the open-water condition.

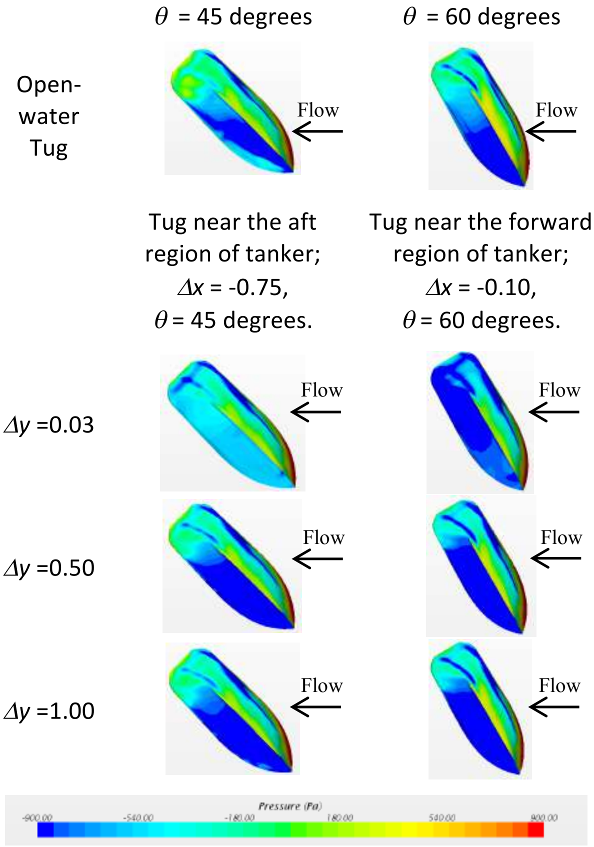


Figure 7: CFD hull pressure contours for a tug at a drift angle (θ) of 45 in the aft region and 60 degrees in the forward region of the tanker. Δx and Δy are the non-dimensionalised longitudinal and lateral separations respectively.

From Figure 7 it is seen that when the tug is in the forward region of the tanker, a drift angle of 60 degrees and Δy = 0.03, the pressure at the bow of the tug on the leeward side higher compared to the open-water tug. This is due to the small gap between the vessels, which hinders the flow past them, and thus increasing the pressure at the location. In addition, the pressure on the tug's stern is well below the pressure on the stern of the open-water tug. As a result, there is a reduction in the lateral attraction force and the bow-in yaw moment, when compared with that on the open-water tug.

As seen in the pressure contours on the tug hull, when the lateral separation is increased to Δy = 0.50 and 1.00, the pressure on the tug's leeward side is reduced compared to the open-water tug. Therefore, as seen in Figure 6, when the tug is drifted to 60 degrees around the forward region of the vessel, the magnitudes of the lateral attraction force and bow-in yaw moment are at a maximum, which in turn increase the danger to the tug during close quarter manoeuvres.

V. CONCLUSION

This study presents the hydrodynamic interaction effects induced on a tug operating at the forward and aft regions of a larger ship during a ship-assist manoeuver. It was carried out through a CFD simulation study, using a previously validated CFD simulation model (Jayarathne et al., 2016). Interaction effects on the tug were determined at two regions of the ship for difference lateral separations, tug drift angles, and two speeds. The results were presented on Hydrodynamic Interaction Region Plots (HIRP) enabling the tug operators to identify safe operational envelopes for a tug to approach the forward and aft regions of the larger vessel during such manoeuvres.

The results revealed that drift angles ranging from zero to 15 degrees and 75 to 90 degrees present the least interaction lateral force and yaw moment. However, within the 75 to 90 degrees drift angle range, the longitudinal force induced on the tug is relatively high. Thus, a tug operating within this drift angle range will struggle to maintain its position relative to the ship due to strong longitudinal forces acting on it. It is therefore recommended that a tug approaches the forward and aft regions of a larger ship along a path that results in a drift angle between zero to 15 degrees. This will results in minimum interaction between the vessels that could otherwise adversely affect the trajectory and behaviours of the tug. Once the tug reaches these regions of the ship, it is the best to align and maintain the tug parallel to the ship as much as possible, thus reducing the interaction effects as the vessels progress forward together. Furthermore, the study identified drift angles between 30 to 60 degrees as a critical range, where the interaction behaviour is most detrimental to the tug. It is therefore prudent to attempt and maintain the tug drift angle within the safe ranges, i.e. between zero and 15 degrees, while moving quickly through the adverse ranges if required.

In future work, the current results will be extended to include varying longitudinal locations of the tug, thus providing data for a range of longitudinal and lateral separations as well as tug drift angles. The results will be used to develop explicit Hydrodynamic Interaction Region Plots (HIRP) to determine safe operational envelopes for tugs to operate during ship-assist manoeuvres.

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