AN EXPERIMENTAL STUDY OF SHIP MOTIONS DURING REPLENISHMENT AT SEA OPERATIONS BETWEEN A SUPPLY VESSEL AND A LANDING HELICOPTER DOCK

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SUMMARY

Hydrodynamic interactions during Replenishment at Sea (RAS) operations can lead to large ship motions and make it difficult for vessels to maintain station during the operation. A research program has been established which aims to validate numerical seakeeping tools to enable the development of enhanced operator guidance for RAS. This paper presents analysis of the first phase of scale model experiments and focuses on the influence that both the lateral and longitudinal separations between two vessels have on the interactions during RAS. The experiments are conducted in regular head seas on a Landing Helicopter Dock (LHD) and a Supply Vessel (SV) in intermediate water depth. The SV is shorter than the LHD by approximately 17%, but due to its larger block coefficient, it displaces almost 16% more than the LHD. Generally, the motions of the SV were larger than the LHD. It was found that hydrodynamic interactions can lead to large SV roll motions in head seas. Directions for future work are provided.

NOMENCLATURE

B_{OA}	Beam overall
C_B	Block coefficient
COs	Commanding officers
DOF	Degree of freedom
Fr	Froude length number
GM_T	Transverse metacentric height
h	Water depth
k	Wave number
K_{xx}	Roll radius of gyration
K_{yy}	Pitch radius of gyration
K_{zz}	Yaw radius of gyration
LCG	Longitudinal centre of gravity
LHD	Landing helicopter dock
L_{OA}	Length overall
L_{PP}	Length between perpendiculars
MS	Midships
T_{AP}	Draft at aft perpendicular
TCG	Transverse centre of gravity
T_{FP}	Draft at forward perpendicular
R	Scale ratio
RAS	Replenishment at sea
SV	Supply vessel
v	Vessel speed
VCG	Vertical centre of gravity
z	Heave
Δ	Displacement
θ	Pitch angle
ϕ	Roll angle
ω_e	Encounter wave frequency
ω_w	Incident wave frequency
λ	Wave length
ζ_a	Wave amplitude
μ	Incident wave direction (180°, Head seas)
σ	Standard deviation

1. INTRODUCTION

Replenishment at Sea (RAS) is a critical capability for all modern navies as it allows vessels to be deployed for extended periods away from home ports. RAS operations typically involve the transfer of fuel, supplies and/or personnel between vessels operating in close proximity at moderate forward speeds (approximately 12 to 16 knots). The vessels travel alongside one another on parallel paths with lateral separations typically ranging between 20 to 60 m (inner side to inner side). Due to the close proximity of the vessels, hydrodynamic interaction loads develop between the hull forms. These loads impact upon both the motions and manoeuvring capability of the vessels.

Hydrodynamic interactions can cause vessels to be drawn into or pushed away from one another, making it difficult for vessels to maintain the desired heading, speed and lateral (transverse) and longitudinal separations in RAS operations. Interactions can also lead to large vessel motions, which can inhibit the crew's ability to conduct the operation safely. Excessive relative motions may cause the lines passed between vessels to break posing a significant risk to the safety of the crew on deck. In the case of replenishment of solid supplies, large relative motions can result in the payload dipping into the water. Increased wave heights between the vessels, due to interactions, also increases the risk of payload submergence and deck wetness. The hydrodynamic interaction loads are highly dependent on the amplitude, encounter angle and frequency of the incident waves as well as the ship speed and load conditions.

Hydrodynamic interactions are unavoidable during RAS operations. Commanding Officers (COs) therefore look to identify a 'sweet spot' operationally, where minimal rudder inputs are required to allow the vessels to safely maintain station for the duration of the operation. This 'sweet spot' will be different for each RAS operation based on the wave environment, the relative size and shape of the vessels involved and their loading conditions. Giving consideration to all these factors the COs need to determine the most appropriate replenishment speed, heading and vessel separation distance (both lateral and longitudinal) at which to conduct RAS. COs are generally required to make these decisions based mainly on experience as existing operational guidance for RAS is limited and quite general in nature.

Defence Science and Technology (DST) are currently undertaking a research program into multi-vessel hydrodynamic interactions during RAS. This program aims to validate numerical seakeeping tools that will enable the development of enhanced operator guidance for the Royal Australian Navy (RAN) during RAS operations. There is very limited experimental data available in the open literature that can be used to validate these tools for RAS.

DST and the Australian Maritime College (AMC), a specialist institute of the University of Tasmania, have setup a collaborative research project to obtain the experimental dataset required to validate the numerical tools. RAS operations between a Landing Helicopter Dock (LHD) and a Supply Vessel (SV) have been selected as a case study for validation. RAS operations between these vessels are of particular interest to the RAN given that the LHD is much larger than any other RAN vessel that would typically receive replenishment. The SV is shorter than the LHD by approximately 17%, but due to its larger block coefficient, it displaces almost 16% more than the LHD. Figure 1 illustrates the roll motion experienced by the supply vessel HMAS Sirius when conducting RAS operations with the LHD HMAS Canberra, during first of class acceptance trials.

Figure 1: RAS operation between HMAS Canberra and HMAS Sirius during the LHD's first of class acceptance trials [1]

This paper presents results of the first phase of scale model experiments investigating the influence of the lateral and longitudinal separation between vessels in regular head seas on the resulting hydrodynamic interactions.

2. LITERATURE REVIEW

In calm water, the interaction forces, moments and motions are predominantly dependent on the vessel geometry, the vessel speed and the relative longitudinal and lateral positions of the vessels. The influence of the interaction between the calm water wave patterns from the vessels will vary depending on the above factors. In waves, the forces, moments and motions are also dependent on the incident wave height and frequency, encountering angle, the interaction between the diffracted waves, the radiated waves due to the ship motions as well as the calm water wave patterns. Traditionally, RAS interactions have been investigated using numerical techniques, physical model scale experiments and, to a lesser extent, full scale trials.

The problem of hydrodynamic interactions between vessels operating in close proximity has been investigated numerically using potential flow solvers, in calm water Skejic *et al*. (2009); Skejic and Berg (2010); Fonfach *et al*. (2011) and also in waves Chen and Fang (2001); Rafiqul Islam and Murai (2013); von Graefe *et al*. (2015); Yuan *et al*. (2015); Thomas et al. (2010); Yuan *et al*. (2016); Kashiwagi *et al*. (2005). The applicability of these simulation techniques to the analysis of hydrodynamic interactions is limited due to the lack of viscosity in the numerical models.

To inform the design of the scale model experiments presented in this paper Mathew *et al*. (2016) made use of a frequency domain 3D panel method tool. This study highlighted the importance of applying appropriately tuned artificial damping to the free surface between vessels when using such codes. McTaggart and Turner (2006) also used a 3D panel method to investigate interaction forces and moments on ships during RAS in the frequency domain. This study included the prediction of viscous forces based on the work of Schmitke (1978) and Himeno (1981).

RANS simulations have been conducted to capture viscous effects in both calm water Sadat-Hosseini *et al*. (2011); Fonfach *et al*. (2011) and in waves Mousaviraad *et al*. (2016). RANS simulation methods offer significant advantages for the analysis of hydrodynamic interactions. These techniques however, remain highly computationally expensive.

Lataire *et al*. (2009) conducted semi-captive physical model scale experiments in calm, shallow water to investigate interaction between an Aframax tanker and a Very Large Crude Carrier (VLCC) with operating propellers during a lightering operation. It was found that the interaction forces and moments were significantly influenced by the ship speed and the relative longitudinal and lateral positions of the vessels.

The interaction between ships operating in regular waves was investigated by McTaggart *et al*. (2003). Head sea tests were conducted on a frigate and supply ship at speeds up to 12 knots at one lateral separation and two longitudinal separations. Zero forward speed tests were also conducted at 120 and 150 degrees encountering angles. It was found that the presence of the larger ship significantly influenced the motions of the smaller ship operating in close proximity.

Thomas et al. (2010) conducted experiments on a frigate and supply tanker undergoing RAS in head seas. This study focussed on the influence of the longitudinal separation between vessel and supply vessel displacement, on the resulting ship motions. Increasing the supply vessel displacement significantly increased the frigate roll response. Whereas, increasing the longitudinal separation (frigate aft of the supply vessel) reduced the motions of the frigate. Andrewartha *et al*. (2007) performed head sea semi-captive model tests on a generic frigate and a larger supply vessel. It was found that the roll, pitch and heave motions of the frigate were strongly influenced by the relative longitudinal and lateral position of the vessels.

Mousaviraad *et al*. (2016) considered the problem of hydrodynamic interactions more generally and reported on semi-captive model tests in deep calm water and regular waves for headings ranging from following to head seas. The longitudinal and lateral positions of the vessels were also varied.

Quadvlieg *et al*. (2011) conducted free sailing model scale experiments in waves using a variety of ship models. It was observed that the entrapped waves between the vessels had a significant influence on the behaviour of the vessels. Full scale trials were also conducted in the Gulf of Mexico.

Physical scale model experiments specifically looking at hydrodynamic interactions during RAS, published in the open literature have typically considered the scenario where the supply vessel is significantly larger than the vessel being replenished. These experiments have also been typically limited to head seas with semi-captive models. To improve understanding of hydrodynamic interactions during RAS and enable validation of numerical tools for analysis of this problem the available experimental dataset needs to be developed further.

3. PHYSICAL SCALE MODEL EXPERIMENTS

3.1 MODEL DETAILS

The experiments were conducted using 1:70 scale ship models of a LHD and a SV. The LHD was fitted with fore and aft bilge keels and ballasted to its full load condition. The SV did not have appendages fitted and was tested at its minimum operating condition. The two extreme loading conditions were chosen as they are expected to represent the worst-case scenario and were kept constant for the entire testing program. The SV was tested without appendages to provide a simplified benchmark case for validation.

Each model was constructed to standards defined by International Towing Tank Conference (ITTC) specifications for geometric tolerances and turbulence stimulation ITTC (2011). To obtain the correct model scale mass distribution, roll decay and inclining tests were performed iteratively. The model scale and full scale particulars are given in Table 1.

Table 1: Ship and Model Particulars

Particular	**LHD**		**SV**	
	Model Scale	**Full Scale**	**Model Scale**	**Full Scale**
L_{OA} (m)	3.30	230.8	2.73	191.3
B_{OA} (m)	0.43	29.9	0.44	31.0
L_{PP} (m)	2.96	207.2	2.4	168.0
T_{FP} (m)	0.10	7.10	0.10	7.18
T_{AP} (m)	0.10	7.10	0.12	8.38
Trim (m)	0.00	0.00	0.02	1.2
Δ	78.2 kg	27486 t	92.9 kg	32662 t
C_B	0.61	0.61	0.80	0.80
LCG (m)	1.43	100	1.27	88.58
VCG (m)	0.19	13.51	0.12	8.08
TCG (m)	0.0	0.0	0.0	0.0
GM_T (m)	0.05	3.72	0.09	6.33
K_{xx} (m)	0.20	13.9	0.16	11.55
K_{yy} (m)	0.76	53.7	0.63	43.82
K_{zz} (m)	0.76	53.7	0.63	43.82

3.2 EXPERIMENTAL SETUP

All tests were performed at the AMC's Model Test Basin (MTB). The MTB is 35 metres long, 12 metres wide and has a maximum depth of 1m. It has a multi-paddle, piston-type wave maker at one end and an artificial wave-dampening beach at the other.

The experiments used an overhead rail system, capable of towing the models at an equivalent full scale speed of 14 knots (Figure 2). Both models were attached to the overhead carriage using a two-post system, with a ball joint connection on the forward post and a ball joint and slide on the aft post. This arrangement allowed the models to freely heave, pitch and roll but constrained them in surge, sway and yaw. The posts were connected to each model on their centreline at heights corresponding to their respective vertical centre of gravity, allowing the presented data to be easily used for numerical validation purposes.

It is noted that constraining the models may induce motions that would not be experienced during an actual RAS operation. Since the centre of roll will move throughout the experiments based on the wetted hull surface, restraining the model to roll about the *VCG* will have some small influence on the measured roll motions. Similarly, a small artificial pitching moment will exist due to towing the models from above their thrust line. Numerical tools could be used to further investigate these affects by conducting simulations with the vessels constrained as in the model testing and a free sailing condition.

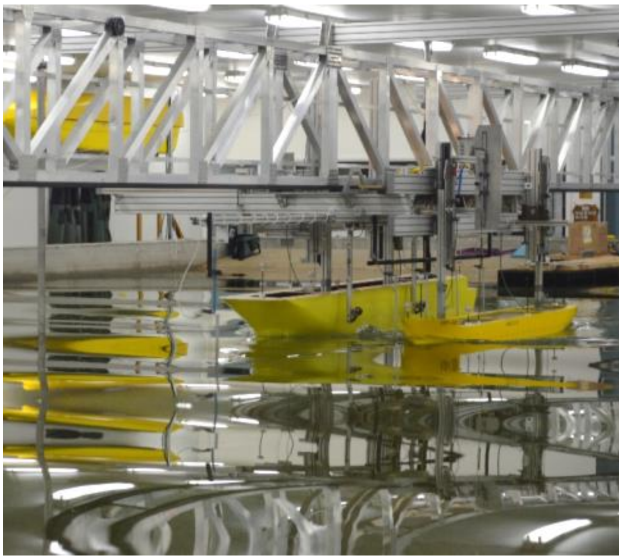


Figure 2: MTB and Testing Apparatus

3.3 INSTRUMENTATION

These experiments made use of the newly upgraded QUALISYS three-dimensional digital video motion tracking system in the MTB. This type of non-contact motion capture system offers a number of advantages for multi-vessel seakeeping experiments over the traditional the Linear Variable Differential Transformers (LVDTs). The non-contact sensors remove the potential for physical interference. They also provide flexibility in the design of the experimental test rig and simplify both the experimental setup and calibration process.

LVDTs were also used to independently measure the motions to provide benchmark data to assess the viability of the upgraded QUALISYS system for this type of multi-vessel experiment. LVDTs were mounted to the forward and aft posts of each model. To acquire roll motion data, a third LVDT was attached to each model on the outboard extremity, having the same longitudinal position as the forward LVDT.

Resistance type wave probes were used to measure the free surface elevation. Two static wave probes were used to capture the incident wave train properties and any dissipation or reflection of this wave over the length of the test basin. A third wave probe was mounted to the carriage forward of the models to measure the encountering waveform. All signals were recorded at a sample rate of 200 Hz.

To assist in understanding the interaction effects and free surface environment, three cameras were also attached to the carriage. Two were focused on the SV's waterline on the inner side of the model. The third camera was mounted forward of both models and aligned to monitor the overall free surface elevation in the gap between vessels.

3.4 TEST CONFIGURATIONS

The model experiments were conducted in regular head seas with a nominal model scale wave amplitude of 0.015 m, equivalent to 1.05 m full scale. The models were towed in parallel at a constant forward speed of 0.86 m/s model scale, equivalent to 14 knots full scale, which is a typical speed for RAS operations. This equates to a Froude Length Number (*Fr*) of approximately 0.16 for LHD and 0.18 for the SV.

Two lateral separations of 40 m and 60 m (full scale, inner side to inner side) were selected as they represent typical real-world separation distances for RAS operations involving two larger vessels (NATO Standardization Agency, 2001). Two longitudinal separations have been tested which represent alignment of a single RAS station on the SV with two RAS stations on the LHD. The longitudinal separations are 15.5 m and 58.9 m between vessels midships, with the SV forward of the LHD in both cases. A schematic of the vessel configurations in each test condition is provided in Figure 3.

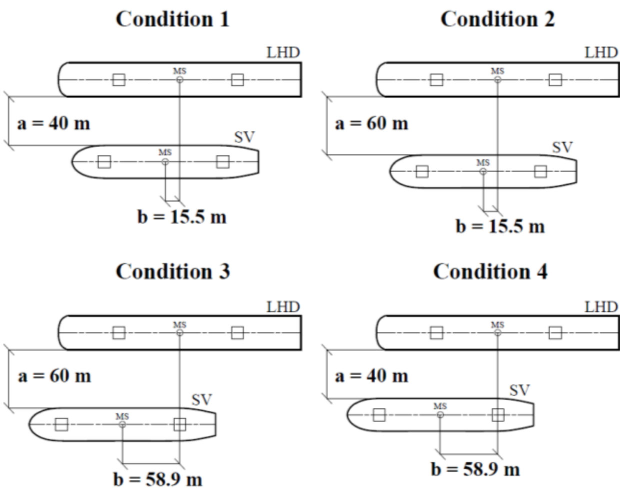


Figure 3: Lateral and longitudinal separations between vessels for each condition. Dimensions of the lateral separation are inner side to inner side and longitudinal separations are midships to midships. Full scale dimension shown in the schematic and model scale dimensions are summarised below:

Condition 1: a = 0.571 m, b = 0.221 m
Condition 2: a = 0.857 m, b = 0.221 m
Condition 3: a = 0.857 m, b = 0.841 m
Condition 4: a = 0.571 m, b = 0.841 m

The water depth in the MTB was 0.75 m for testing which is approximately 53 m at full scale. To avoid wave reflections in the dataset an appropriate time delay between the start of the wave maker and the start of the carriage was established for each wave frequency tested. The lowest practical circular wave frequency was found to be 2.95 rad/s model scale.

For all conditions tested, the circular wave frequency was varied between 2.95 and 6.41 rad/s model scale, equivalent to 0.35 and 0.77 rad/s full scale. Due to the limited water depth in the basin and the frequency range of interest, the majority of experiments were not undertaken in deep water ($h > \lambda/2$) Bhattacharyya (1978), but rather in intermediate water depths. Bottom effects are therefore present in the waves encountered by the models. When using this data to validate the chosen numerical tool it may be possible to account for the effects of the intermediate water depth waves in the simulations.

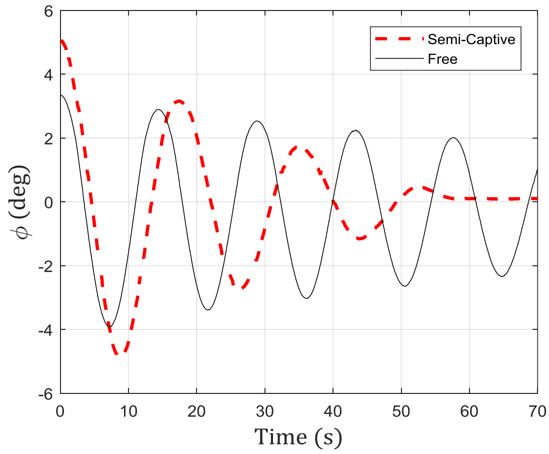
3.5 ROLL DECAY EXPERIMENTS

Free floating, calm water roll decay experiments were conducted for both vessels at zero speed. The experiments were undertaken in a water depth of 0.75 m and the roll displacement (ϕ), was measured using the non-contact QUALISYS motion capture system. To gauge the influence of the semi-captive test setup on the roll behaviour of the models, further calm water roll decay experiments were conducted for each of the models while attached to the carriage.

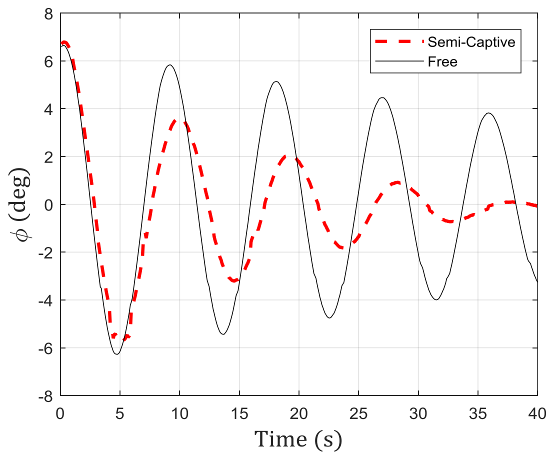
Example roll decay time series for both the free and semi-captive experiments are shown at full scale in Figure 4. The average natural roll frequencies in both the free and semi-captive arrangement are summarised in Table 2. The semi-captive natural roll frequency is lower than that of the free response for both vessels.

Table 2: Average full scale natural roll frequencies of the LHD and Supply Vessel

Natural Roll Frequency	LHD	SV
Free (rad/s)	0.436	0.705
Semi-captive(rad/s)	0.359	0.675



(a) LHD



(b) SV

Figure 4: Examples of free and semi-captive roll decay time series

4. RESULTS AND DISCUSSION

The heave (z), roll (ϕ), and pitch (θ) motion responses of the vessels in regular waves are presented as a function of full scale encounter frequency. The motions are non-dimensionalised as per Equations 1-3, and the full scale encounter frequency is calculated as per Equation 4. The motion ordinates are calculated based on the standard deviation of the steady state portion of the time series. This approach has been used to account for the irregularity observed in some of the time domain motion traces. For cases where the water depth was classified as intermediate, the wave length was determined using the method presented by Fenton and McKee (1990).

$$Heave = \frac{\sigma_z}{\sigma_{\zeta_a}} \quad (1)$$

$$Roll = \frac{\sigma_\phi}{\sigma_{\zeta_a}.k} \quad (2)$$

$$Pitch = \frac{\sigma_\theta}{\sigma_{\zeta_a}.k} \quad (3)$$

$$\omega_e = \omega_w.\left(1 - \frac{\omega_w.v}{g}\cos(\mu)\right).\frac{1}{\sqrt{R}} \quad (4)$$

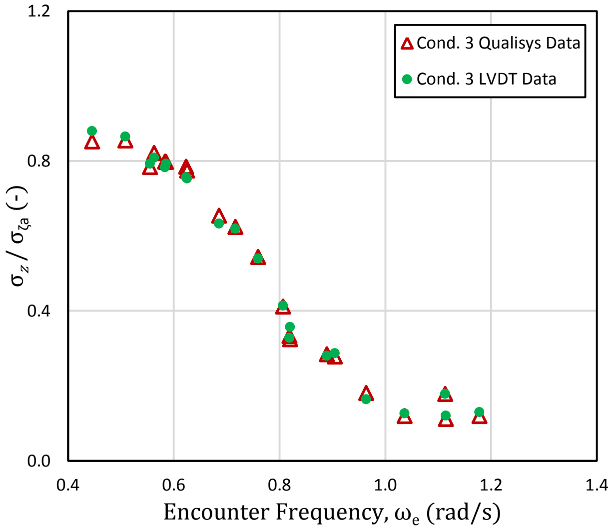
To investigate the influence of the relative vessel positions on the free surface elevation between vessels, a qualitative analysis of the calm water wave interactions between the vessels in each condition is made. This visual comparison is then extended to the wave interactions between vessels in head seas for two example cases.

4.1 QUALISYS AND LVDT COMPARISON

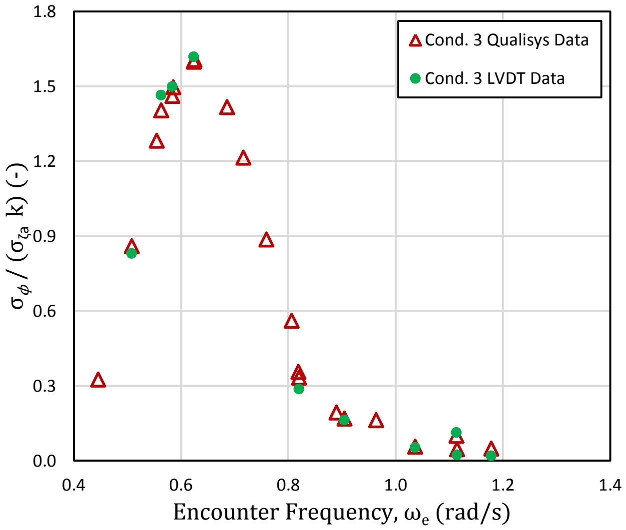
To obtain confidence in the use of the non-contact motion measuring system for this application, the motion results were benchmarked against that of the traditionally used LVDT arrangement. Figure 5 shows an example of the derived motion results based on the LVDT and Qualisys measurements, for the SV motion in Condition 3. The motion measurements from the two systems match closely in all cases. It is noted that there are some data points missing for the roll motion derived from the LVDT measurements. This is due to a technical issue encountered with one of the LVDTs. This issue was promptly identified and addressed during the experiments but due to time constraints it was decided not to re-run these cases. The heave and pitch motions derived from the LVDTs were not affected by this issues.

4.2 VESSEL MOTION RESPONSES

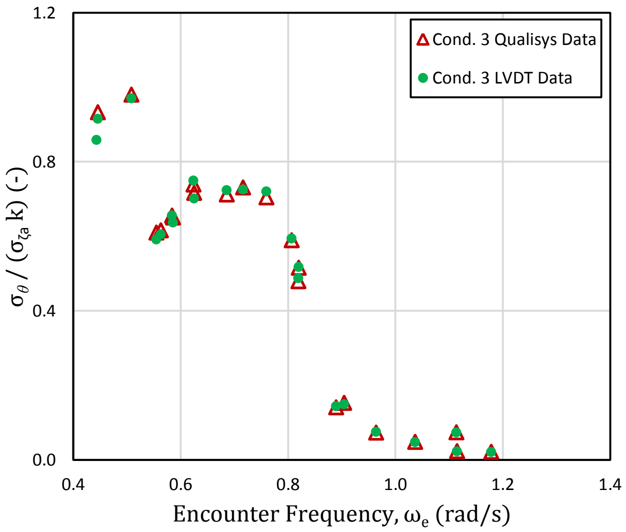
For each combination of lateral and longitudinal separation between vessels, the resulting heave (z), roll (ϕ) and pitch (θ) responses of the SV are shown in Figure 6. All results are presented at full scale, as a function of encounter frequency. Generally, the peak motion responses are larger for the SV than for the LHD. Therefore, the discussion focusses mainly on the SV motions. However, the LHD pitch response is shown in Figure 7 to illustrate that the lateral and longitudinal separation influence the motion response of the LHD and SV differently.



(a) Heave

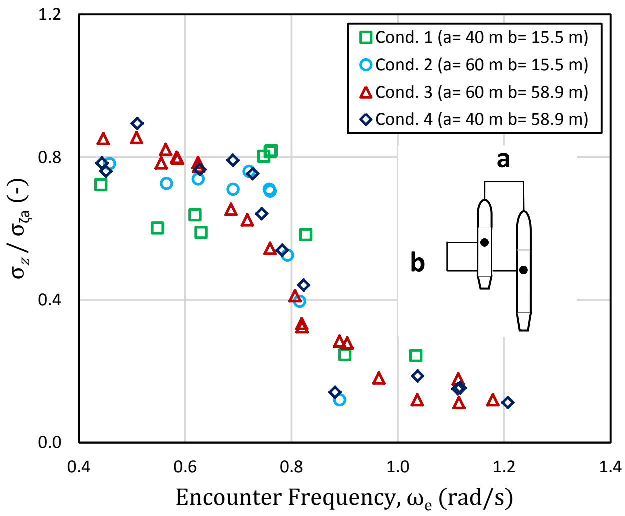


(b) Roll

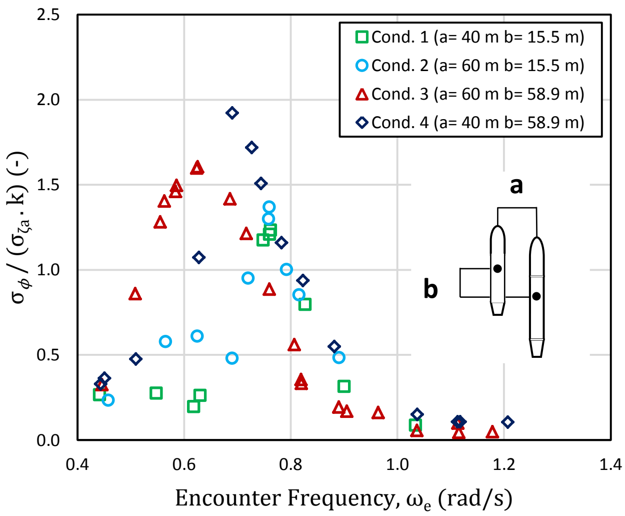


(c) Pitch

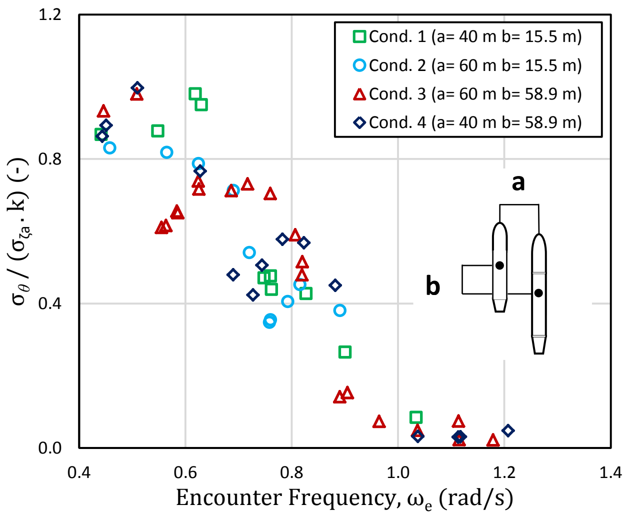
Figure 5: Non-dimensional motion responses resulting from Qualisys and LVDT measurements.



(a) Heave



(b) Roll



(c) Pitch

Figure 6: SV non-dimensional motion response

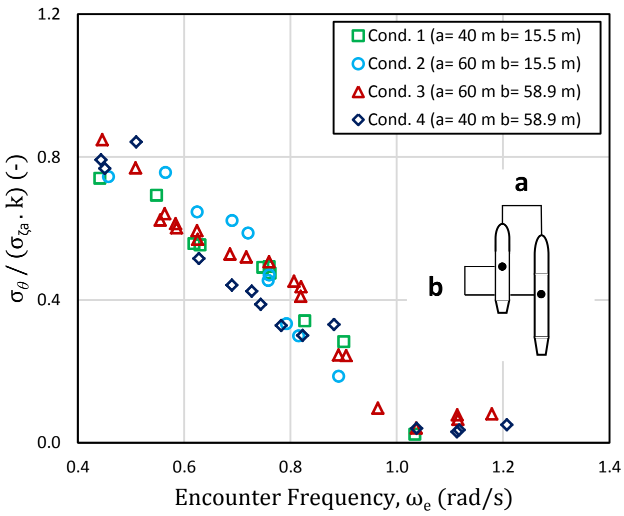


Figure 7: LHD non-dimensional pitch motion response

4.2 (a) SV Heave Response

The largest SV peak heave response occurred with a lateral separation of 40 m and longitudinal separation of 58.9 m (Condition 4). The smallest peak heave response was observed with a lateral separation of 60 m and a longitudinal separation of 15.5 m (Condition 2). The peak heave response for Conditions 2, 3 and 4 occurred in the encounter frequency range of 0.44 – 0.51 rad/s. However, for the case with the smallest tested lateral and longitudinal separation (Condition 1), the peak heave response occurred at a higher encounter frequency (0.76 rad/s).

Increasing the lateral separation between vessels, whilst maintaining a longitudinal separation of 15.5 m (Conditions 1 to 2), slightly reduces the peak heave response of the SV. With a longitudinal separation of 58.9 m, increasing the lateral separation (Conditions 4 to 3) also reduces the peak heave motion response.

Increasing the longitudinal separation between vessels, with a lateral separation of 40 m (Conditions 1 to 4) increased the peak heave response. Similarly, with a lateral separation of 60 m between vessels increasing the longitudinal separation (Conditions 2 to 3) results in an increase in peak heave response.

The vessel configuration that results in the smallest heave response is largely dependent on the encounter frequency. For example, in the frequency range of 0.56 to 0.62 rad/s Condition 1 results in the lowest heave response. Contrastingly, in the range of 0.69 to 0.76 rad/s the smallest response occurs in Condition 3.

4.2 (b) SV Roll Response

It can be seen that hydrodynamic interactions induce significant SV roll motions in all conditions tested. This means that during RAS operations in head seas the SV will need to withstand not only the typically dominant longitudinal motions but also significant lateral plane motions.

The largest peak SV roll response occurred with a lateral separation of 40 m and longitudinal separation of 58.9 m (Condition 4), the same condition that resulted in the largest peak heave response. The peak response in this condition occurs at an encounter frequency close to the semi-captive natural roll frequency of the SV (0.68 rad/s), as seen in Table 2. Smaller frequency spacing around the peak roll response would be desirable to more accurately capture the peak values.

Increasing the lateral separation between vessels at a longitudinal separation of 58.9 m (Condition 4 to 3) reduces the peak roll response. However, at a longitudinal separation of 15.5 m the peak roll response is marginally increased when the lateral separation is increased from 40 m to 60 m (Condition 1 to 2).

Increasing the longitudinal separation between vessels with a lateral separation of 40 m (Condition 1 to 4) increases the magnitude of the peak roll response and shifts it to a lower encounter frequency. The same trends are seen as a result of increasing the longitudinal separation between vessels with a lateral separation of 60 m.

Given the lack of appendages on the SV, its roll damping will be low and mainly due to wave radiation. The large variations seen in the peak roll response with change in lateral and longitudinal separation can be partially attributed to its low roll damping. This causes the magnitude of the peak roll response to be highly sensitive to variations in the amount of damping present. The semi-captive experimental setup may compound these effects as the radiated waves can become somewhat captured between the models. The way in which the waves between the models interact is a complex problem and may have a significant effect on the peak roll response of the SV. The resulting interaction loads will vary greatly depending on whether the wave interactions are constructive or destructive. This is discussed further in section 4.3.

As is the case for heave motion, the vessel configuration that provides the smallest roll motion varies with encounter frequency. Between 0.56 and 0.62 rad/s the smallest roll response occurs in Condition 1. This is the same condition that produced the smallest heave response in this frequency range. For encounter frequency of 0.76 rad/s and above, Condition 3 results in the smallest roll response.

In Condition 1 the peak heave and roll responses occur at the same encounter frequency. For all other configurations, at the encounter frequency corresponding to the peak roll response, the magnitude of the heave response is also close to its peak value. This indicates that the roll and heave excitation forces due to hydrodynamic interactions vary in a similar way. These interactions cause the roll response of the SV to change dramatically especially at resonance. The variations in heave response due to these interactions are less severe because the heave motions are more heavily damped.

4.2 (c) SV Pitch Response

The magnitude of the SV peak pitch response is similar for Conditions 1, 3 and 4. Condition 2 results in the smallest peak pitch response. With a longitudinal separation of 15.5 m, increasing the lateral separation between vessels (Condition 1 to 2) reduces the peak SV pitch response. In contrast, the peak SV pitch response is relatively unaffected as a result of increasing the lateral separation between vessels with a constant longitudinal separation of 58.9 m (Conditions 4 to 3). The peak pitch response for Conditions 2, 3 and 4 occurred within the encounter frequency range of 0.44 –0.51 rad/s.

Contrastingly, for Condition 1 the frequency of the peak pitch response was higher at 0.62 rad/s. This trend is similar to that discussed in section 4.2 (a) for the peak SV heave response. As in the case of both the SV heave and roll responses, the condition that produces the smallest pitch response varies with the encounter frequency.

4.2 (d) LHD Pitch Response

In general, the longitudinal and lateral separations between the vessels have a smaller influence on the pitch motion response of the LHD than on the SV. This may be partly attributed to the differences in hull form, loading condition and that the SV was not fitted with bilge keels.

The magnitude of the peak pitch motion is greatest for the largest longitudinal separation (Conditions 3 and 4). Some consistent trends can be identified over small ranges of encounter frequency. For example, for encounter frequencies between 0.56 and 0.72 rad/s the pitch motion is largest for Condition 2. For encounter frequencies between 0.62 rad/s and 0.82 rad/s the pitch motion response is consistently lowest for Condition 4.

4.3 FREE SURFACE ENVIRONMENT OBSERVATIONS

4.3 (a) Calm Water Patterns

The wave patterns from the vessels moving in calm water were investigated using photographs and video footage to provide insight into their influence on the motions experienced by the vessels. The wave patterns between the two models when moving through calm water with an equivalent full scale speed of 14 knots can be seen in Figure 8 for each condition.

(a) Condition 1 (a = 40 m, b = 15.5 m (full scale))

(b) Condition 2 (a = 60 m, b = 15.5 m (full scale))

(c) Condition 3 (a = 60 m, b = 58.9 m (full scale))

(d) Condition 4 (a = 40 m, b = 58.9 m (full scale))

Figure 8: Wave patterns between models in calm water, (LHD Left, SV Right).

In Conditions 1 and 2, where the midship sections of the vessels are more closely aligned longitudinally, the waves from each vessel meet closer to the centre of the gap between the vessels. While in Conditions 3 and 4 where the SV is further forward of the LHD, the waves meet closer to the LHD. This is due to the waves from the SV travelling further before meeting the waves off the LHD in Conditions 3 and 4.

In Condition 1, 2 and 4 it appears that after the waves meet, the diffracted waves that travel in the direction of the SV contact the aft starboard side of the SV. In contrast, for Condition 3 (largest tested lateral and longitudinal separation) it appears that the waves do not contact the SV but rather pass behind its aft extent. The waves that contact the aft extent of the SV may contribute to roll motion, not only by exerting an exciting moment on the vessel, but also by altering the instantaneous wetted surface area of the hull and therefore its transverse stability.

The observations conducted in calm water were used to provide an understanding of the free surface environment for a simplified case. However, the wave patterns from the vessels in calm water will be influenced when the vessels move into a head sea.

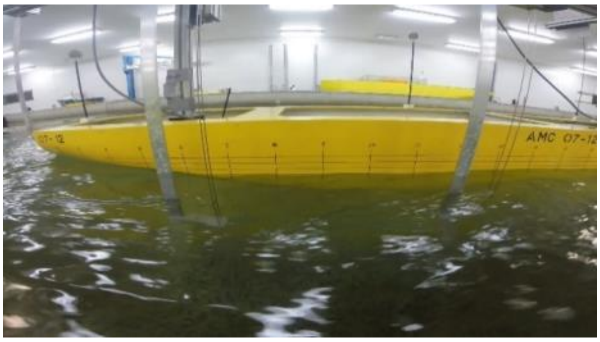
4.3 (b) Free Surface Environment in Waves

The effect that interactions have on vessels in calm water is largely a function of their speed, hull geometry and relative positions. In head seas however, the forces, moments and motions are also dependent on the incident wave amplitude and frequency, the interaction between the diffracted waves, the radiated waves due to the ship motions as well as the calm water wave patterns discussed in section 4.3 (a).

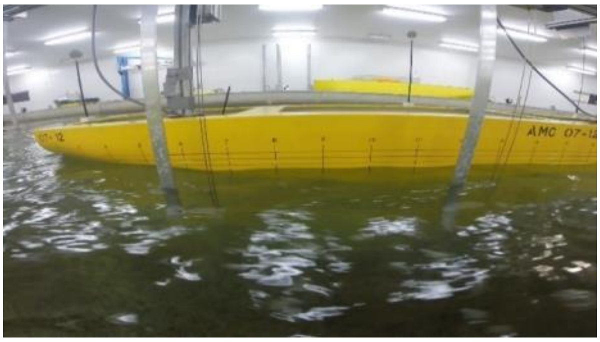
The free surface elevation observed between the two vessels advancing in waves was chaotic and highly irregular. It also varied significantly for changes in both vessel configuration and encounter frequency. Wave trapping between the hulls due to vertical motions as described by Faltinsen (2005) may potentially contribute to the observed free surface characteristics for some of the conditions tested. Figures 9 and 10 illustrate the free surface elevation between vessels for Conditions 3 and 4 respectively, at an encounter frequency of 0.73 rad/s full scale. Each figure contains three sequential images with a time step 0.6 seconds full scale between images. The images were taken from the aft camera between the vessels.

In Condition 3 the free surface environment is relatively undisturbed in the region of the aft starboard shoulder of the SV. As discussed in Section 4.3 (a), the bow wave of the LHD contacts the aft quarter of the SV in Condition 4 but not in Condition 3.

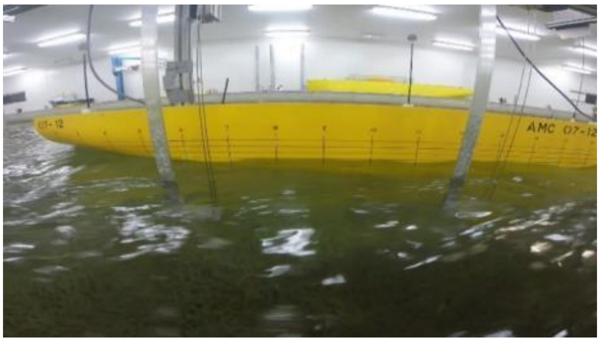
The wave elevation is notably larger and more chaotic in Condition 4 than in Condition 3. It is also noted that there is a distinct forward propagation of a wave along the hull of the SV in Condition 4. Both of these features may influence the excitation moments on the SV and may contribute to the larger SV roll response seen in Condition 4.



(a)



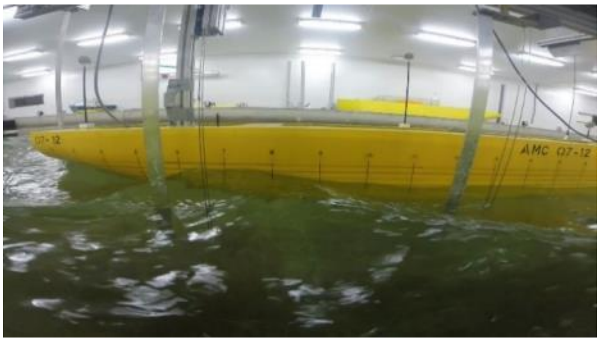
(b)



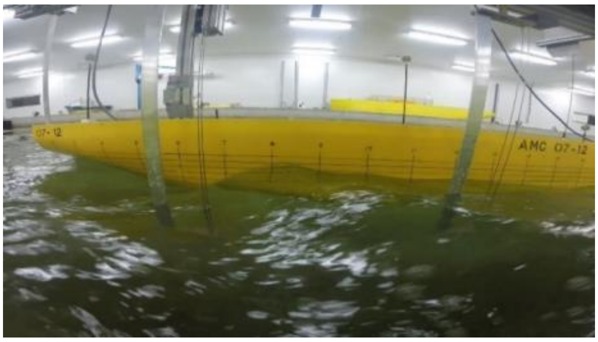
(c)

Figure 9: Sequential images of the free surface elevation between vessels in Condition 3 at encounter frequency of 0.73 rad/s full scale. The time step between images is 0.6 s full scale.

(a)



(b)



(c)

Figure 10: Sequential images of the free surface elevation between vessels in Condition 4 at encounter frequency of 0.73 rad/s full scale. The time step between images is 0.6 s full scale.

5. CONCLUSIONS

This paper presents analysis of physical scale model experimental results of hydrodynamic interactions during RAS. These studies focussed on the influence of lateral and longitudinal separation between vessels on interactions between a supply vessel (SV) and a landing helicopter dock (LHD) operating in head seas.

Variations in the lateral and longitudinal separation between vessels were found to have more influence on the pitch response of the SV than that of the LHD. The LHD roll response was close to zero for all conditions. In contrast, it was found that hydrodynamic interactions could result in large SV roll motions. This means that during RAS operations in head seas the SV will need to withstand not only the typically dominant longitudinal motions but also significant lateral plane motions.

A single configuration resulted in the largest peak SV heave, roll and pitch motion responses. In this configuration the vessels were separated by 58.9 m longitudinally and 40 m laterally. The vessel configuration that resulted in the smallest SV heave, roll and pitch responses varied with encounter frequency.

The lateral and longitudinal separations between vessels were found to have a large influence on the peak roll response of the SV. Increasing the longitudinal separation increased the peak SV roll response. Increasing the lateral separation between vessels reduced the peak SV roll response at a longitudinal separation of

58.9 m. In contrast, increasing the lateral separation at a longitudinal separation of 15.5 m marginally increased the peak roll response.

Visual comparison was made of the free surface elevation between the vessels in calm water and for a selected case when advancing in head waves. The selected comparison considered the influence of changing the lateral separation between vessels with a constant longitudinal separation of 58.9 m. With 60 m lateral separation, the bow wave of the LHD was found not to contact the SV. When the lateral separation was reduced to 40 m, the bow wave of the LHD made contact with the aft extent of the SV. The reduced lateral separation also resulted in larger wave elevations and a more chaotic free surface between the vessels. These features may influence the excitation moments on the SV and contribute to the increase in roll response with reduced lateral separation which was seen for these conditions.

6. FUTURE WORK

Future scale model experiments will aim to quantify all hydrodynamic loads acting on the models as well as the wave elevation between them. This will enable a thorough understanding of the way in which the waves between the models interact and the resulting hydrodynamic interactions. As part of this study the potential for wave-trapping between the hulls as described by Faltinsen (2005) will be investigated in detail. The additional experimental data will also be highly valuable when it comes to validating numerical tools.

Another valuable experimental dataset for validation could be obtained by conducting single vessel radiation and diffraction experiments. This would be similar to the approach taken by Carette (2016) when considering the problem of validating numerical tools for analysis of hydrodynamic interactions during launch and recovery. This will enable validation of numerical tools for a simplified case before moving to the more complicated case with two vessels operating in close proximity.

Validation of the chosen numerical tool will be undertaken in multiple phases. The experimental dataset presented here will be used as the basis for the first phase of validation. Once the influence of lateral and longitudinal separation between vessels on hydrodynamic interactions in head seas is well understood, the focus of studies will be expanded to include consideration of vessel heading and forward speed.

To inform the development of an efficient test program for the next phase of scale model experiments, parametric studies will be conducted using the partially validated numerical tool. A key focus of these studies will be how each of the contributions to the roll exciting moment is influenced by variation in the lateral and longitudinal separation between vessels as well as vessel heading and speed. Numerical studies will also be used to examine the influence of the semi-captive experimental setup by conducting simulations with the vessels constrained as they were in the experiments and also in free sailing condition.

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8. REFERENCES

1. http://images.navy.gov.au/20151124ran 8100087_069.jpg (Accessed 20th July 2016)
2. SKEJIC, R., BREIVIK, M., FOSSEN, T. I. & FALTINSEN, O. M. (2009) *Modeling and control of underway replenishment operations in calm water*. Proceedings of 8th IFAC Int. Conference on Manoeuvering and Control of Marine Craft, Trondheim, Norway, 2009.
3. SKEJIC, R. & BERG, T. E. (2010) *Combined seakeeping and maneuvering analysis of a two ship lightering operation*. Proceedings of the 29th International Conference on Ocean, Offshore and Arctic Engineering – OMAE, Shanghai, China, 2010.
4. FONFACH, J. M. A., SUTULO, S. & GUEDES SOARES, C. (2011) *Numerical study of ship-to-ship interaction forces on the basis of various flow models*. 2nd International Conference on Ship Manoeuvring in Shallow and Confined Water, Trondheim, Norway, 2011.
5. CHEN, G. R. & FANG, M. C. (2001) *Hydrodynamic Interactions Between Two Ships Advancing in Waves*. Ocean Engineering, Elsvier Science Ltd., 28**,** 1053-1078, 2001.
6. RAFIQUL ISLAM, M. & MURAI, M. (2013) *Dynamic interaction of parallel moving ships in close proximity*. Journal of Marine Science Application, 12**,** 261-271, 2013.
7. VON GRAEFE, A., SHIGUNOV, V. & EL MOCTAR, O. (2015) *Rankine source method for ship–ship interaction problems*. Journal of Offshore Mechanics and Arctic Engineering 137, 2015.
8. YUAN, Z. M., INCECIK, A., S. DAI, ALEXANDER, D., JI, C. Y. & ZHANG, X. (2015) *Hydrodynamic interactions between two ships travelling or stationary in shallow waters*. Ocean Engineering, 108**,** 620-635, 2015.
9. THOMAS, G., TURNER, T., ANDREWARTHA, T. & MORRIS, B. (2010) *Ship Motions During Replenishment at Sea Operations in Head Seas*. Trans RINA. Vol. 152, Part A4, Intl J Maritime Eng, Oct-Dec 2010.
10. YUAN, Z., JI, C., INCECIK, A., ZHAO, W., DAY, A. (2016) *Theoretical and Numerical Estimation of Ship-to-Ship Hydrodynamic*

Interaction Effects, Ocean Engineering, 121, 239-253, 2016.

11. KASHIWAGI, M., ENDO, K., YAMAGUCHI, H. (2005) *Wave Drift Forces and Moments on Two Ships Arranged Side by Side in Waves*, Ocean Engineering, 32, 529-535, 2005.
12. MATHEW, J., SGARIOTO, D., TURNER, T. & LIN, F. (2016) *Numerical Exploration of Ship Motions during Replenishment at Sea between a Supply Vessel and a Landing Helicopter Dock*. Proceedings of the Maritime/Air Systems and Technologies Europe Conference and Exhibition (MAST Europe), Amsterdam, 2016.
13. MCTAGGART, K. & TURNER, T. (2006) *Ship Motions Including Interaction Forces During Replenishment at Sea*. Pacific Internation Maritime Conference, 2006 Sydney, Australia.
14. SCHMITKE, R. T. (1978) *Ship Sway, Roll and Yaw Motions in Oblique Seas*. Transactions, Society of Naval Architects and Marine Engineers, 86**,** 26-46, 1978.
15. HIMENO, Y., *Prediction of Ship Roll Damping. A State of the Art*. The University of Michigan College of Engineering, 1981.
16. SADAT-HOSSEINI, S. H., WU, P., TODA, Y., CARRICA, P. & AND STERN, F. (2011) *URANS Studies of ship-ship interactions in shallow-water*. 2nd International Conference on Ship Manoeuvring in Shallow and Confined Water, Trondheim, Norway, 299-309, 2011.
17. MOUSAVIRAAD, S. M., SADAT-HOSSEINI, S. H., CARRICA, P. M. & STERN, F. (2016) *Ship–Ship interactions in calm water and waves. Part 2: URANS validation in replenishment and overtaking conditions*. Ocean Engineering, 111**,** 627-638, 2016.
18. LATAIRE, E., VANTORRE, M. & DELEFORTRIE, G. (2009) *Captive model testing for ship-to-ship operations*. MARSIM, 2009.
19. MCTAGGART, K., CUMMING, D., HSIUNG, C. C. & LI, L. (2003) *Seakeeping of Two Ships in Close Proximity*. Ocean Engineering, 30**,** 1051-1063, 2003.
20. ANDREWARTHA, T., THOMAS, G., TURNER, T. & LIN, F. (2007) *Replenishment at Sea: Motions of Ships Operating Side-by-Side in Head Seas*. International Journal of Maritime Engineering 149 63-72, 2007.
21. MOUSAVIRAAD, S. M., SADAT-HOSSEINI, S. H. & STERN, F. (2016) *Ship–ship interactions in calm water and waves. Part 1: Analysis of the experimental data*. Ocean Engineering, 111, 2016.
22. QUADVLIEG, F. H. H. A., HALLMANN, R., HUGHES, G. & HARRIS, D. H. (2011) *Using dynamic positioning for side-by-side cargo transfer operations*. 2nd International Conference on Ship Manoeuvring in Shallow and Confined Water, Trondheim, Norway, 2011.
23. ITTC, *Recommended Procedures and Guidelines, Ship Models*, 7.5-01-01-01, Revision 3, 2011
24. NATO STANDARDIZATION AGENCY, *ATP 16(D)/MTP 16(D) Replenishment at Sea*. 2001.
25. BHATTACHARYYA, R., Dynamics of Marine Vehicles, New York, USA, John Wiley and Sons Inc. 1978.
26. FENTON J.D., MCKEE, W.D. (1990) *On calculating the lengths of water waves*, Coastal Engineering, 14 (1990), pp. 499-513, 1990.
27. FALTINSEN, O. M. (2005) *Hydrodynamics of High-Speed Marine Vehicles*. Cambridge University Press.
28. CARETTE, N. (2016) *Physical testing of RHIB and mother ship interactions for launch and recovery simulation validation*. Proceedings of Launch and Recovery Symposium, 2016 Linthicum Heights, MD, USA.