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Assessment of Ship-Bank Interactions on LNG Tanker in Shallow Water

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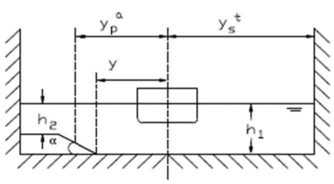
Graphical abstract



Abstract

Liquefied Natural Gas (LNG) tanker often travels through shallow waters with visible banks to load and unload its hazardous cargo. Manoeuvring of vessel in shallow water is relatively difficult and always exposed to higher risk of grounding and collision compared to deep water due to effect of ship-bank interaction. This research work examines ship-bank interaction effects of a LNG tanker in shallow water. CFD analysis is performed to investigate the hull hydrodynamic forces/moments and ship-bank interaction forces/moments which are further validate by captive model tests.

Keywords: Bank effects; shallow water; computer fluid dynamics (CFD)

1.0 INTRODUCTION

Liquefied Natural Gas (LNG) tanker often travels through shallow waters with visible banks to load and unload its hazardous cargo. When ship travel in restricted water and close to the bank, the asymmetric flow around the ship inducted by vicinity of the banks results in sway force and yaw moment that tend to swing the bow of ship away from the bank which can lead to potentially dangerous situations, especially for LNG tanker. Such effect of combination of sway force and yaw moment is known as bank effect.

To have the effect minimized, the hydrodynamic forces between ship and bank should be properly understood. Work on bank effect has been reported for the past years. Model scale experiments have been conducted by Duffy (2002) and showed that the effect depends on various parameters such as vessel speed, vessel draught, bank height, water depth, bank slope and ship to bank distance.

An extensive set of model tests also performed by Lataire *et al*. (2007) to investigate bank effects induced by surface-piercing bank and submerged bank. A mathematical model is later formulated by Lataire *et al*. (2009) for sway force and yaw moment based on the model tests. Lee and Lee (2008) has further extended the study of hydrodynamic forces between ships in the proximity of bank in restricted waterways for a few more practical and complicated situations.

Even though model test remain the primary source of data for marine hydrodynamic test, model test are costly and time consuming. The use of computational fluid dynamics (CFD) techniques as a means of predicting the hydrodynamic forces acting on vessel is gradually increasing in the maritime community, for example, Lo (2009) applied CFD to investigate hydrodynamic forces of bank effect acting on hull of a ship in restricted waterway. The results presented generally confirmed the feasibility of CFD technique to study on bank effect.

In the present study, the focus is to examine ship-bank interaction effects of a LNG tanker in shallow water using CFD simulation. The simulations focus specifically on the effects of ship speed and distance of ship to bank on the resulted sway force and yaw moment. General purpose CFD code, FLUENT, which uses a 3D Reynolds-averaged Navier-Strokes (RANS) solver based on finite volume method (FVM) is applied. Predicted sway force and yaw moment are further compared to the results of model tests for validation.

2.0 FORMULATION

2.1 Governing Equation

In the simulations performed in this study, the flow around ship hull is modeled using the Reynolds Averaged Navier-Strokes (RANS) equations. The solution variables in these equations are decomposed into the mean and fluctuating components. For the velocity components:

$$u_i = \bar{u}_i + \acute{u}_i \quad (1)$$

Where $\bar{u}_i$ and $\acute{u}_i$ are the mean and fluctuating velocity components, in which $i = 1, 2, 3$. For pressure components:

$$p = \bar{p} + \acute{p} \quad (2)$$

Where $\bar{p}$ and $\acute{p}$ are the mean and fluctuating pressure components. If the fluid is assumed incompressible, the mean flow field is governed by the RANS equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (3)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = \quad (4)$$

$$-\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{\acute{u}_i\acute{u}_j}\right)$$

in which ρ and μ are the density and viscosity of the fluid. The Reynolds stresses $-\rho\overline{\acute{u}_i\acute{u}_j}$ are modeled and related to the mean velocity gradients as:

$$-\rho\overline{\acute{u}_i\acute{u}_j} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_t\frac{\partial u_k}{\partial x_k}\right)\delta_{ij} \quad (5)$$

2.2 Turbulent Model

The shear-stress transport (SST) κ–ω model is used for turbulence closure in this research. The SST κ–ω model is an empirical model transport equations solving for the turbulence kinetic energy (κ) and the specific dissipation rate (ω) and remained as one of the most accurate and reliable turbulence models for external hydrodynamics.

κ function:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_k\frac{\partial k}{\partial x_j}\right) + \tilde{G}_k - Y_k + S_k \quad (6)$$

ω function:

$$\frac{\partial}{\partial t}(\rho\omega) + \frac{\partial}{\partial x_i}(\rho\omega u_i) = \frac{\partial}{\partial x_j}\left(\Gamma_\omega\frac{\partial \omega}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega + S_\omega \quad (7)$$

Where $\tilde{G}_k$ and G_ω represents the generation of turbulence kinetic energy due to mean velocity gradients and the generation of ω. $\Gamma_k$andΓ_ω represent the effective diffusivity of κandω. $Y_k$andY_ω represent the dissipation of $\kappa$and ω due to turbulence. $D_\omega$represents the cross-diffusion term, S_k and S_ω are user-defined source terms.

3.0 METHODOLOGY

3.1 Establishment of ship model

The object studied in this paper is a hull of LNG tanker at scale of 1/112. Table 1 shows the principal particulars of the LNG tanker used in model test and numerical calculation.

Table 1 Principal dimensions of the ship and model

	Full scale	Model
L_{bp} (m)	266	2.375
Beam (m)	41.3	0.3714
Draft (m)	11.13	0.099
C_b	0.746	0.746
Wetted surface area (m^2)	14032.66	1.12

3.2 Establishment of Test Velocity

The same Froude number in model and full scale ensures the model and full-scale ships exhibit similar behavior. In general, the Froude number, Fr, is defined as:

$$\text{Fr} = \frac{V}{\sqrt{gL_{\text{wl}}}} \quad (8)$$

Where V is the velocity of the ship (m/s), g is the acceleration due to gravity (m/s2), and L_{wl}(m) is the length of the ship at waterline level. Utilizing the Froude number as a similarity parameter, the tests velocity in simulation is shown in Table 2.

Table 2 Comparison of real ship and model velocity

Ship velocity (knots)	Ship velocity (m/s)	Froude number (Fr)	Model velocity (m/s)
6	3.08	0.06	0.29
8	4.11	0.08	0.39
10	5.14	0.10	0.49
12	6.17	0.12	0.58

3.3 Establishment of Computational Domain

The prediction of the hydrodynamic interaction forces was performed for conditions which the tanker running straight close to bank in a numerical towing tank at model scale. Figure 1 presents a schematic illustration showing the computational domain of the numerical towing tank for current CFD simulations measuring the sway force and yaw moment generated by the bank effect.

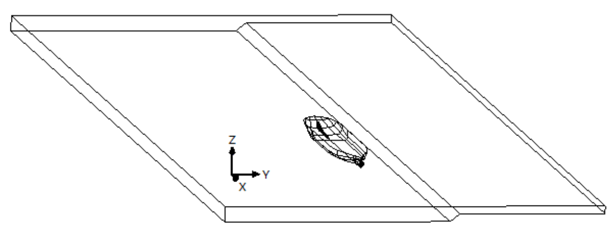


Figure 1 Computational domain

A coordinate system fixed with respect to the position of the ship is defined with z in the vertical upward direction passing through the center of gravity of ship, x in the longitudinal direction of the ship pointing to the bow, and y perpendicular to the x axis and in port direction. The origin is in the plane of the undisturbed free surface.

It is assumed that effects of air drag and surface wave is relatively small and neglected in simulation. Effect of propeller and rudder is not included for simplification. Thus, only underwater part of the ship hull is simulated.

To prevent the accuracy of the simulation results for the ship-bank interactions from being affected by the waves reflected from far bank, the width of the waterway model was specified as 10 times the beam of the ship and the length was specified as 5 times the length of ship. The computational domain comprised a total of approximate one million unstructured grids. Boundary conditions of the domain were set in the preprocess stage as follow:

1) Inflow : velocity inlet
2) Outflow : pressure outlet
3) Ship surface : wall
4) Fluid domain : fluid

The simulations to measure sway force and yaw moment of ship-bank interactions were performed for various ship speed and ship-bank distance. The bank model includes a vertical bank at one side, and a sloping bank with inclination 0.79 radian at another side. The correlation between the draught of ship and the water depth is expressed by the ratio h/D = 1.2 shallow water condition in this study. The ship-bank distance is expressed by the ratio y/B = 0.4, 0.5, 0.7 and 1.0 in this study.

3.4 Numerical Simulation using FLUENT

Simulations in this paper are completed using FLUENT software, SST κ–ω model and standard wall function. Some major computational settings are shown in Table 3 while the other options remain default. Force and momentum data are recorded every step.

Table 3 Overview of computational settings

Parameter	Setting
Pressure-velocity Coupling	SIMPLE
Gradient spatial discretization	Least Squares Cell Based
Pressure spatial discretization	Standard
Momentum spatial discretization	First Order Upwind
Turbulent Kinetic Energy spatial discretization	First Order Upwind
Specific dissipation rate spatial discretization	First Order Upwind

3.5 Experiment

Experimental towing tank test in Marine Technology Centre, UniversitiTeknologi Malaysia with scaled LNG model have been performed for validation of numerical calculation. Some of these experimental data have been published in Maimun *et al.* (2009).

In the experiment, the model fully constrained in surge, sway and yaw was towed at predetermined speed parallel to the lateral bank. Vicinity of the model and the lateral bank will be adjusted which the transverse forces and moment recorded. Cross-sectional view of the experiment and various parameters of bank geometry were shown in Figure 2.

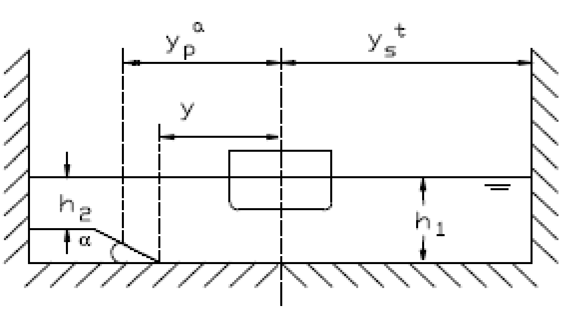


Figure 2 Parameters of bank geometry

The hydrodynamic sway forces and yaw moment acting on the ship is shown in non-dimensional form as follow.

$$Y' = \frac{Y}{\frac{1}{2}\rho L^2 U^2} \tag{9}$$

$$N' = \frac{N}{\frac{1}{2}\rho L^3 U^2} \tag{10}$$

4.0 RESULTS AND DISCUSSION

4.1 Results

Sway force and yaw moment experienced by LNG tanker under influence of bank effect are simulated for different ship speed and ship-bank distance. Based on the methodology above, Figure 3 show the computational and experimental results of ship's position versus non dimensional sway force with different Froude numbers and Figure 4 show ship's position versus non dimensional yaw moment with different Froude numbers.

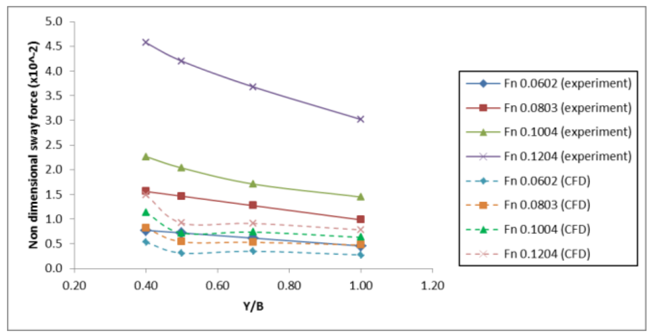


Figure 3 Ship's position versus non dimensional sway force with different Froude numbers

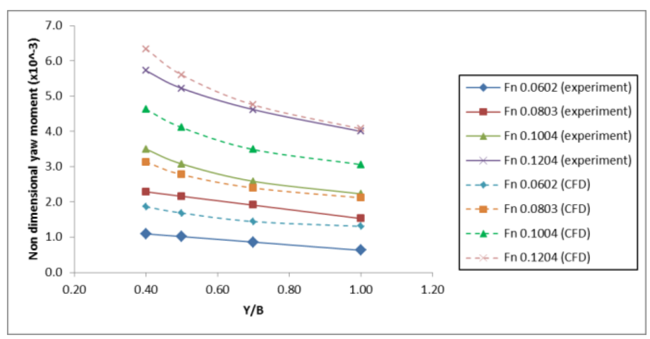


Figure 4 Ship's position versus non dimensional yaw moment with different Froude numbers

From these figures, the vessel experiences an attraction force to the bank and bow out moment. In general, the bank effect reduces with increase of ship-bank distance. For a given ship-bank distance, the effects generally increase with increases of ship speed.

The simulation results of sway force and yaw moment are varies with experimental data. The agreement between computed and experimental sway force is unsatisfactory, even though both the results shows sway forces reduces with increases of ship-bank distance. Better agreement is found only for smaller Froude numbers. Computed yaw moments at the other side are much closer with experimental results. In particular, the amplitudes of the two sets of results are comparable for higher Froude number (Fn = 0.1204). From these figures, we can observe that the accurate simulation of sway force is much more difficult than that of yaw moment.

4.2 Discussion

CFD analysis is performed for investigation of the hull hydrodynamic forces/moments due to ship-bank interaction. Results of current simulations agree well with experimental data only for yaw moment in high Froude number, and vary for the rest. The differences represent modeling error in numerical computations. Study on different aspects of the computational requirements and their relation to numerical accuracy is required.

Bank effect depends on ship-wave interaction between hull and bank, which is neglected in the computational analysis in this study. Besides, the wind factors in neglected in as well. The iterative error in simulation need to be further reduces to ensure numerical accuracy.

The estimated hydrodynamic force and moment is dependent on the turbulence model selected. The computed results for a given turbulence model will be difference with other turbulence model. The studies on influences of computational domain size and its effect on numerical accuracy are required as the results are always dependent on type and size of grid. Unstructured mesh is applied in current study due to its simplicity.It is recommend that structural mesh can be applied for better numerical accuracy in future. Due to various possible errors in simulation, conclusions on bank effect have to made carefully to avoid any misleading.

■5.0 CONCLUSIONS

The CFD simulations and experimental result presented in this study for bank effects acting on a LNG tanker in shallow water condition with water depth to draught ratio of 1.2 yield conclusion that the hydrodynamic interactive force and moment due to bank increase with reducing of ship-bank distance. For a given ship bank distance, the bank effect is more pronounce with an increasing of ship speed.

Nomenclature

B	Vessel beam (m)
C_b	Block coefficient
D	Vessel draught (m)
F_r	Froude number
g	Gravity acceleration (m/s^2)
h_1	Water depth (m)
h_2	Water depth over bank (m)
L_{bp}	Length between perpendicular (m)
L_{wl}	Length of water line (m)
N	Yaw moment (Nm)
N'	Non dimensional yaw moment
V	Velocity (m/s)
Y	Sway force (N)
Y'	Non dimensional sway force
y	Distance from centerline of ship to bank

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