Evaluation Study on Ship-to-Ship Loading/Offloading Safety Operation by Numerical Fluid Dynamics Method

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Abstract. The demand of energy from our society is rapidly increased year on year linear to the world economic growth. Ocean gives great energy potential resources to fulfill energy need. For instance, oil and gas exploitation activities in offshore field had been established for a long time. Thus, such kind of operation should be improved in manner of safety to achieved global economy goal for a cleaner, safer, and sustain of the ocean. One of the process during oil and gas exploitation is cargo loading and offloading from ship-to-ship. Due to consider as dangerous goods, oil and gas cargo transfer process is obligated to fulfill several safety criteria. A ship-to-ship configuration has more complex hydrodynamic-induced motion behavior than the single ship. Due to its complexity, a proper evaluation study is needed to evaluate a safety of the ship-to-ship operation. This simulation study is performed by Numerical Fluid Dynamic method in ideal fluid approach. In order to observe the complex hydrodynamic behavior, incident random wave is applied to side-by-side ships in different configuration by considering three mains steps during ship-to-ship operation i.e. berthing, moored, and un-berthing scenario. Criteria had been being evaluated are ships clearances, relative motion between ships, ships roll motion, forces acting on ships and tug boat, mooring lines loads and fenders deflection. Not only internal factor from the ships evaluated as safety criteria but also the external factor is evaluated. The external factor considered from weather are wind speed and wave height limitation.

Keywords: Ship to Ship, Safety Operation Criteria, Fluid Dynamics, Ships Interaction

1 Introduction

Oil and gas is remain one of the proven solution in present energy need. The exploitation of this resource usually conduct in onshore and offshore site with each site have their challenging situations. When exploitation is conduct in offshore, the operation will face a condition that environment is going to harsh during storm weather. Therefore, the exploitation facilities should be able to withstand during its operation. Oil and gas offshore field are either located in shallow water or deep water depend on number of this resource beneath ocean seabed. In deep water, exploitation facilities is utilize floating structure due to its feasibility compare to fixed structure. Fixed structure is technically and economically feasible to install in shallow water up to mid water depth, for instance the deep water is not more than 100m. Oil and Gas

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exploitation activity will include storage and transportation stage, in this stage ship is needed to transport the product if there are no pipeline at the site. Ship or shipshape structure is not only to do the cargo transportation and storage but also is normally utilized to undertake the production operation, e.g. FPSO, FLNG, and FSRU. Floating structure compare to fixed structure when serve as facilities to exploit oil and gas in offshore, have a beneficial to be able move in new location after the service time is over. With this flexibility, floating structure is not only utilize in deep water but also operated in shallow to mid water depth.

Ship when transferring cargoes of Oil and Gas should be able to perform safe due to it is classified as dangerous cargoes as per IMDG Code [1]. Especially when cargo transfers are performed by Ship-to-Ship (STS) method, the operation is regularly conducted in marine terminal. The safety of cargoes, environment, asset, and people who work around need to be full concern for all related stakeholders. Floating offshore structure which stay for a long time in certain location is classified as marine terminal, therefore STS operation is a common and regular operation in such situation. There are several limitation criteria during STS transfer, which should be fulfilled so the operation is guarantee safe prior to begin loading/offloading the cargo. The STS transfer is limited by ship roll motion, relative motion between ships, ships clearances, forces acting on ships and tugboat, spring mooring line strength, fender deflection, mechanical limitation for cargo transfer equipment, and weather criteria i.e. wave height, wind speed, swell, and current speed. OCIMF, SIGGTO, CDI, ICS are among of best practice standard and limitation criteria, which have been adopt and refer by the marine industrial operator [2].

Cargoes transfer between two adjacent ships is attract researchers for a long time to study the behavior and characteristic from interaction between them. Lightering ship, ship to be offload, is approach by the service ship that utilize as shuttle vessel. A complex situation occurred when STS operation conduct in deep water between two running ships. Study has been conducted for moving ships in different ship draft indicating cargo transfer operation process [3]. The study is performed in experiment and numeric methods. Experiment held in towing tank facilities without any wave generate from the wave maker machine. Model scale of Very Large Crude Carrier and Aframax tanker observed during the experiment. Furthermore, numerical method is conducted in full-scale ship size with hydrodynamic coefficient parameter obtain from the model test in towing tank. From the observation during the study both experimentally and numerically is the effect of lightered ship draft play important role for the added mass and rudder force characteristic. Moreover the asymmetric configuration of ships that created during maneuvering also bring great impact to the force and moment acting on the ship hull especially in surge, sway, and yaw motion. It is believed that in emergency scenario, maneuvering between two adjacent ships is affect the maneuver ability. Ship-to-ship cargo transfer activity is not only conduct by lightering of the larger ship but also reverse transfer from smaller ship to larger ship. During the maneuvering ship to approach each other, it is difficult to maintain preferred heading due to complex interaction between adjacent ships. Based on observation made by numerical method study resulting that the smaller vessel is more difficult to maintain preferred heading due to interaction loads[4].

For STS operation in shallow waters, the interaction will be more complex due to interaction between ships hull and seabed to ship hulls. This operation is challenging because there are overtaking scenario between two adjacent ships, initial maneuvering phase, to the final desired maneuvering phase. A numerical approach has been conducted by Computational Fluid Dynamic (CFD) simulation, which ship trim is neglected [5]. Several configuration between ships observed to evaluate complex effect from the system. The scenario has been observed are effect of ships parallel lateral distance and longitudinal distance. Thus force and moments acting on ships, which related to pressure distribution and fluid velocity can be inspected. Interesting observations on this study has been made, that longitudinal distance variations scenario affecting resistance of smaller ship depend on its position relative to the larger ship. The larger longitudinal distance the more force to push away between two ships, in contrast the smaller longitudinal distance the more force to attract of the two ships. Then in lateral distance scenario, force and moments between two ships also have attractive result. The closer lateral distance between two ships have stronger force and moments acting on the ship hull. Thus, this force pulled two ships hull towards each other. Since the size of two ships are different, the yaw moment push the bow and stern away each other.

Currently two systematical approach can deliver a solution for the problems of ship-to-ship interaction in water. The solution is delivered by numerical model simulation and experimental physical model test. Numerical approach instead of have disadvantages, there also give advantages to simulate the model in full-scale dimension. It is also can deliver the solution more efficiently in sake of time consume than experimental model test. In order to assess the uncertainty in numerical approach, a comparative study has been done for hydrodynamic interaction between ships and ships to bank [6]. Potential flow panel method and CFD are two numerical method to be assessed. Panel method that treat the fluid as an ideal flow which ignore the viscous effect, give a beneficial during computational step and give faster result in comparison to CFD. Despite of its limitation, panel method obtained good result in ship-to-ship interaction between encountering ships. However, the panel method solution for ships and bank interaction yield an outcome relatively far from the result from experimental model test. At very close proximity of ships and ship to bank, this panel method give unsatisfied result.

Present paper will study a STS operation for the interaction between ship during maneuvering i.e. berthing un-berthing and moored scenario. The STS operation is evaluated based on limiting criteria from best practice standard. Sea environment is assumed in open sea and medium water depth thus the system have enough space for maneuvering operation. This study evaluate sequence STS scenario on numerical fluid dynamic approach by panel method utilized to handle the problems. Mother Ship have zero speed during all scenario while the Daughter Ship assumed have certain ship speed during berthing and un-berthing phase. That evaluation study is followed by governing equation from the theoretical background, applied method for conducting the study, and closed by conclusion based on comparative analysis. The main objective on this study is to achieve STS operation satisfied safe operation criteria without omitting consider fleet availability, economic total cost investment i.e. Capital Expenditure (CAPEX) and Operation Expenditure (OPEX).

2 Numerical Modeling

2.1 Governing Equations

Potential flow solver codes is assumed fluid remain inviscid, incompressible, and irrotational. This definitions leads to ideal fluid acting on floating bodies. Body fixed coordinate system is adopted thus the body motions can be describe. Centre of rotation is applied to the body respect to the translated coordinate system. Due to the ideal fluid is inviscid, the flow field can describe by the potential velocity gradient. The fluid is governed by Laplace equations that shall satisfy the proper boundary conditions. In harmonic motions, the velocity potential can be describe as:

$$\Phi(x,t) = Re[\phi(x)e^{-i\omega t}] \quad 1)$$

Laplace equation that govern the harmonic motions as follow:

$$\frac{\partial^2 \Phi(x,z,t)}{\partial x^2} + \frac{\partial^2 \Phi(x,z,t)}{\partial z^2} = 0, -d \leq z \leq \zeta \quad 2)$$

The boundary condition shall satisfy the following condition on free surface, bottom, and at the body as follow:

Bottom boundary condition: $$\frac{\partial \Phi}{\partial z}(x, z = -d, t) = 0 \quad 3)$$

Free surface boundary condition: $$\frac{\partial \Phi}{\partial t}(x, 0, t) = -g\zeta(x, t) \quad 4)$$

Body boundary condition: $$\frac{\partial \phi}{\partial n} = U_n \quad 5)$$

The solver code describe the motion response by specific generalized coordinate in more specific form. The equation of motion are arranged by Lagrange's equations. Motion equation formula can be express as:

$$I\ddot{q} + C\dot{q} + Kq = s \quad 6)$$

I, *C*, *K* denotes inertia matrix, tangent damping and stiffness matrices at the state of q_0 and q_0. *s* is a vector that called generalized forces. In addition, when velocities and acceleration are given thus the above formula can re-arrange as:

$$Kq = s - I\ddot{q} + C\dot{q} \quad 7)$$

In addition, motion equation in frequency domain approach is a sum of static part plus a small deviation. The approximation will yield residual from the approximated inertia, damping, and stiffness matrices to evaluated mean position. Residual *r* can write as:

$$r = I\ddot{q} + C\dot{q} + Kq - s \quad 8)$$

Based on basic motion equation by algebraic process, thus find generalized force as:

$$[-\omega_k^2(I + A) + i\omega_k \overline{D}_k + K]\overline{q}_k = a_k u_k \quad 9)$$

This equation refer to frequency domain of floating body. *A* denotes added mass matrix, and in addition a imaginary part of radiation damping matrix D_k. Radiation damping unfortunately not quite precise to predict response near to resonance zone. To deal with it a linearization technic shall be applied by modifying wave steepness.

Motion response for floating structure known as Response Amplitude Operator (RAO) is consist of two terms, which is translational response and rotational response. The translational RAO are surge, sway, and heave (k =1,2,3, or x,y,z) means direct ratio between response amplitude to incident wave amplitude. Both of them are in length units.

$$RAO = \frac{\zeta_{k0}}{\zeta}(m/m) \quad 10)$$

Whereas non dimensional RAO for rotational response are roll, pitch, and yaw (k=3,4,5 or θ, ϕ, ψ) means direct ratio between response amplitude in radians to the wave steepness. Wave steepness are multiply of wave number k_w to incident wave amplitude.

$$RAO = \frac{\zeta_{k0}}{k_w \zeta} = \frac{\zeta_{k0}}{(\omega^2 g)\zeta_0}(rad/rad) \quad 11)$$

Moreover, in order to capture non-linear behavior from the system then dynamic analysis is necessary to perform. Prior to conduct the dynamic analysis it is good point to calculate the static behavior. Static calculation is believed can deliver the determination of equilibrium position consider weight, buoyancy, hydrodynamic properties, tension and shear, bending and torque, seabed friction and friction, contact forces, and applied forces.

$$\sum F = 0; \sum M = 0 \quad 12)$$

Dynamic simulation is basically refer to the motion equation formula 6) that involve inertia load, damping load, stiffness load, external load regard to position, velocity, and acceleration in each time steps. From the Newton's law then motion equation's is reformed for each system as:

$$I\ddot{q} = s - C\dot{q} - Kq \quad 13)$$

This equation is utilized to calculate local motion for each free body definition. Dynamic calculation is performed by start from acceleration vector at each beginning of time step. Then integrating this by forward Euler integration. The value for the end of time step $t+1$ as:

$$v_{t+1} = v_t + dt.a_t \quad 14)$$

$$p_{t+1} = p_t + dt.vt_{+1} \quad 15)$$

The equation denotes position, velocity, and acceleration each time step t by p_t, v_t, and a_t respectively. Time steps denote as d_t. In the end of each times step will produce positions and orientations of all body and nodes thus the process can be repeated.

2.2 Model Definitions

In order to determine safe loading/offloading from STS operation, hydrodynamic analysis is carried out. The analysis should be perform at least for 10-years metocean return period. Combination of potential flow theory and three hours (3h) sea-state simulation to observe diffraction/radiation problem from the side-by-side ships. This study will assess two ships by main particular as seen in Table 1 and metocean parameter in Table 2. The assumption made to this study are Mother Ship as floating marine terminal with tower yoke moored at the forepeak, while Daughter Ship as conventional vessel that need to approach the mother ship to conduct loading/offloading operation. The analysis will represent hydrodynamic parameters, mooring line load, fender forces, and side-by-side ships characteristic including weathervaning behavior. The whole analysis result should be fulfil several safety criteria given in Table 3. The criteria for mooring equipment are refer to OCIMF guidelines i.e. mooring line loads. Tug boat availability also mark as criteria during STS cargo transfer in floating marine terminal. The rest criteria are project dependent aspect, those that consider mechanical limitation and personnel safety. Desired final moored configuration in cargo transfer operation can be seen in Figure 1.

Table 1. Principle Dimension of Mother Ship and Daughter Ship.

Parameter	Symbol	Units	Mother Ship	Daughter Ship
Length Overall	*LOA*	m	302	285.4
Breadth	*B*	m	46	43.4
Depth	*H*	m	26	26
Draft	*T*	m	9.1	12.1
Displacement mass	Δ	ton	89,100	108,079
Vertical CG	*VCG*	m	15.6	15
Longitudinal CG	*LCG*	m	151	142.7
Transversal CG	*TCG*	m	0	0
Roll Radius Gyration	K_{xx}	m	14.72	13.8
Pitch Radius Gyration	K_{yy}	m	87.58	82.76
Yaw Radius Gyration	K_{zz}	m	87.58	82.76
Wind Front Area	A_F	m^2	831.5	438.7
Wind Lateral Area	A_L	m^2	2363.1	1246.63

Note: VCG + above keel, LCG + from forepeak, LCG + starboard from center line

The daughter ship will alongside the mother ship during cargo transfer operation with standby tugboat attached on it. During berthing, three tugs will assist the daughter ship to maneuver alongside until mooring lines tightened for two ships. The number of tugboat in this case is in ideal situation, some adjustment could be perform at site since met the safety criteria. Tugboat not only utilized to assist the daughter ship to berth, but also remain tugboat is utilized to maintain the heading of mother ships.

Table 2. Environmental Parameter in 10-years Omni Directional

Parameter	Symbol	Units	Value
Significant Wave Height	*Hs*	m	2.4
Peak Period	*Tp*	s	6.8
Sea Spectrum	-	-	Jonswap
Wind Speed	w_s	knots	30
Current Speed	c_s	m/s	0.7

Prior to evaluate the STS operation regarding to safety criteria, several parametric study will perform in frequency domain approach in order to validate the model definition. Wind and current force neglected during initial study to simplify the problems. Hydrodynamic analysis in frequency domain is perform to determine hydrodynamic coefficient i.e. added mass, damping, forces and moment, and RAO in different wavelength. Nevertheless, ships lateral distance also being carried out in analysis to observe the gap effect. Ships model consider in frequency domain analysis refer to that been carried out in available published numerical analysis [7] and also compare to experimental analysis open published results [8]. This will be discussed in the following section.

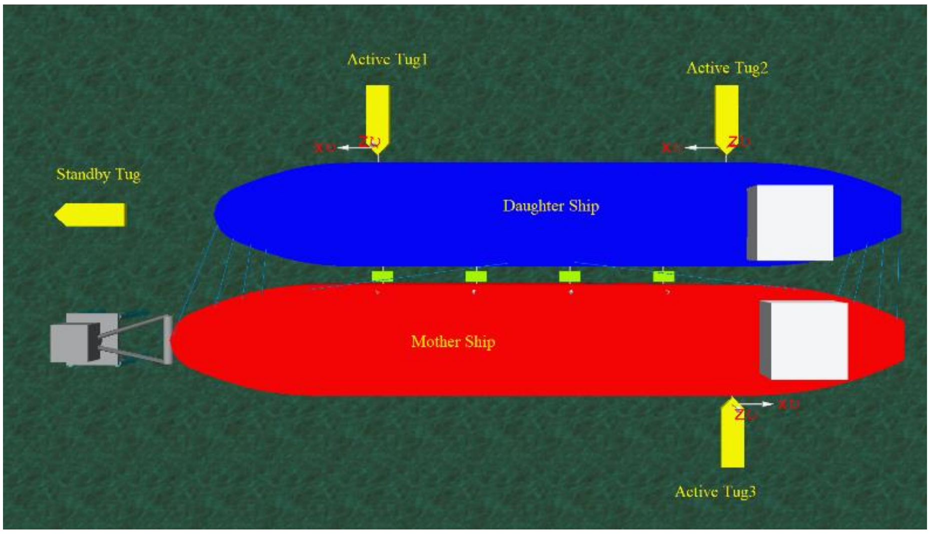


Figure 1. *Ship-to-Ship Moored Arrangement*

Table 3. Safety Criteria for Side-by-Side Offloading

Criterion	Description
Tug operability	Minimum required bollard pull capacity to provide assistance as per sea-state for berthing and un-berthing
Wind speed	< 35 knots on going cargo transfer can continue while shuttle vessel being moored
Wave height	< 5m cargo transfer immediately stopped with all transfers equipment is ready being to release
Mooring line load	<50% maximum breaking load to avoid line failure
Fender deflection	<50% fender deflection to avoid damage to fender. Fender forces should not exceed their rated reaction forces
Relative motions of the ships	Surge x_{max} <10m, sway y_{max} <3m, heave z_{max} <3m Determined based on cargoes transfer equipment specification
Clearance between ships	> 2 m to avoid collision
Daughter ship roll	< 4° to avoid collision

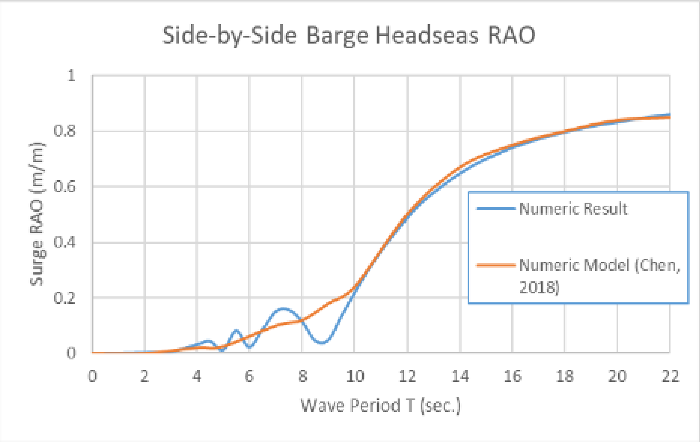
2.3 Model Validations

This section will examined the proposed numerical fluid dynamic model to the available published experimental and numerical model reports. The description of validating model is briefly explained in Table 4. Barge shape ships model are identically have similar principle dimension and form. Both model placed alongside with gap distance about 41 meter. A frequency domain analysis had been carried out by diffraction theory in deep water condition refer to experimental model test setup. Frequency domain analysis is performed in several different scenarios in headseas load cases. Hydrodynamic interactions between twin barges are evaluated by the 6-dof added mass coefficients, damping coefficients, forces and moments in frequency range ω from 0.01 rad/sec. to 3.66 rad/sec. However since the compared waves heading only headseas, thus the presented results only in most significant 3-dof i.e. surge, heave, and pitch.

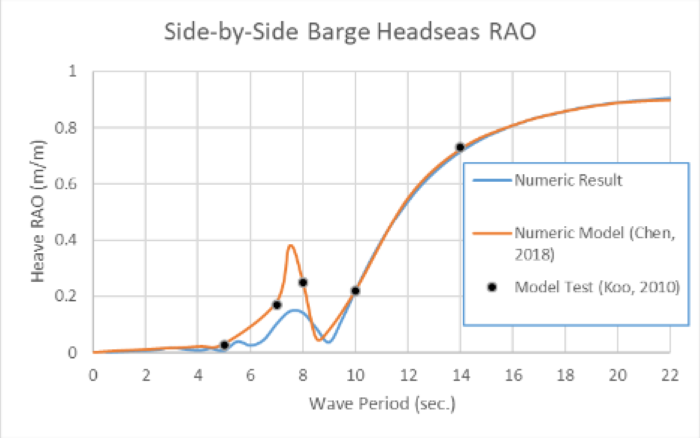
Table 4. Validated Ships Model

Item	Symbol	Units	Value
Ships Type	-	-	Barge Shape
Length	*LOA*	m	122
Breadth	*B*	m	32
Depth	*H*	m	8
Draft	*T*	m	4.875
Water Depth	*wd*	m	347.8
Gap distance	*d*	m	41

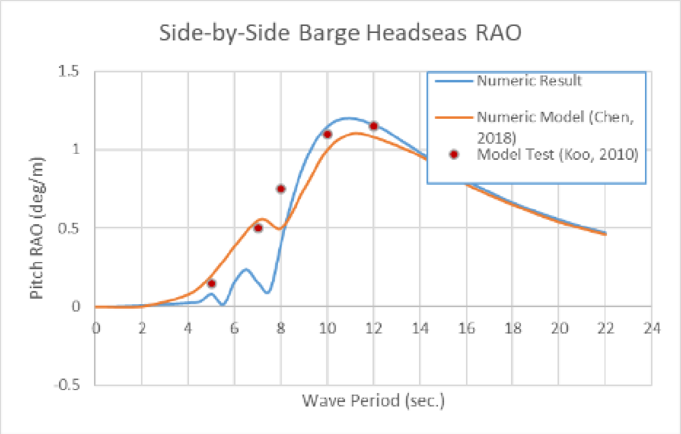
With refine panels number that obtained by grid independence study, the validation result can be seen in Figure 2 for headseas RAO twin barge in side-by-side configuration. As can be seen, good agreement between numerical result to model test result in heave and pitch RAO. When present numerical result compare to published numerical model report have the same trend between them. Despite there are spotted slight different result in certain wave periods, but these result seem reasonable. Those results also fit with experimental data for twin barge in heave and pitch RAO. From this results it can be informed that in low wave periods 0 to 8 seconds, the 3-dof motion has low motion response. Then gradually increased from 9 seconds wave period up until 22 seconds, except for pitch motion have peak value during 10 seconds wave period. After that pitch response gradually decrease until 22 seconds wave period.



(a) Headseas surge RAO comparison in results of numerical method



(b) Headseas heave RAO results comparison numeric & experiment method



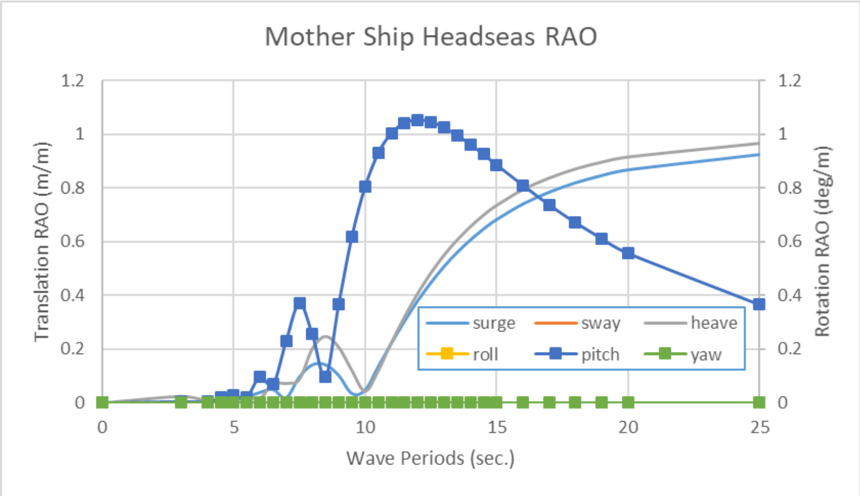
(c) Headseas pitch RAO results comparison numeric & experiment method

Figure 2. *Comparison Side-by-Side Barge 3-Dof RAO under Headseas Condition*

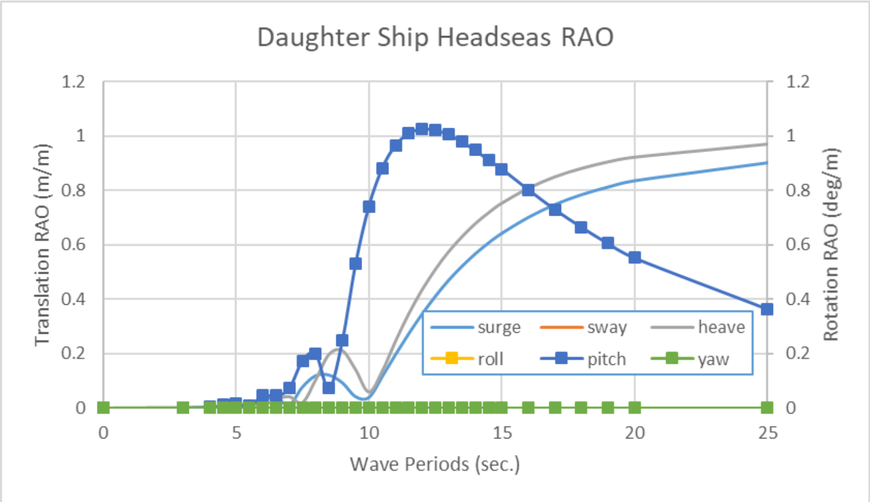
3 Results and Discussion

3.1 Frequency Domain Results

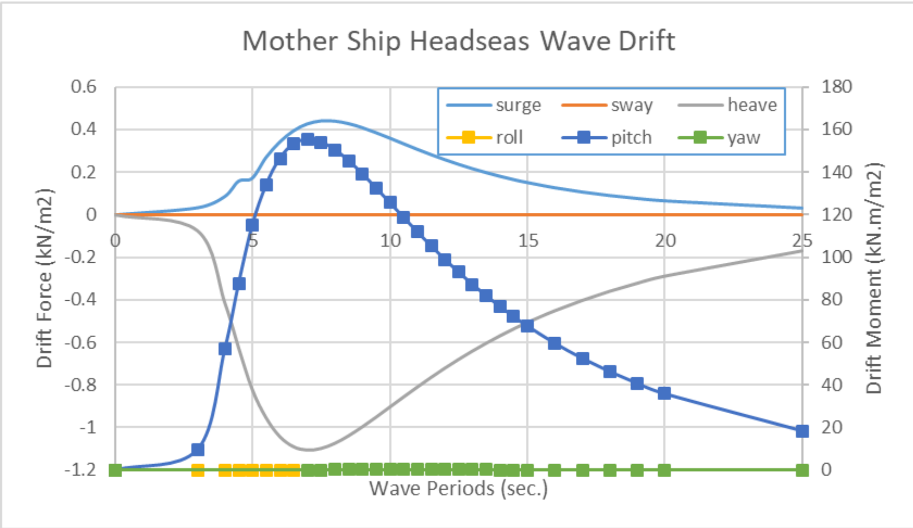
Since the system is weathervaning ship as marine terminal, thus only headseas sea-state observe in this section. RAO and wave drift can be seen in Figure 3. Translational RAO motion both for mother ship and for daughter ship has similar pattern. Based on the RAO result for sway, roll, and yaw motion is have non-noticeable value. This is due to wave direction from headseas, those that the motions is not affected by wave. It should be mentioned that the adjacent ships make gap distance become small cannot predicted really well by current approach.



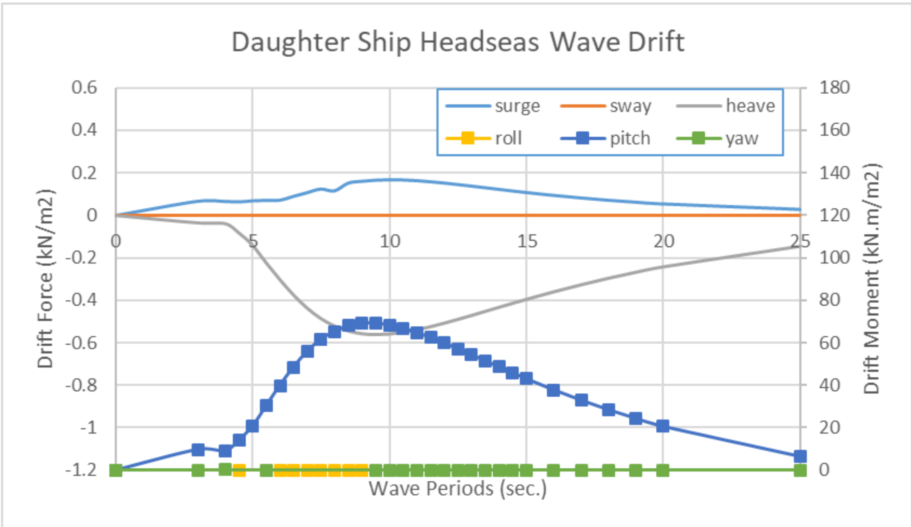
(a) Mothership headseas RAO in 6-DOF motion



(b) Daughtership headseas RAO in 6-DOF motion



(c) Mothership headseas wave drift forces & moments in 6-DOF motion



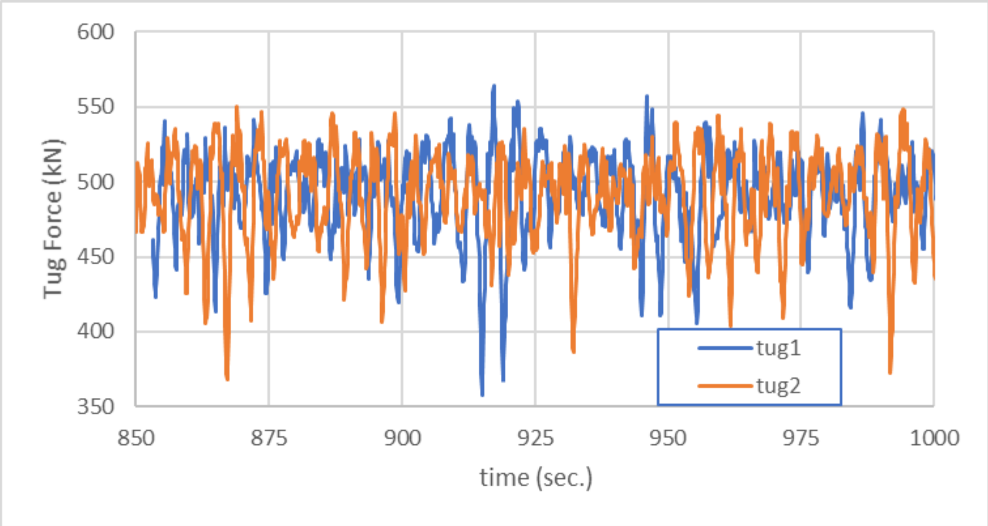
(d) Daughtership headseas wave drift forces & moments in 6-DOF motion

Figure 3. *Ships RAO and Wave Drift Forces Moments under Head Waves Condition*

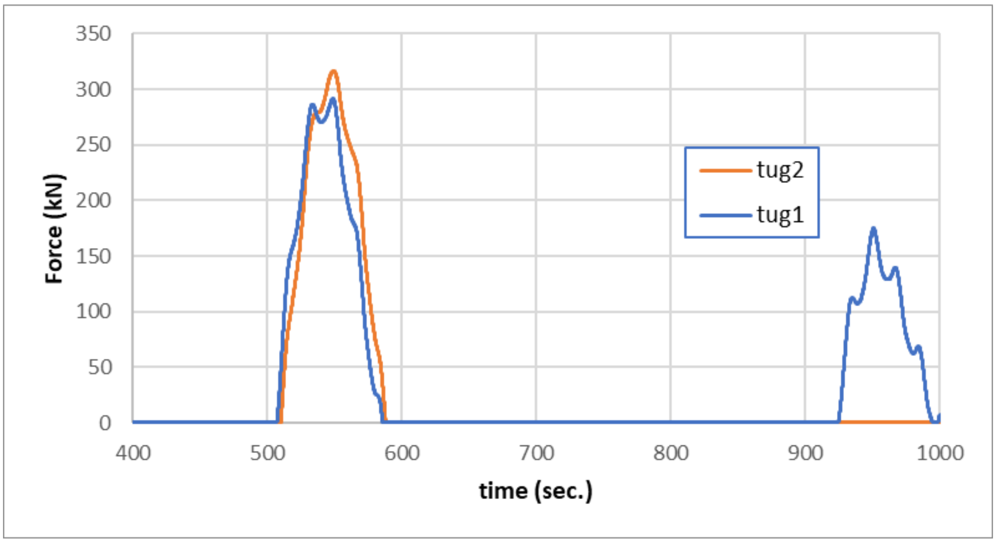
Wave drift results indicates that sway, roll, and yaw has very small forces and moments in all wave periods range. This is related to the RAO results with similar motion result to the wave drift forces and moments. However, even though surge, heave, and pitch motion have similar wave drift pattern between mother ship and daughter ship there are noticeable magnitude between them. Daughter ship has lower wave drift forces and moments than that mother ship due to the mother ship is lighter than daughter ship. In this case, daughter ship is assumed in fully loaded draft condition while the mother ship is in ballast draft condition. For instance, in a similar wave height and wave period ratio, mother ship have 160 kN/m^2 pitch moment while the daughter ship have 70 kN/m^2.

3.2 Time Domain Analysis Results

Results for time domain analysis are presented in Figure 4. First of all, in order to determine tug capacity during berthing and un-berthing scenario, time domain analysis is conducted. The analysis result will be consideration to fleet availability in site-specific location. Bollard pull capacity is then required to fulfill the maximum forces as per sea-state condition. As can be seen in tug force result Figure 3 (a) and (b), the maximum tug force is 550 kN which mean the required bollard pull tugboat specification should not less than 550 kN (56 MT).



(a)



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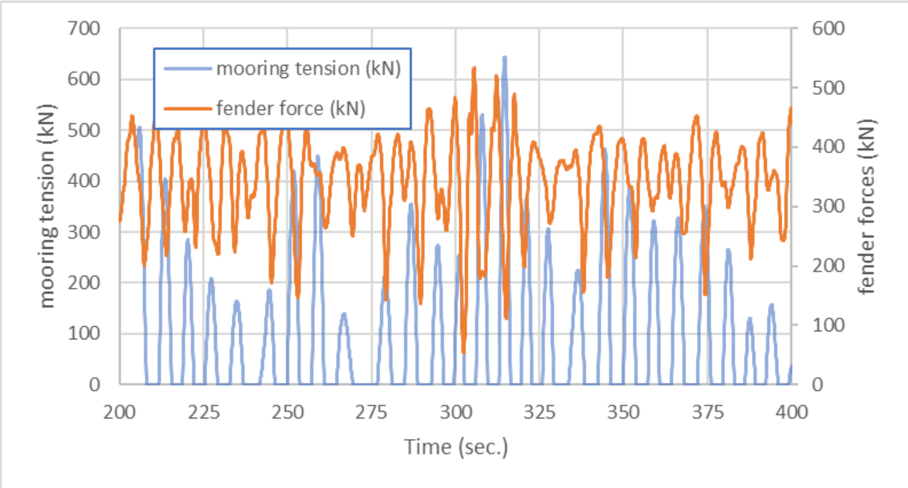

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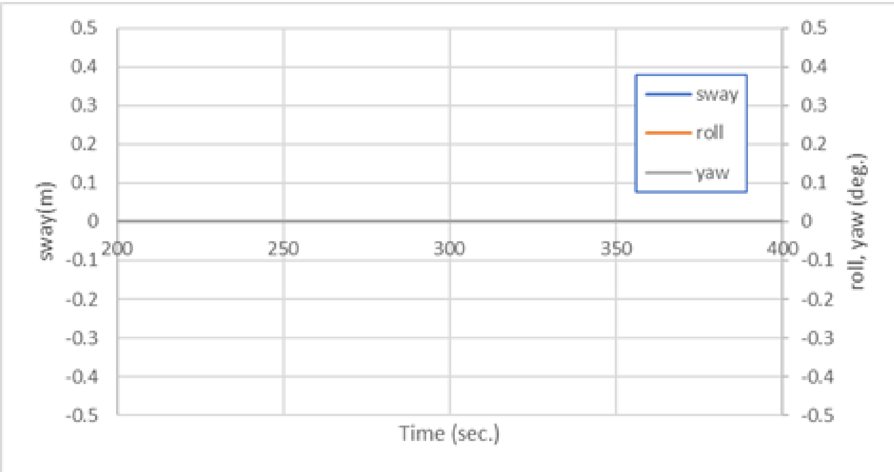


(d)

Figure 4. *Time Domain Analysis Results (a) tug force in berthing scenario, (b) tug force in un-berthing scenario, and for moored scenario are (c) mooring tension and fender force in moored, and (d) daughter ship relative transversal motion*

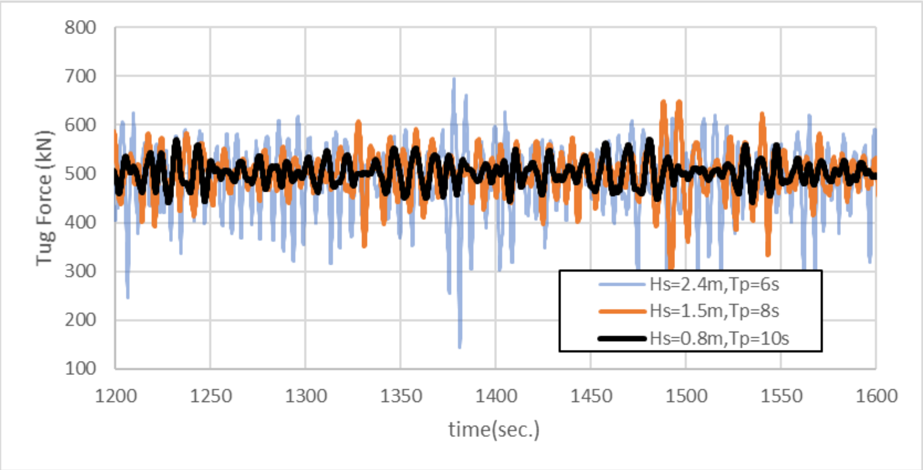
Combination of wave, wind, and current sea-state will affect to the mooring lines and fender performance. As per safety criteria in Table 3, mooring line tension should not exceed 50% Minimum Breaking Load (MBL) and the fender forces should not exceed the rated reaction force. It can be inferred from the mooring tension and fender force result, the minimum required mooring line tension should at minimum have twice as from 650 kN maximum tension. Moreover, fender forces specification should also adequate at least receive force 1100 kN.

Relative motion between adjacent ships, roll motion of daughter ship, and ships clearance are the next criteria should satisfy the safety criteria. Those intended criteria are to avoid potential collision between ships, mechanical cargo transfer equipment limit and personnel safety consideration. Based on the result it is indicated there are no significant transversal motion that lead to both of the ships is collided. The value of sway, roll, and yaw motion is near to zero, thus it can be neglected.

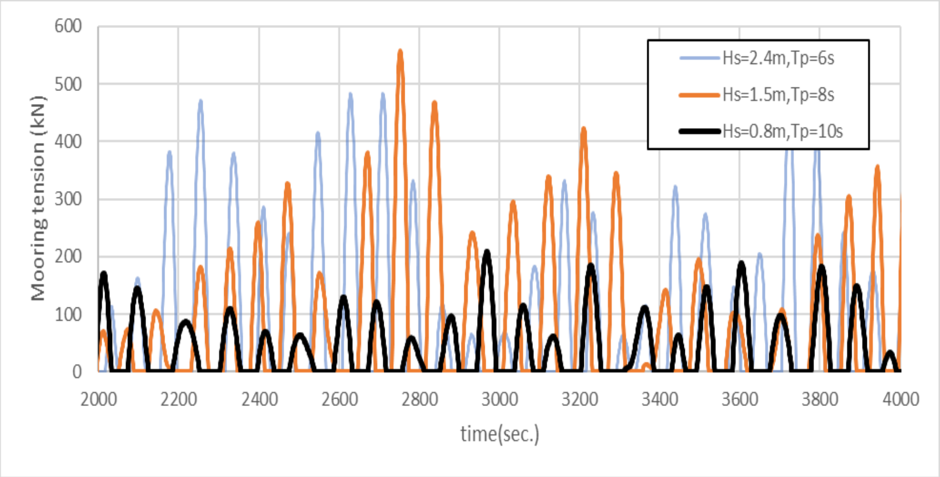
3.3 Safety Trhershold for STS Operation

To reduce potential failure during STS operation, safety threshold is needed to develop and apply. The current study safety threshold reduce significant wave height in combination with wave periods. As can be seen in Figure 5, the following parameter value are decrease along with the wave height reduction. However, the mean value is considerably have similar result.

It should be noted that the longest wave periods the higher line tension occurred, thus safety threshold need to reduce significant wave height from *Hs*=2.4m to *Hs*=1.5m and *Hs*=0.8m. Not only applied in line tensions criteria, but also in fender forces and tug forces for the reduced weather limitation.



(a)



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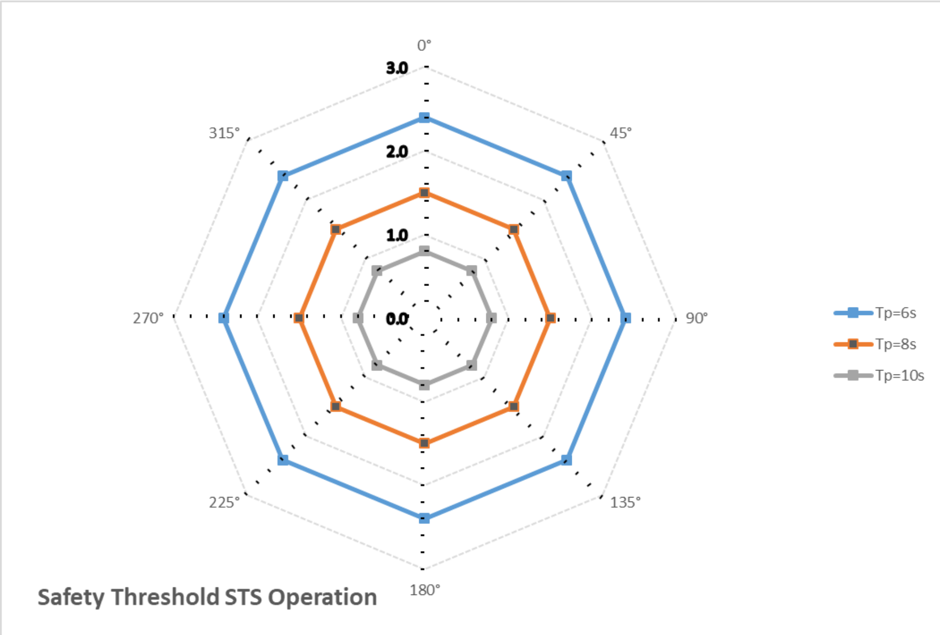

(c)

Figure 5. *Reduced Weather Results in (a) tug force in berthing scenario, (b) mooring line tensions and fender forces for moored scenario (c) safety threshold to conduct STS operation.*

4 Conclusions

Safety evaluation in STS operation has been discussed and studied in this paper. Safety criteria is considered by the OCIMF recommendation for fender and mooring system performance. In addition, motion response that lead to potential collision between ships affected by the environment especially wave height and wind speed is assessed. Ships clearance, relative motion, and daughter ship roll responses will lead to mechanical performance limitation of cargo transfer equipment, and personnel safety consideration. Tugboat fleet availability should also considered regarding their bollard pull capacity, the higher required bollard pull the higher capital and/or operational cost needed. Therefore, several conclusion based on numerical fluid dynamic approach could be mention as follows:

- Under headseas sea-state condition, proposed model has been validated against available published report that have been obtained from model test and numerical simulation. Good agreement result between current approach and the reported data.
- Frequency domain analysis results in conducted for ballast draft mothership and fully loaded draft daughter ship in only headseas sea-state in assumption which mother ships is a weathervane floating terminal. It can be inferred from the results that the mother ship and daughter ship has similar RAOs and wave drift forces pattern. As the mother ship is lighter than daughter ship due to its loading condition, thus that mother ship has higher drift force than daughter ship in the similar wave height and wave periods range.
- The headseas roll response operator could not satisfy multi body interactions phenomena in close proximity between two adjacent ships. Further study is needed to give more comprehension on STS safety operation.

- In defined 10-year return period sea-state, time domain analysis is performed to evaluate the safety criteria. Tugboat bollard-pull capacity is evaluated to tug force in berthing and un-berthing scenario. The results indicated required bollard pull should not less than 56 MT.
- Fender forces and mooring lines load result could inform the minimum required specifications. Fender should be able to receive at minimum 1100 kN force. And for the mooring lines requiring to receive minimum tension more than 650 kN.
- Since the transversal RAOs motions are less significant, the daughter ship motions is also un-significant. Sway, roll, and yaw motion has value near to zero.
- Safety threshold for STS operation are evaluated to the acceptable limiting weather. The 10-year return period environment is reduced from *Hs*=2.4m *Tp*=6.8s, to *Hs*=1.5m *Tp* = 8s and *Hs*=0.8s *Tp*=10s.

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