FORCE ANALYSIS OF A MOORED TANKER SHIP DUE TO WAVE INDUCED BY VESSEL PASSING PARALLEL

An Undergraduate Research Scholars Thesis

By

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ABSTRACT

Force Analysis of a Moored Tanker Ship Due to Wave Induced by Vessel Passing Parallel

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Literature Review

Most accidents in ports are oil and gas spills. Both national and international regulations prevents this spillage which leads to not only economic loss, but also serious pollution. In 2013, the International Maritime Organization (IMO) announced a recommendation for prevention to use risk analysis that gives proper and accurate scientific data in specific environmental conditions and hazards (European Commission, 2013). Tankers are one of the most common transportation methods of oil and gas transportation in waterway traffic. To meet the IMO's recommendation and prevent spillage, tankers must be examined thoroughly and accurately in their given condition. Incident waves generated by another vessel passing parallel to the tanker will significantly affect the moored tanker. Research related to the incident waves in different conditions has been carried out numerically and empirically. Wang (1975)'s hydrodynamic force and moment equations for this type of wave are frequently used and compared with the empirical equation (Flory, 2002 and Varyani, 2003).

Thesis

The waves induced by a passing vessel parallel to the tanker are calculated and the force and moment affecting moored vessel is measured where the tanker is in shallow water to transport oil and gas to onshore tank farms.

Theoretical Framework

Three hydrodynamic equations are considered to analyze the case. A numerical equation and two empirical equations are considered to analyze surge and sway force, and yaw moment of a moored tanker. The deep and shallow water results using the equations are compared.

Project Description

While a tanker is loading and offloading oil and gas onshore, it is effected by waves generated by parallel passing vessels. The mooring system and motion of the tanker experiences excitations in surge, sway, and yaw. Force and moment loadings on moored vessels are analyzed with various equations. Different environmental conditions are considered for the same scenario, and the results are compared.

ACKNOWLEDGEMENTS

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NOMENCLATURE

B_i	Beam width of Ship *i*
h	Water depth
L_i	Length of Ship *i*
n	integer number
n_i	Unit normal vector on surface of Ship *i*
R	Wave resistance
S_i	Cross sectional area curve of Ship *i*
$S`_i$	Slope (derivation) of mid-ship section of Ship i
x	Forward distance from amidships
X	Surge force
y	Distance towards port from centerline of the vessel
Y	Sway force
z	Upward distance from keel
η	Separation distance between moored vessel and passing vessel
θ_z	Yaw moment
$\mu_{ix}(x_i)$	Doublet strength distributed on body of Ship *i* oriented in direction of x created by x directional oncoming flow with coordinate of Ship *i*
ξ	Distance between amidship of moored vessel to amidship of passing vessel.
∇_i	Displacement Volume of Ship *i*

CHAPTER I

INTRODUCTION

Analysis of the force effecting moored vessels is essential for mooring configuration in port area. Accurate evaluation leads secure mooring system to prevent ship accidents and the spillage of oil and gas. The passing vessel effect is one of the most disturbing factors causing ship accident while a vessel is moored at port. Understanding theoretical study of the case is the priority to approach the solution. The experimental study allows realistic computation for the specific case. In this paper, theoretical and experimental solutions are compared and discussed when a vessel is passing parallel to a moored vessel.

Motivation

High waterway traffic due to oil and gas transportation, safety concerns of moored tanker ships in ports increases day by day. Spillage results in lost chemical and economic benefits and can lead to massive environmental hazards and long-time disaster. The public has witnessed several serious spills and are educated about the consequences. Fifty-one percent of in-port accidents are related to oil spills (Valdor, 2015). For instance, the tanker Jupiter was burnt down due to the passing vessel effect. Another vessel, Buffalo was passing Jupiter proceeding at 4.2 knots with a gap between the two vessels of about 20 meters. The passing vessel effect caused breakage of mooring lines and discharge of unleaded gasoline. Jupiter then caught on fire, and it resulted in one death and 18 injuries. When a release occurs, neighboring terminals and waterways should shut down due to the possibility of leakage spreading to those facilities. It leads to a tremendous loss of money for the entire area and serious safety concerns.

To prevent spillage and preserve the safest loading and unloading of oil and gas, accurate analysis of the vessel should be a top priority. The International Maritime Organization states that prevention and incident responses using risk analysis and proper scientific data gives accurate results to prevent spillage should have a specific environmental condition and hazard (European Commission, 2013). With the known information of forces and moment acting on the vessel, the mooring system can be better designed which will lead to safer operation of loading and discharge of oil and gas.

Case Setting

To obtain accuracy, analysis is taken in a specific scenario. In most ports, tanker ships are moored parallel to the waterway. Passing vessels sailing along the waterway generates waves that hit the hull body of the moored vessel. As Wang indicated, this type of wave can induce force and moment that is large enough to cause breakage of mooring lines, when the passing vessel is large and close to the moored ship (Wang, 1975). In this case, surge, sway, and yaw motions of the moored vessel are larger compared to other degrees of freedom, and are considered more in mooring configuration to attain permissible loads (Varyani, 2003). The passing vessel is creating a shallow water wave in calm water. The problem is solved in two aspects, numerical and empirical, to obtain forces and moment acting on the moored vessel. In this study, a coastal tanker is moored and analyzed while a handysize bulk carrier is passing parallel.

CHAPTER II

FORCES AFFECTING MOORED VESSEL

Three different methods to analyze surge, sway, and yaw are introduced and used for computation. Based on the numerical method for infinite water depth condition, two empirical equations are developed to obtain results in finite water depth and to ease their usage. Wave resistance of a ship moving forward also can be calculated using Michell's integral.

Numerical Method

In *Journal of the Waterways, Harbors and Coastal Engineering Division, August* 1975, Shen Wang introduced a velocity potential between a moored vessel and a vessel passing parallel. Velocity potential is a great tool in wave mechanics to describe how the wave is moving and how fast it is in each direction. Wang's equations are known as accurate Slender Body Theory (Swieger, 2011) and is used in similar research. His numerical equation is developed with the following assumptions:

- Beam and draft are small compared to the length of vessel.
- The fluid is infinitely deep and potential flow.
- The passing vessel moves parallel to the moored vessel and keeps a constant speed.
- The free surface effect is negligible and treated as a rigid boundary.

Although the assumptions are quite restrictive, important factors vary, such as size and shape of vessel, speed of passing vessel, separation distance, water depth, and mooring configuration. The factors Wang considered the speed of vessel, the cross-sectional areas, the positions and separation of both vessels. Also, the separation between the ships are assumed large compared to their beam.

A coordinate system (x_1, y_1, z_1) is fixed at the midship of the moored ship. A second coordinate system (x_2, y_2, z_2) is fixed at the midship of the passing ship. Number 1 and 2 indicate moored ship and passing ship. The separation distance, η, is constant, and the distance between the midship of Ship 1 and Ship 2 is represented as ξ. Figure 1 represents the coordinate systems of the scenario.

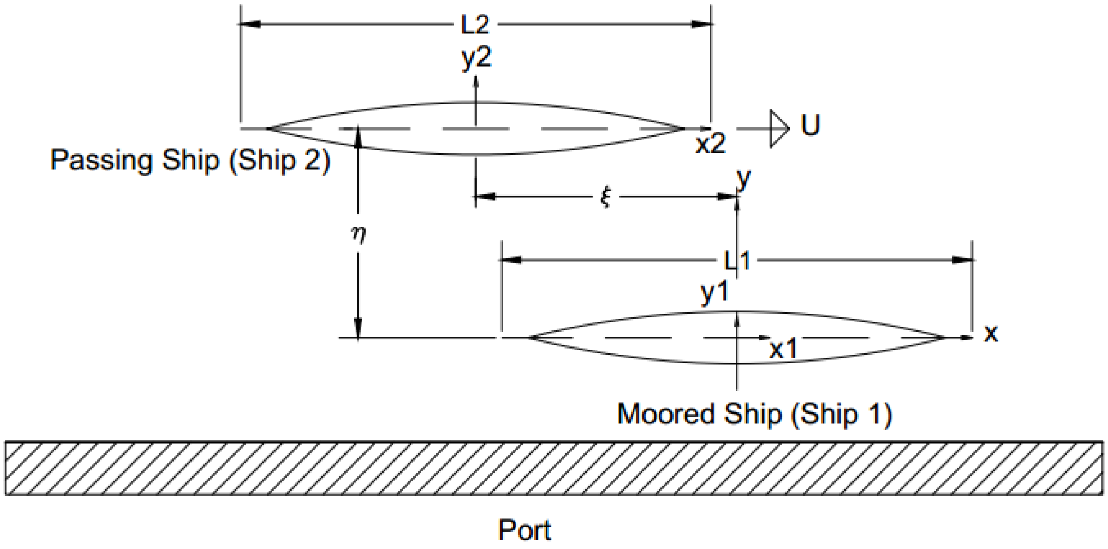

Figure 1. Coordinate System

Ship 1 is stationary and Ship 2 is moving forward with constant speed, U. Boundary conditions of each vessel are expressed in terms of potential flow velocity. The unit normal vector, n, is on the surface of Ship 1 and 2.

$$\frac{\partial \phi}{\partial n_1} = 0 \qquad (1)$$

$$\frac{\partial \phi}{\partial n_2} = U \frac{\partial x_2}{\partial n_2} \tag{2}$$

Since this research concerns the breaking strength of mooring lines, the surge, sway, and yaw forces are determined by Wang's study. These degrees of motion are often considered as factors that create excessive loading on mooring lines.

With a uniform axial velocity stream, oriented doublets are distributed on the surface of the passing vessel along the centerline, or longitudinal axis. A doublet is created when the distance between source and sink approach zero, and their strength are equal to each other. The following equation shows doublet strength around Ship 2, which is a widely-used approximation given by Munk (1929).

$$\mu_{2x}(x_2) = \frac{1}{2\pi} S_2 U \tag{3}$$

The doublet strength, μ, is caused by the forward speed of Ship 2, distributed along the sides of Ship 2, and oriented along this longitudinal x-axis. As the equation indicates, the velocity of Ship 2 and ship shape are factors affecting the stream field, which are shown as sectional area of Ship 2, S_2 and constant velocity, U. S is assumed to be zero at both ends of the vessel. The velocity potential of the wave induced by Ship 2 is given below. Fixed reference frame is shown as (x, y, z).

$$\phi_2(x, y, z) = -\frac{U}{2\pi} \int_{L_2} \frac{S_2(x - x_2 - \xi) dx_2}{[(x - x_2 - \xi)^2 + (y - \eta)^2 + z^2]^{1.5}} dx_2 \tag{4}$$

Although Ship 1 is not moving, a vortex surrounding Ship 1 is created due to the wave velocity generated by Ship 2. The doublet distribution of Ship 1 is oriented in both the x and y directions as a result of the two-dimensional theory.

$$\mu_{1x}(x_1) = -\frac{1}{2\pi} S_1 u(x_1) \tag{5}$$

$$\mu_{1y}(x_1) = -\frac{1}{\pi} S_1 v(x_1) \tag{6}$$

Where *u* and *v* represent the forward and side velocities of the wave velocity potential.

Now the equations are merged into the unsteady Bernoulli's equation. Surge and sway forces, and yaw moment exerted on Ship 1 are expressed as followings. Since these equations do not consider the finite water depth, they are applicable for the deep water wave condition.

$$X(\xi,\eta) = \frac{\rho U^2}{2\pi} \int_{L1} S_1' \int_{L_2} \frac{S_2'(x_2 - x_1 + \xi)}{[(x_2 - x_1 + \xi)^2 + \eta^2]^{1.5}} dx_2 dx_1 \tag{7}$$

$$Y(\xi,\eta) = \frac{\rho U^2 \eta}{\pi} \int_{L_1} S_1' \int_{L_2} \frac{S_2'}{[(x_2 - x_1 + \xi)^2 + \eta^2]^{1.5}} dx_2 dx_1 \tag{8}$$

$$\theta_z(\xi,\eta) = \frac{\rho U^2 \, \eta}{2\pi} \int_{L_1} [x_1 S_1' + S] \int_{L_2} \frac{S_2'}{[(x_2 - x_1 + \xi)^2 + \eta^2]^{1.5}} dx_2 dx_1 \tag{9}$$

When the ratio of water depth and wavelength is less than one-twentieth, the condition is considered shallow or intermediate water wave. The water conditions in port areas are mostly shallow water, which encounters finite depth. The bottom boundary condition, -h, is applied with constant water depth. The partial differentiation of the velocity potential at the bottom with respect to the upward direction is always zero because the bottom does not move. This bottom boundary condition is given as Equation 10.

$$\frac{\partial \phi}{\partial z} = 0 \qquad \text{at } z = -h \tag{10}$$

The equations are rewritten with finite water depth, which is corresponding to h = ±z/2n. n is integer number.

$$X(\xi,\eta,z) = \frac{\rho U^2}{2\pi}\sum_{n=-\infty}^{\infty}\int_{L_1} S'_1 \int_{L_2} \frac{S`_2(x_2-x_1+\xi)}{[(x_2-x_1+\xi)^2+\eta^2+4n^2h^2]^{1.5}}\,dx_2dx_1 \tag{11}$$

$$Y(\xi,\eta,z) = \frac{\rho U^2\eta}{\pi}\sum_{n=-\infty}^{\infty}\int_{L_1} S'_1 \int_{L_2} \frac{S`_2(x_2-x_1+\xi)}{[(x_2-x_1+\xi)^2+\eta^2+4n^2h^2]^{1.5}}\,dx_2dx_1 \tag{12}$$

$$\theta_z(\xi,\eta,z) = \frac{\rho U^2\eta}{\pi}\sum_{n=-\infty}^{\infty}\int_{L_1} (x_1S'_1 + S_1) \int_{L_2} \frac{S'_2}{[(x_2-x_1+\xi)^2+\eta^2+4n^2h^2]^{1.5}}\,dx_2dx_1 \tag{13}$$

Empirical Equation

After Wang’s well-read study, other researchers conducted experiments on passing vessel effects on moored vessels and achieved empirical equations for more realistic use. The empirical studies of Flory (2002) and Seelig (2001) are widely used in this case, and the equations and correction factors are discussed in this paper. The authors considered only the surge, sway, and yaw degrees of freedom as well, since they are the most significant degrees of freedom effecting moored vessels. They agree that the one of the causes of passing ship effect is the Bernoulli effect, which is when the fluid moving faster than its surrounding develops a lower pressure and creates suction on the moored ship.

Seelig (2001) added current to the test while Wang (1975) sets the scenario as calm water. He denoted the sum of velocity of the passing vessel and the current speed as the relative ship speed. When the relative speed is zero (passing vessel and current are equal in magnitude and direction), then the passing ship effect is minimal. When the direction of the current and the passing vessel are opposite and the relative speed is increasing, the effect becomes much more significant on the moored vessel (Seelig, 2001).

In Flory(2001)'s research, the equation of maximum forces and moment are obtained. Froude scaling is applied to develop the equations below.

$$X_{max} = S_F C_x V^2 \left[0.171 + 0.134 \ln\left(\frac{\nabla_2}{\nabla_1}\right) - \left\{0.71 + 0.28 \ln\left(\frac{\nabla_2}{\nabla_1}\right)\right\} \ln\left(\frac{\eta}{L_c} - 0.06\right) \right] \quad (14)$$

$$Y_{max} = S_F C_y V^2 \left[e^{1.168DR-2.25} - \left\{4.41 + 1.93 \ln\left(\frac{\nabla_2}{\nabla_1}\right)\right\} \ln\left(\frac{\eta}{L_c}\right)\right] \quad (15)$$

$$\theta_{z,max} = S_M C_m V^2 [e^{-0.47DR+2.651} - \left\{171.9 + 51.4 \ln\left(\frac{\nabla_2}{\nabla_1}\right)\right\} \ln(\frac{\eta}{L_c} - 0.06)] \quad (16)$$

where S_F and S_M are scale factors, C is the under keel clearance coefficient for the corresponding force and moment, V is the relative speed, ∇ is the displacement of the corresponding ship, and L_c is the characteristic length.

The scale factors and characteristic length of vessel are given by Flory as

$$S_F = 1.5\times10^{-5} L_1^2 \quad (17)$$

$$S_M = 59\times10^{-9} L_1^3 \quad (18)$$

$$L_c = \frac{L_1 + L_2}{2} \quad (19)$$

Flory (2002) accepted the experimental study by Seelig (2001) and included the relative speed (V) in the equation. The relative speed is the difference between the passing vessel's speed and the current speed. The under keel clearance coefficient is also determined experimentally. The value of the ratio of the under keel clearance to the draft, UKCDR, is determined with the greater of the drafts between the two ships.

$$C_x = e^{0.0955 - 0.6367\, UKCDR} \quad (20)$$

$$C_y = e^{0.5157 - 3.438\, UKCDR} \quad (21)$$

$$C_m = e^{0.343 - 2.288\,UKCDR} \tag{22}$$

UKCDR can be calculated using an alternative equation, which is shown below.

$$UKCDR = 1 - \frac{T}{d} \tag{23}$$

where T is the draft of the moored or passing vessel, which ever draft is greater.

Since a concern for safety has turned into actual accidents, the Commander, Naval Facilities Engineering Commands, Engineering Innovation & Criteria Office (NAVFACENGCOM) developed a model test to study how passing vessels effect moored vessels. The research was established based on Wang's work and divided into two parts, such as Deepwater and Shallow Water. Seelig (2001), the author, claimed that Wang's study was useful for the deep-water case, but did not fully consider the most critical design case, which is shallow water region.

Deepwater Test

In Seelig(2001)'s report, physical model tests based on Wang's work were run for both the deep and shallow water conditions. Seelig claims that Wang's study should be useful since the ratio of draft of moored vessel and water depth is small. This statement is approved as the test results is similar to Wang's. The test results show that when the passing vessel is larger, especially in length, the forces and the moment increase noticeably. Especially the sway force is three times higher than the surge force and the yaw moment when the length of passing vessel is twice of moored vessel.

Shallow Water Correction Factor

Seelig's correction factor is simply the ratio of experimental forces and moment to Wang's theoretical forces and moment. Interestingly the test results with the same correction factor for sway force and yaw moment. The results show that when the lateral distance between the ships is greater and the ratio of draft of moored ship to the water depth becomes less, the forces and moment approaches to the same value of deep water.

$$CF_x = 1 + 16\frac{T}{d}\left[e^{-0.08\left(\frac{\eta}{B}-3.5\right)^2}\right] \tag{24}$$

$$CF_y = CF_m = 1 + 25\left(\frac{T}{B}\right)^{-0.35}\left(\frac{T}{d}\right)^4\left[e^{-0.08\left(\frac{\eta}{B}-3.3\right)^2}\right] \tag{25}$$

where B is maximum width of Ship 1.

The coefficients CF_x, CF_y, and CF_m are multiplied to Wang's deep water equations to compute surge and sway force, and yaw moment in the shallow water region. The sway force and yaw moment increase more rapidly than the surge force according to Seelig's equations above. Seelig obtained by experiment that the forces and moment increase when the draft to water depth ratio increases.

Michell's Integral

Wave resistance is a form of drag force that reflects energy radiated by waves through a large hemisphere surrounding the ship and moving with it (Birkhoff, 1954). Michell's integral was also developed based on Slender Body theory, initially flat free surface (smooth water), and infinite water depth (Michell, 1898). Michell's integral allows one to calculate the pressure field on the surface of the hull, which lead to a more accurate analysis of the passing vessel effect on a moored vessel.

First, Michell derived boundary condition of a thin ship with forward speed by combining the kinematic free surface boundary condition and the dynamic free surface boundary condition.

$$\frac{\partial\phi}{\partial z} = \frac{U^2}{g}\frac{\partial^2\phi}{\partial x^2} \tag{26}$$

Applying other boundary conditions of the water at the hull surface, wave resistance (R) is derived as,

$$R = -2\rho U \iint \frac{d\phi}{dx}\frac{d\eta_w}{dx}\,dx\,dz \tag{27}$$

where η_w is wave elevation. Equation 27 also satisfy the symmetry of the ship shape, which can be expressed as

$$\frac{d\phi}{dy} = -U\,\frac{d\eta_w}{dx} \tag{28}$$

In 1954, Garrett Birkhoff further explained Michell's integral for wave resistance.

$$R = \rho U^2 B^2 C_w$$

where

$$C_w = \frac{8Fr^2}{\pi}\int_1^\infty [I^2(\lambda) + J^2(\lambda)]\,\frac{\lambda^2}{\sqrt{\lambda^2 - 1}}\,d\lambda$$

$$I(\lambda) = \iint h(\xi,\zeta)e^{-\lambda^2 Fr}\cos(\lambda Fr\xi)\,d\xi\,d\zeta$$

$$J(\lambda) = \iint h(\xi,\zeta)e^{-\lambda^2 Fr}\sin(\lambda Fr\xi)\,d\xi\,d\zeta$$

$$\xi = \frac{x_1}{L1}, \quad \zeta = \frac{z_1}{L_1}$$

$h(\xi,\zeta)$ is horizontal slope of the moored vessel hull surface, λ is wavelength.

CHAPTER III

COMPUTATION

Using the same scenario in Figure 1, some data sets are attained using equations introduced in the paper. MATLAB is used to compute the analysis. 12 m water depth is set since the average water depth in U.S. Channels is 12 m (Seelig, 2001). The average current speed in the Houston Channel is used, which is 1 knot (NOAA). The moored vessel is an average coastal tanker. Coastal tankers are smaller tankers compared to bulk carriers. They are used to transport refined products (Hamilton, 2014). The average size of a coastal tanker is 205m in length, 29 m in maximum beam width, and 16m draft (Rodrigue,). The displacement of the vessels are 45 metric tons. A handysize bulk carrier is considered as a passing vessel. Dimensions of vessels are present in Table 1.

Table 1. Particulars for moored and passing vessels

	Length (m)	**B_max (m)**	**Draft (m)**	**Displacement (metric tons)**	**Constant Velocity (knots)**
Ship 1 **(Coastal tanker)**	205	29	10.2	45	-
Ship 2 **(Handysize bulk carrier)**	205	29	10.2	45	4

In this computation, length and beam are the same as the average coastal tanker. The ratio of the vessel draft to water depth (T/d) is 0.85, which makes the draft of the vessel to be 10.2 m. The ship shape for both vessels is chosen to be parabolic. The beam of the vessel can be described with following equation.

$$B(x) = B\_\max\left[1 - \frac{x^2}{\left(\frac{L}{2}\right)^2}\right] \tag{26}$$

Then, sectional area curve (S) of the coastal tanker is calculated with dimensions.

$$S_1 = -0.0282x_1^2 + 295.8 \tag{27}$$

$$S_2 = -0.0351x_2^2 + 224.4 \tag{28}$$

Since the ship shape is parabolic, the sectional area curve is also parabolic.

Hydrodynamic Force and Moment

Surge, sway and yaw in deep water condition is first calculated using Wang's deep water equation and results are presented in figures below. The x-axis of the graphs represents the horizontal distance between amidships of both vessels.

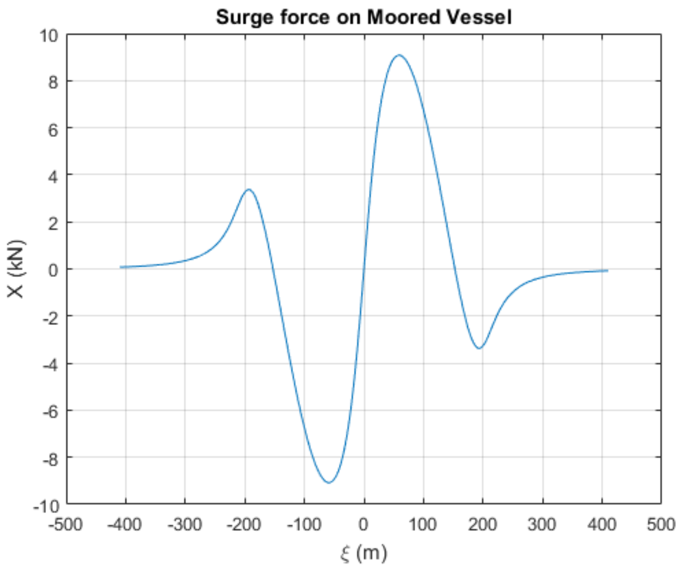

Figure 2. Surge force on moored vessel due to passing vessel

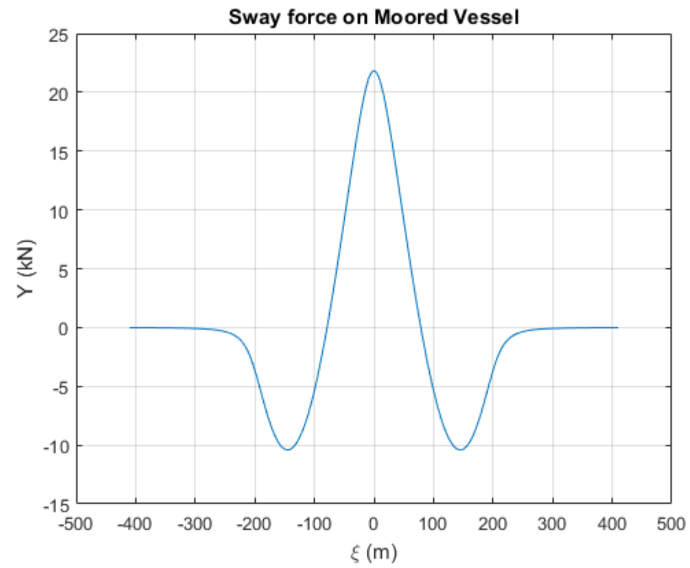

Figure 3. Sway force on moored vessel due to passing vessel

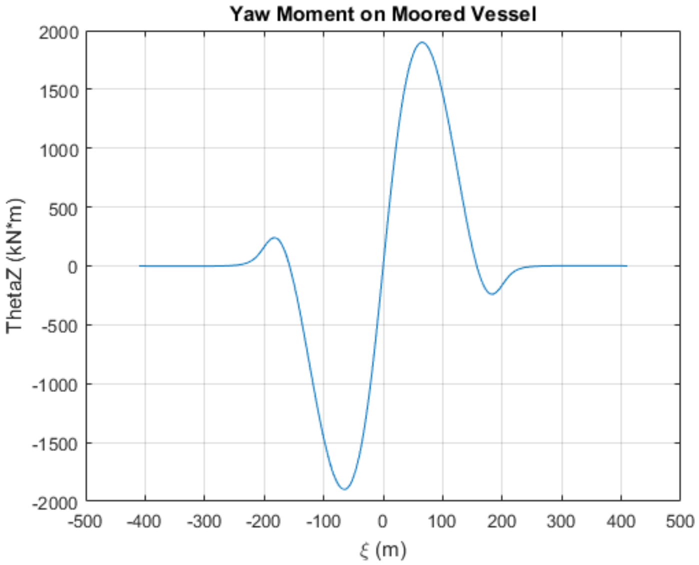

Figure 4. Yaw moment on moored vessel due to passing vessel

The surge force is created when the passing vessel is approaching approximately at the distance of twice the length of moored vessel. The sway force and the yaw moment start to affect moored vessel when the distance between the ships is about one and one-half times the moored vessel. The surge and yaw are at the maximum when the distance between the ships are about one-quarter of the moored vessel. The maximum sway occurs when two amidships of the vessels are aligned. Suction in y-direction happens first when the passing vessel is approaching to moored vessel. Then the passing vessel effect pushes the moored vessel to the opposite direction from the passing vessel.

Then, Seelig's shallow water coefficient are applied to deep water equation. Comparison of forces and moment between the shallow water and deep water regions are shown in Figure 5 thru 7. Results of maximum forces and moment with different methods are compared in Table 2.

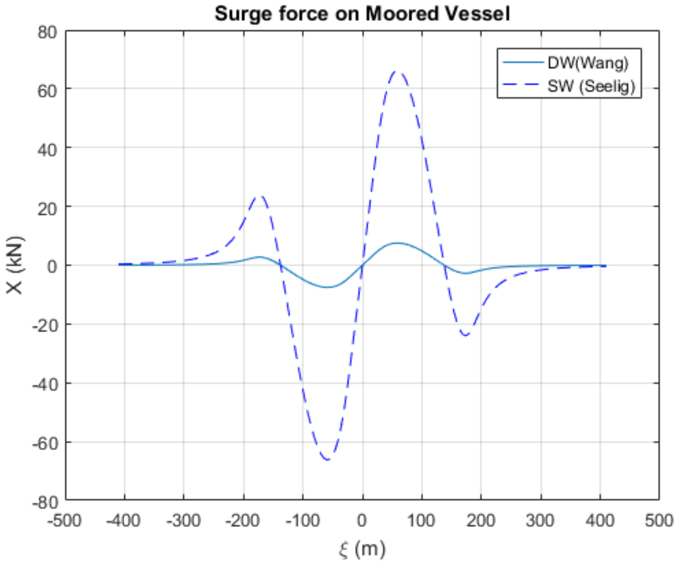

Figure 5. Comparison of surge force in shallow water and deep water region

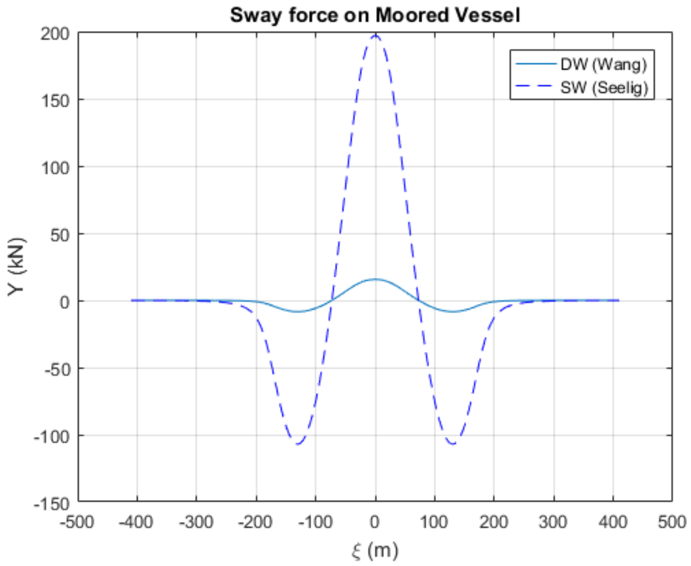

Figure 6. Comparison of sway force in shallow water and deep water region

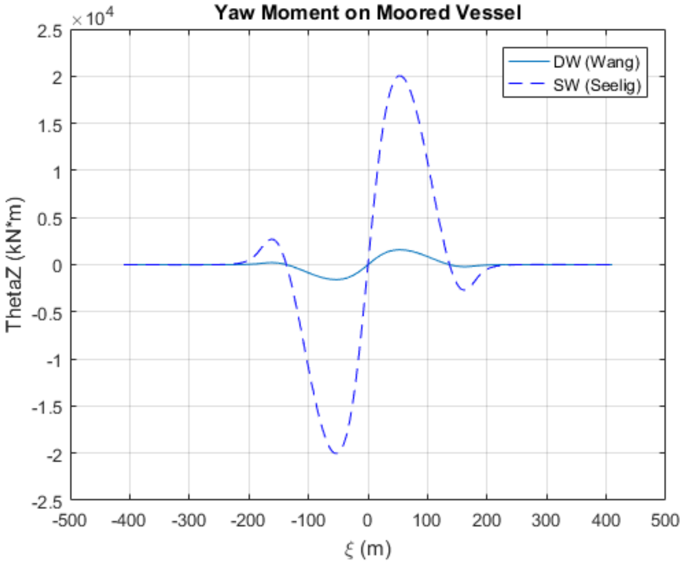

Figure 7. Comparison of yaw moment in shallow water and deep water region

Table 2. Maximum surge, sway and yaw comparison

Maximum	Surge (X) (kN)	Sway (Y) (kN)	Yaw (θ_z) (kN*m)
Wang (numerical)	7.5272	15.5162	1.5790 X 10^3
Flory (empirical)	29.2991	133.9586	5.3328 X 10^3
Seelig (empirical)	66.1957	196.9559	2.0043 X 10^4

Forces and moment exerted on the moored vessel increase when the condition is the shallow water region. The sway force and yaw moment increase more than 10 times in shallow water as compared to the deep water region. Tankers with greater draft in a port with shallow water depth will have much larger force that push the vessel to starboard. It causes larger loads on fenders and mooring lines.

CHAPTER IV

CONCLUSION

The passing vessel effect can lead to large loading on a moored vessel, even when the passing vessel velocity is small. Loading analysis of moored vessel is essential for mooring configuration and can be measured with different types of linear solution. Empirical solutions attain results for more realistic condition and are effective for usage. With the solutions, mooring analysis can be completed effectively.

Further research on wave resistance is developed in work of Yu and Falzarano (2017). While Michell's integral is mentioned earlier as a solution for a thin ship and linear free surface, higher order wave resistance are introduced in the article. Neumann-Kelvin methods requires higher order of the hull surface and linear free surface. The hull surface will be more realistic but linear free surface limits results, especially at the waterline where the most critical loading exist. Rankine source method satisfies nonlinear for both hull and free surface. Rankine method is considered as the best among wave resistance solution but requires complex iterations. Results of Neumann-Kelvin and Rankine panel methods are compared with experimental data (Yu and Falzarano, 2017a). Further study of Rankine panel method is introduced in another research, which nonlinear Rankine source method is applied to calculate the pressure over the surface of the hull in calm water (Yu and Falzarano, 2017b).

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