SHIP MOTIONS DURING REPLENISHMENT AT SEA OPERATIONS IN HEAD SEAS

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(DOI No: 10.3940/rina.2010.a4.194)

SUMMARY

During replenishment at sea operations the interaction between the two vessels travelling side by side can cause significant motions in the smaller vessel and affect the relative separation between their replenishment points. A study into these motions has been conducted including theoretical predictions and model experiments. The model tests investigated the influence of supply ship displacement and longitudinal separation on the ships' motions. The data obtained from the experimental study has been used to validate a theoretical ship motion prediction method based on a 3-D zero-speed Green function with a forward speed correction in the frequency domain. The results were also used to estimate the expected extreme roll angle of the receiving vessel, and the relative motion between the vessels, during replenishment at sea operations in a typical irregular seaway. A significant increase in the frigate's roll response was found to occur with an increase of the supply ship displacement, whilst a reduction in motion for the receiving vessel resulted from an increase in longitudinal separation between the vessels. It is proposed that to determine the optimal vessel separation it is vital that the motions of the vessels are not considered in isolation and all motions need to be considered for both vessels simultaneously.

NOMENCLATURE

$[A]$	Ship added mass matrix
$[B]$	Ship damping matrix
CL	Centreline
CoG	Centre of gravity
$[C]$	Ship hydrostatic stiffness matrix
$\{F\}$	Wave exciting force vector
GM	Metacentric height (m)
k	Wave number (m^{-1})
LBP	Ship length between perpendiculars (m)
LCG	Longitudinal centre of gravity (m)
MS	Midships
$[m]$	Ship inertial matrix
RM'	Non-dimensional distance between RAS points
VCG	Vertical location of the CoG (m)
x_g	Longitudinal location of the CoG (m)
x_p	Longitudinal location of the RAS point (m)
y_g	Transverse location of the CoG (m)
y_p	Transverse location of the RAS point (m)
z_g	Vertical location of the CoG (m)
z_p	Vertical location of the RAS point (m)
Δx	Point motion in the x direction (m)
$\Delta x'$	Non-dimensional point motion in the x direction
Δy	Point motion in the y direction (m)
$\Delta y'$	Non-dimensional point motion in the y direction
Δz	Point motion in the z direction (m)
$\Delta z'$	Non-dimensional point motion in the z direction
η_k	Displacement in k direction where k = 1-6 (m)
$\{\ddot{\eta}\}$	Ship acceleration vector
$\{\dot{\eta}\}$	Ship velocity vector
$\{\eta\}$	Ship displacement vector
ω	Wave frequency (rad/sec)
ζ	Wave amplitude (m)

1. INTRODUCTION

Replenishment at sea (RAS) is a critical exercise which allows a naval vessel to remain at sea for extended periods of time and thus provide an ongoing presence, and an immediate response if required, to a developing situation.

In a typical RAS operation, see Figure 1, a naval ship travels side-by-side with a supply ship maintaining constant speed and lateral separation. Hoses and span-wires are then used to transfer fuel, ammunition, supplies, and personnel between the ships.

Figure 1: Replenishment at sea operation between HMAS SIRIUS and HMAS Toowoomba (photograph courtesy RAN)

During a RAS operation, as the ships travel in close proximity, the presence of the larger vessel can greatly influence the motions of the smaller. This interaction will usually affect the relative separation between the replenishment points on the vessels and hence the tension

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in the cable connection. If the relative motions of the ships become too large the hose may dislodge or the cable break, a serious safety issue.

Traditionally Commanding Officers (COs) have relied on their own knowledge and experience to determine the suitability of conditions to undertake RAS. Operator guidance is therefore required for use by COs of the ships in the selection of suitable conditions for replenishment operations. Several key factors may influence the overall successful outcome of this type of operation; these include vessel loading condition, wave height and period, ships heading and speed as well as the longitudinal and lateral separation of the vessels.

The hydrodynamic response of two bodies in close proximity is a complex hydrodynamic interaction problem; so it is not surprising that only limited research has been conducted into this field. Much of the work has focussed on the interactions between two moored vessels, a situation often found in the offshore oil and gas industry. Many of the developments in this field are extensions of the seminal work of Ohkusu [1, 2, 3]. Ohkusu [1] commenced by developing a method, based on Ursell's [4] classical solution for a single heaving cyclinder, to the case of two cylinders in a catamaran configuration. Using a combination of the multipole method and strip theory, Ohkusu [3] calculated the response of ship-like bodies at zero speed in beam seas. Kodan [5] subsequently extended Ohkusu's method to study the motions of two bodies in close proximity in oblique seas. Similarly Buchner et al. [6] extended the numerical model of van Oortmerssen [7] for the time domain simulation of a side-by-side offloading operation and compared the results favourably with model experiments.

Fang and Kim [8], Fang [9] and Chen and Fang [10, 11, 12] extended the work of Kodan [5] by developing a three-dimensional panel method including forward speed and hydrodynamic interaction effects. Three-dimensional panel codes were also developed independently by McTaggart et al. [13] and Wang et al. [14]. Due to the complexity of the set-up there has been very limited experimental testing to obtain data to validate theoretical predictions. Kodan [5] conducted model tests at zero forward speed only; whilst McTaggart et al. [13] conducted semi-captive model tests with the two models constrained in surge, sway and yaw for forward speeds of up to 12 knots in head seas.

The Defence Science & Technology Organisation (DSTO) and the Australian Maritime College (AMC) have established a collaborative research program to study the hydrodynamic interactions between vessels whilst travelling in close proximity. Andrewartha et al. [15] conducted a series of simulated RAS model tests using an S-175 container ship and frigate to investigate a series of parameters, including transverse and longitudinal separation, on the ships' motions. The experimental data was used to validate a theoretical ship motion prediction method, using a 3-D zero-speed Green function with a forward speed correction in the frequency domain [16].

One perceived shortcoming of the work of Andrewartha et al. [15] was the use of a containership model, a vessel type not used for RAS supply operations by the Royal Australian Navy (RAN). This has been rectified in the current work, where a model of a typical replenishment tanker, as utilised by the RAN, is tested in simulated RAS operations with a representative frigate. Full scale RAS manoeuvres conducted by the RAN have drawn attention to the possibility of a significant influence of the displacement of the supply vessel on the motions of the receiving ship. This work therefore extends the previous study by testing the supply vessel in two realistic loading configurations.

This paper reports on both numerical and experimental analyses. Model tests were conducted where the motions of both vessels were recorded and the influence of various parameters, including longitudinal separation and supply ship displacement, on the ships' motions studied. These motions were then used to estimate extreme roll motion of the frigate and the relative motions between the ships in a series of realistic operating conditions. The data obtained from the experimental study has also been used to further validate a theoretical prediction method. Once fully validated the three-dimensional panel method seakeeping code can be used as part of the development of operator guidance tools for vessels operating in close proximity to each other.

2. THEORETICAL PREDICTIONS

The theoretical predictions were made using a potential flow, three-dimensional panel method seakeeping code, *FD-Waveload* [16]. It is based on the zero-speed Green function with a forward speed correction (a modification of the hull boundary condition only) in the frequency domain. The motions of a single vessel in waves are governed by the equation of motion given in Equation 1 [17]:

$$[m+A]\{\ddot{\eta}\}+[B]\{\dot{\eta}\}+[C]\{\eta\}=\{F\} \tag{1}$$

where $[m]$ is the ship inertial matrix, $[A]$ is the added mass matrix, $[B]$ is the damping matrix, $[C]$ are hydrostatic stiffness terms and $\{F\}$ is the wave exciting force vector which includes terms due to both incident and diffracted waves, $\{\ddot{\eta}\}$ is the acceleration vector, $\{\dot{\eta}\}$ is the velocity vector and $\{\eta\}$ is the displacement vector. The damping matrix includes terms due to wave radiation, lift forces, and viscous forces; the viscous roll damping consists of contributions from bilge keels, eddy-making resistance of the hull, hull friction and the viscous effect of other appendages.

Equation 1 is solved, for six degrees of freedom using six simultaneous equations, by first estimating the roll amplitude in order to evaluate the nonlinear roll damping forces. Therefore a final solution is obtained after iterating until, for a given set of conditions, the roll amplitude converges.

Twelve coupled equations of motions are solved to determine the motions of two ships in waves, for the full 6 degrees of freedom of each ship. This ensures that the presence of both ships simultaneously within the wave field is represented.

The matrices and vectors are divided into terms dependent on ship *a* and ship *b*, with corresponding superscripts added to terms. For example, the added mass and damping sub-matrices $[A^{ab}]$ and $[B^{ab}]$ represent the forces on ship *a* due to the motions of ship b. The hydrodynamic components *A*, *B* and *F* are then computed by solving a model consisting of two ships with 12 radiation modes.

Reproducing the approach used for single vessel motions, the nonlinear roll damping forces for two ships are evaluated by solving Equation 2 iteratively until the roll motion amplitudes for both ships converge.

$$\begin{bmatrix} m^a + A^{aa} & A^{ab} \\ A^{ba} & m^b + A^{bb} \end{bmatrix} \begin{Bmatrix} \ddot{\eta}^a \\ \ddot{\eta}^b \end{Bmatrix} + \begin{bmatrix} B^{aa} & B^{ab} \\ B^{ba} & B^{bb} \end{bmatrix} \begin{Bmatrix} \dot{\eta}^a \\ \dot{\eta}^b \end{Bmatrix} + \begin{bmatrix} C^a & 0 \\ 0 & C^a \end{bmatrix} \begin{Bmatrix} \eta^a \\ \eta^b \end{Bmatrix} = \begin{Bmatrix} F^a \\ F^b \end{Bmatrix} \quad (2)$$

3. EXPERIMENTAL PROGRAM

The model tests had two main aims. Firstly, to measure the motions of two realistic vessels operating side-by-side and investigate the influence of various parameters, including wave period, longitudinal separation and supply ship displacement. Secondly to obtain data to further validate the three-dimensional panel method seakeeping theory.

3.1 MODEL DETAILS

The 1:70 scale ship models selected for the experimental programme were a frigate and a supply tanker typically used by the RAN. The supply tanker was tested at two displacements: minimum operating (MO) and full load (FL). Both the model and full scale particulars of the ships are shown in Table 1. The frigate model was fitted with bilge keels which were 205 mm in length and 17 mm in depth.

3.2 EXPERIMENTAL SET UP

The experiments were conducted in the AMC's towing tank. This facility is part of the Australian Maritime Hydrodynamics Research Centre (AMHRC) which is a collaborative research organisation established by the AMC, DSTO and the University of Tasmania. The towing tank is 100 m in length, 3.6 m wide with a water depth of up to 1.6 m. Waves are generated by a hydraulically operated wet backed, single flap paddle. A wide variety of wave forms can be generated by the paddle including regular and irregular wave systems.

Both models were towed using a two post system, utilising a ball joint forward, and a ball joint and slide aft. The ball joints were located on the roll axis of the model. This system allowed the models to move freely in heave, pitch and roll whilst being constrained in surge, sway and yaw. The heave, pitch and roll motions of the vessels were measured using a total of eight linear voltage displacement transducers (LVDTs). Four LVDTs were fitted to each model: fore and aft LVDTs were attached to the fore and aft posts, while the port and starboard transducers were attached via a string and pulley system to the model topsides.

Table 1: Ship and Model Particulars

	Frigate		**Tanker (MO)**		**Tanker (FL)**	
	Model	**Full Scale**	**Model**	**Full Scale**	**Model**	**Full Scale**
LBP (m)	1.578	108.9	2.455	171.9	2.455	171.9
Beam (m)	0.198	13.7	0.44	30.8	0.44	30.8
Draft (m)	0.064	4.45	0.111	7.8	0.145	10.15
Roll Gyradius (m)	0.074	5.17	0.167	11.7	0.167	11.7
Pitch Gyradius (m)	0.364	25.5	0.631	44.2	0.631	44.2
Yaw Gyradius (m)	0.364	25.5	0.631	44.2	0.631	44.2
LCG (m) from MS	-0.048	-3.345	0.086	6.013	0.072	5.025
TCG (m)	0	0	0	0	0	0
VCG (m)	0.086	6	0.113	7.9	0.125	8.8
C_B	0.481	0.481	0.704	0.704	0.724	0.724
Δ	10.324 kg	3630 t	92.9 kg	32661 t	112.56 kg	39574 t

A stationary wave probe was positioned near the wave maker to measure the water surface profile and hence determine the incident wave elevations and frequencies. Data logging was conducted at 100 Hz for each run period of approximately 15 seconds.

A visual record of the experiments was achieved using both still and video photography. A photograph of a test run is shown in Figure 2.

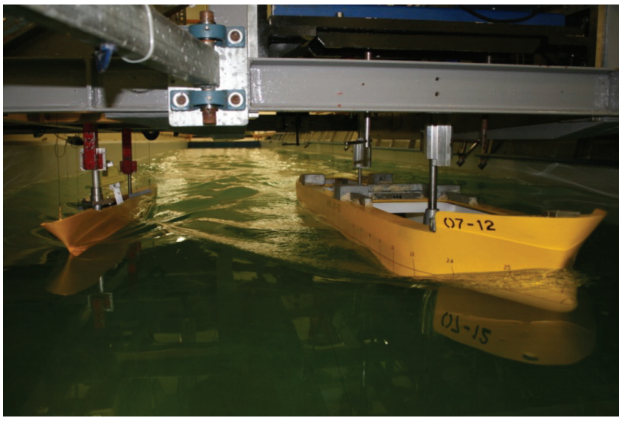

Figure 2: Models during RAS test in the towing tank

3.3 TEST CONFIGURATIONS

The operational profile of the supply tanker will clearly involve significant changes to its displacement due to the transfer of fuel. Whilst the supply tanker was designed to operate for the majority of its time at a specific full-load draft, replenishment ships will often be required to operate at other than optimal displacements. In light of this, the supply tanker was tested at two drafts to represent full load, and minimum operating to maximise the difference in displacement and the associated influence on vessel motions. The conditions tested are summarised in Table 2 and Figure 3. All tests were conducted at a speed of 0.87 m/s, equivalent to 14 knots full scale. The wave height was set at 30 mm model scale for all conditions tested, equivalent to 2.1 m full scale. A transverse separation between the centrelines of the vessel of 72.52 m was used in the study, this is a typical separation for RAS operations. For this experimental program two longitudinal separations were studied. The "short" separation was 11.13 m full scale between the vessels' midships, whilst the "long" separation was 45.78 m. These distances, with the frigate aft of the supply vessel, equate to 0.159 and 0.654 m respectively in model scale.

The range of wave frequencies over which the tests were conducted there were no interference effects from the tow tank wall was calculated [18]. Due to the change in separation between the models this frequency range varied with the conditions.

4. RESULTS & DISCUSSION

The results from the towing tank experiments were converted into response amplitude operators (RAOs) with the translational motion of heave being non-dimensionalised by wave height, while angular motions of pitch and roll were non-dimensionalised using wave slope, as follows:

non-dimensional heave: $$\eta_3' = \frac{|\eta_3|}{\zeta} \qquad (3)$$

non-dimensional roll: $$\eta_4' = \frac{|\eta_4|}{k\zeta} \qquad (4)$$

non-dimensional pitch: $$\eta_5' = \frac{|\eta_5|}{k\zeta} \qquad (5)$$

where k is the wave number and ζ is the wave amplitude.

For certain frequencies three repeat runs were completed to assess experimental uncertainty. Repeatability was found to be very good; for example for the frigate motions the repeat runs were mostly within 0.5% of the average value.

In Figure 4 the experimental model results are compared to the numerical predictions for Condition 1. The experimental RAOs for the supply tanker are of a typical form for head seas RAOs, while when considering the motions of the frigate it is apparent that the vessel is behaving very differently to the way it would in isolation. For comparison, the motion RAOs for the frigate operating alone in head seas may be found in Andrewartha et al. [15]. Of most significance is the presence of considerable roll motion for the frigate, with the roll RAO having a resonant peak of approximately 7.5. This suggests that the interactions have a significant impact on the rolling motions of the smaller vessel. An important feature to note is the coincidence of the heave resonant peak of the supply tanker with the roll resonant peak of the frigate. This suggests that the heave motion of the larger vessel is a major influence on the establishment of roll motions in the smaller vessel.

It is interesting to note the increase in magnitude of the roll motion of the frigate when the supply vessel is the tanker, compared to the S-175 [15]; even though the transverse separation is increased for these tests. Although the tanker and S-175 have similar motions, the increased size and displacement of the tanker means that larger radiated waves will be produced through its heave motion, which will promote increased rolling of the smaller vessel.

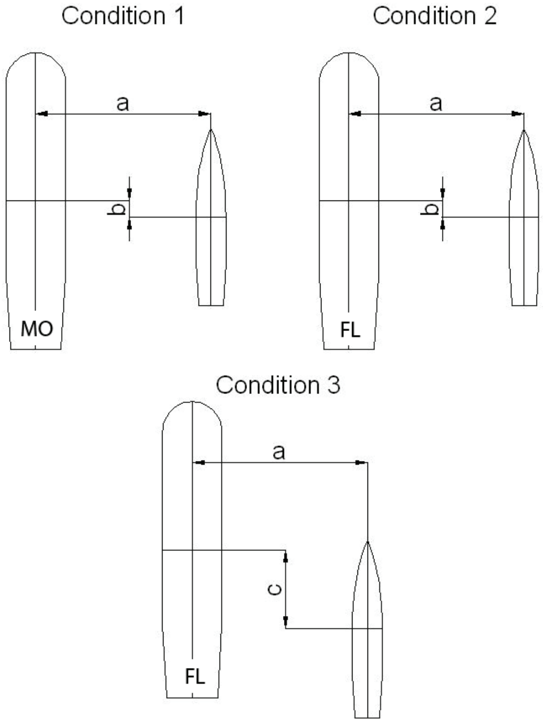

Figure 3: Test configurations including tanker loading
(full scale)
a = 72.52 m, b = 11.13 m, c = 45.78 m
(model scale)
a = 1.036 m, b = 0.159 m, c = 0.654 m

Comparing the experimental results with the predictions it appears that the theory may be over predicting the viscous roll damping of the frigate resulting in a reduced roll magnitude, although the resonant frequencies correlate reasonably well. The under-prediction may alternatively stem from inaccuracies in the prediction of the diffracted and radiated wave patterns and hence the interaction effects. The theoretical heave and pitch RAOs for the frigate correlate relatively well with their respective experimental results. However there are some fluctuations predicted which were not apparent in the experiments; there also appears to be a small shift in both the heave and pitch resonant frequencies.

The correlation for the supply tanker heave and pitch motions is excellent apart from at the lowest frequencies. The peak magnitudes and frequencies line up well with very little deviation between the theoretical and experimental results across the frequency range examined. The roll motions of the tanker are not well predicted. Numerically a relatively large peak is apparent at a wave frequency of approximately 0.45 rad/s which is not visible in the experimental data. Clearly the theory is predicting that the interaction between the vessels will cause the tanker to roll, but this does not occur in reality with the interaction effects on the tanker being minimal.

With an increase in the displacement of the supply tanker, the results for Condition 2 (see Figure 5) are similar to those for the lighter displacement, although with notable exceptions. The experimental heave and pitch motions of the frigate are similar to those with the lighter tanker displacement, but the roll motion of the frigate has increased significantly from a resonant peak of 7.5 to one of over 9.0. This clearly demonstrates that the operating displacement of the supply vessel can have a significant influence on the motions of the smaller receiving vessel.

The numerical predictions again correlate well with the experimental results for the supply tanker heave and pitch motions. Interestingly the theory has predicted a significant reduction in roll motion of the tanker with the increase in displacement; again the actual roll motions of the tanker are insignificant.

The numerical heave and pitch frigate RAOs match relatively well with the experiments, but once again there are significant oscillations in the predictions at frequencies greater than the resonant peak. The magnitude and frequency of the resonant peaks are predicted quite well. The frigate's roll motions are again under predicted; this may stem from over estimation of the viscous roll damping, or inaccuracies in the predicted radiated and diffracted waves emanating from the supply vessel.

A summary of the theory's performance in predicting the motion RAOs as determined through the experiments is shown in Table 2.

The numerical method can remove the effects of irregular frequencies by adding an 'inner free surface' panel layer on the waterplane of the vessels similar to the treatment proposed by Lee and Sclavounos [19]. The calculations presented in the paper used this technique; however the effect of not removing the irregular frequencies was found to be insignificant.

Another possible explanation for these oscillations could be the simulation of resonant waves trapped between the two vessels whilst they are in close proximity. Since the velocity potential theory cannot directly simulate any effects of viscosity and wave breaking, it predicts an exaggerated trapped wave and obtains an over estimated RAO at these frequencies. One of the possible options to decrease these trapped wave effects would be to add an artificial damping patch on the free surface between the two ships.

The effect of supply ship displacement is more clearly shown in Figure 6 which contains experimental heave, pitch and roll RAOs for both the supply tanker and the frigate for Condition 1 (tanker operating at minimum operating (MO) condition) and Condition 2 (tanker operating at full load (FL) condition).

Heave is the only motion mode of the supply tanker which is significantly affected by the increase in

Table 2: Summary of Theory's Performance to Predict Motion RAOs

	Condition	**Heave**	**Roll**	**Pitch**
Supply Tanker	1	Good	Overpredicted by 300%	Good
	2	Good	Overpredicted by 200%	Good
	3	Good	Good	Good
Frigate	1	Satisfactory*	Underpredicted by 50%	Satisfactory*
	2	Satisfactory*	Underpredicted by 50%	Satisfactory*
	3	Satisfactory*	Underpredicted by 40%	Satisfactory*

* denotes that the RAO numerical results exhibited additional oscillations not present in experimental results

displacement. With a heavier displacement the vessel experienced larger heave motions around the resonant frequency, while either side of this the motions were largely unchanged. The roll magnitude is very small, thus little can be deduced from these results. Comparing the two pitch RAOs no notable change in motion is apparent for an increase in displacement.

The effect of a change in displacement is visible in the motions of the frigate. There is a small increase in the heave primary peak magnitude with an increase in the displacement of the tanker; but no discernable increase in the frigate pitch motion. As mentioned above there is a significant increase in the frigate's roll RAO with an increase of the supply ship displacement. This again suggests that the heave motion of the tanker is the key factor influencing the roll motion of the frigate, especially with the coincidence of the tanker heave resonant peak with the roll resonant peak of the frigate.

For Condition 3 the longitudinal separation between the vessels was increased, see Figure 7. As expected, the motions of the tanker changed little from the smaller longitudinal separation condition (Condition 2). In contrast the motions of the frigate have changed appreciably: the frigate heave RAO has reduced from a resonant peak of 1.4 to 1.2; the roll RAO peak has reduced from a resonant peak of 9 to 8; whilst the pitch motion has remained fairly constant. This reduction in motion for the receiving vessel with an increase in longitudinal separation concurs with the results presented in Andrewartha et al. [15]. The reduction in motions is probably due to the offset position of the frigate, so that the influence of the radiated waves from the supply tanker reduced.

The correlation between the experimental results and predictions for supply tanker in Condition 3 is excellent for all three motions. It is interesting to note that the roll magnitude is relatively small, though the correlation is good; this suggests that for the other conditions tested the theory is indeed predicting the effect of interference between the vessels on the tanker roll which is not observed experimentally.

The frigate motions are generally poorly predicted. The heave response is significantly over predicted and the double peak nature of the RAO is not clearly defined by the theory. The theory also predicts an increase in heave motions whereas the experimental results show a decrease. The frigate roll motions are again under predicted quite significantly with a resonant magnitude of only 3.3, compared to an experimental peak of approximately 8.0. The theory predicted the frigate pitch resonant peak magnitude quite well, but at a lower frequency than the experiments.

Whilst the magnitude of the motions of each vessel during a RAS operation is important, of greater consequence is the relative motion between the two vessels. The relative motion between the replenishment points on the vessels, and hence the tension in the cable connection, will be critical for a successful operation. Therefore the relative motion between the two vessels, which accounts for their heave, pitch and roll motions, was investigated for the various operating conditions.

The motions at the replenishment point in the *x, y* and *z* directions can be expressed using the following set of three equations:

$$\begin{aligned} \Delta x &= \eta_1 + (z_p - z_g)\eta_5 - (y_p - y_g)\eta_6 \\ \Delta y &= \eta_2 + (x_p - x_g)\eta_6 - (z_p - z_g)\eta_4 \\ \Delta z &= \eta_3 + (y_p - y_g)\eta_4 - (x_p - x_g)\eta_5 \end{aligned} \qquad (6)$$

where η_k is the displacement in the k direction for $k = 1$ to 6. The location of the replenishment point in each of the directions *x, y* and *z* is denoted by the subscript *p* whilst the subscript *g* denotes the vessel's centre of gravity in the specified direction. Thus, for example, $x_p - x_g$ represents the distance from the vessel's centre of gravity to the replenishment point in the x direction. For this study, surge, sway and yaw are neglected and hence these terms are reduced to give the following equation set which are non-dimensionalised with respect to the wave amplitude, ζ.

$$\begin{aligned}\Delta x' &= \frac{1}{\zeta}(z_p - z_g)\eta_5 \\ \Delta y' &= -\frac{1}{\zeta}(z_p - z_g)\eta_4 \\ \Delta z' &= \frac{1}{\zeta}\left[\eta_3 + (y_p - y_g)\eta_4 - (x_p - x_g)\eta_5\right]\end{aligned} \tag{7}$$

Using equation (8), the non-dimensional relative variations in separation were determined for conditions 1, 2 and 3, where the subscripts F and T represent the frigate and tanker respectively. In this equation, the three terms consider the instantaneous location of the RAS point on each vessel relative to the other. The RM' was then determined over a given time-step. This method ensures that the phase relationship between the different vessel motions is considered.

$$RM' = \sqrt{(\Delta x'_F - \Delta x'_T)^2 + (\Delta y'_F - \Delta y'_T)^2 + (\Delta z'_F - \Delta z'_T)^2} \tag{8}$$

The RAS point locations used for the change in relative separation analysis are given in Table 3, relative to vessel midships, centreline and keel. The frigate aft RAS point was used for Conditions 1 and 2 while Condition 3 used the frigate forward RAS point.

Table 3: Location of RAS Points

	Frigate		**Tanker**
	Aft	**Forward**	
x (m) from MS	-6.45	28.20	-17.58
y (m) from CL	6.85	6.85	15.5
z (m) from keel	10.77	10.77	10.77

The relative motion RAOs are shown in Figure 8 to Figure 10. The experimental results show a small increase in relative motion due to an increase in supply tanker displacement. Pitch clearly has more effect in Condition 3 compared to Conditions 1 and 2, given the use of the forward RAS point. This is demonstrated by the significant increase in relative motion with an increase in longitudinal separation. By using this forward RAS point, the distance between the CoG and the point used to calculate the relative motion is quite large; therefore pitch motion will result in a relatively large vertical displacement at the RAS.

Overall these plots show a relatively poor correlation between predictions and experiments; with the numerical results under predicting the relative motions by approximately 50%. The lower magnitude may be attributable to the under prediction of the frigate's roll, the dominant vessel motion. The predictions appear to exhibit very similar resonant frequencies to those found experimentally; though several additional peaks are apparent at higher frequencies. These peaks in the data are probably due to the large oscillations in the frigate heave and pitch RAOs.

To date no full scale data for vessel motions during RAS operations have been obtained, mainly since its acquisition would require a major effort to overcome a variety of technical and logistical issues. However in the future it may provide additional data for validation purposes.

Classification Society rules, for example [20], governing RAS operations state that only the dynamic behaviour of the supplying ship needs to be considered when designing RAS systems. It is clear from this work, and a previous study [15] that the motions of the receiving ship should also be accounted for during the design process.

5. VESSEL RESPONSES IN IRREGULAR SEAS

To ascertain the effect of longitudinal separation on the responses of the vessels in a realistic seaway, wave spectra were applied to both the numerically and experimentally derived RAOs. Four different sea states were modelled using the two-parameter Bretschneider (ITTC) spectrum in accordance with the DEF (AUST) 5000 Materiel Requirement Set [21] for seakeeping to represent the mean of sea states 3, 4, 5 and 6 (Table 4). The significant wave height and period combinations of these spectra are based on the typical conditions in the waters around Australia, so that these sea states represent the range of typical sea conditions experienced during RAS operations.

Table 4: Sea State Parameters [21]

Sea State	**Significant Wave Height** (m)	**Modal Period** (sec)
3	0.875	8.9
4	1.875	10.3
5	3.25	11.7
6	5.00	12.8

The motions of the vessels in irregular seas were examined in terms of the extreme displacement with 1 percent exceedence probability in 3 hours [22] with the tanker in full load condition. A time period of 3 hours was chosen since this is a typical duration of a RAS operation.

The expected extreme roll angles for the frigate, with respect to the vessel separation, are shown in Figure 11. The reduction in roll angle with increasing longitudinal separation can be clearly seen. For example in sea state 6, at a separation of 11.13m the extreme roll of the frigate was 30.27 degrees, reducing to 23.1 degrees at a separation of 45.78m, equating to a reduction of 23.7%. The numerical predictions, whilst significantly smaller in magnitude, produced a reduction of 25.7%, a very similar value to the experiments.

Increasing the longitudinal separation tended to increase the extreme relative separation between the vessels, as shown in Figure 12. This is probably due to the RAS location point being used on the frigate; for the larger separation the forward RAS point was used, while the smaller separation used the midship RAS point. The pitch motions will have a much greater effect on the change in relative motions when the forward point is used, due to its distance from the LCG. Thus, while the extreme roll angle is shown to decrease as the frigate is moves aft, the extreme change in relative motion does not necessarily follow the same trend. The theoretical predictions only predict a small increase in relative motion with an increase in longitudinal separation and the overall relative motions are significantly under predicted.

Overall, the experimental and numerical results show that significant reductions in the extreme roll are likely to occur with an increase in longitudinal separation. Increasing transverse separation has previously been found to reduce the change in relative motion [15]. However increasing longitudinal separation tends to increase the relative motion, since the forward RAS point on the frigate must be used. This means that the resulting reduction in roll by moving the frigate aft is offset by the increased effect of pitch, therefore producing a resultant increase in relative motion.

It is therefore apparent that to determine the optimal vessel separation it is vital that the motions of the vessels are not considered in isolation. To study the appropriateness of a RAS configuration all three main motions (heave, pitch and roll) need to be considered for both vessels simultaneously. These comparisons have been conducted using a statistical approach in which a sea spectrum is applied to the vessel RAOs. It may be beneficial to conduct further experiments in irregular seas. This may highlight any issues with the interaction of vessel wakes with irregular incident waves. The pseudo-random encounter frequencies experienced by vessels in irregular seas may result in large magnitude waves forming due to superposition with the interacted wave forms. This may impact on the vessel motions, and is not accounted for by simply applying spectra to the RAOs. In addition the linearity of the vessel motions during RAS operations should be studied by performing model experiments in a range of wave heights.

In the current investigation only the magnitude of the change in relative motion was investigated. While this characteristic will impact on the physical RAS set up in terms of the length of the span wire, the velocity and acceleration of this parameter will possibly have greater implications as these characteristics will impact on the performance of both the RAS rig and the safety of the operators.

6. CONCLUSIONS

The motions of two vessels travelling side by side into head seas, a common operating condition for naval vessels when undertaking RAS activities, have been studied. Model tests were conducted using a supply tanker and a generic frigate model travelling in close proximity. The following conclusions, for the vessels and conditions tested, may be drawn from the experimental study:

- The smaller vessel was found to experience significant roll motion when travelling side by side with the larger supply vessel, with the roll RAO having a resonant peak of approximately 7.5.
- Since the heave resonant peak of the supply vessel coincides with the roll resonant peak of the frigate, the heave motion of the larger vessel will significantly influence the roll motions of the smaller vessel.
- With an increase in displacement of the supply vessel (minimum operating to full load) the roll motion of the frigate increased significantly. The heavier displacement supply vessel experienced larger heave motions around the resonant frequency, although the other motions were not affected.
- When the longitudinal separation between the vessels was increased the motions of the supply vessel changed little from the smaller longitudinal separation condition. In contrast the heave and roll motions of the frigate reduced appreciably. The reduction in motions is probably due to the offset position of the frigate, so that the influence of the radiated waves from the larger vessel is reduced.
- When the motions of the vessels in irregular seas were examined in terms of the extreme value that would not be expected to be exceeded in a 3 hour period with a confidence of 99 percent; in sea state 6, at a longitudinal separation of 11.13m the extreme roll of the frigate was 30.27 degrees, reducing to 23.1 degrees at a separation of 45.78m, equating to a reduction of 23.7%.

The following conclusions may be drawn through comparing the theoretical predictions from a 3-D zero-speed Green function, with a forward speed correction in the frequency domain, with the experimental results:

- The theory under predicts the roll motion of the frigate whilst the theoretical heave and pitch RAOs for the frigate correlate relatively well with their respective experimental results.
- The correlation for the supply vessel heave and pitch motions is excellent. The peak magnitudes and frequencies line up well with very little deviation between the theoretical and experimental results across the frequency range examined. However the roll motions of supply vessel are not well predicted.
- When the motions of the vessels in irregular seas were examined in terms of the extreme value with 1 percent exceedence probability in 3 hours; the theory under-predicted both the extreme roll motion of the frigate and the relative motion between the RAS points.

This work shows that to determine the optimal RAS operational scenario, including vessel separation, it is vital that the motions of the individual vessels are not considered in isolation, rather all motions need to be considered for both vessels simultaneously. Further work is required to improve the accuracy of the theoretical predictions.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge the work of James Caspar in the conduct of the towing tank experiments. Dr Stuart Cannon, Defence Science and Technology Organisation, is also acknowledged for his support of this project.

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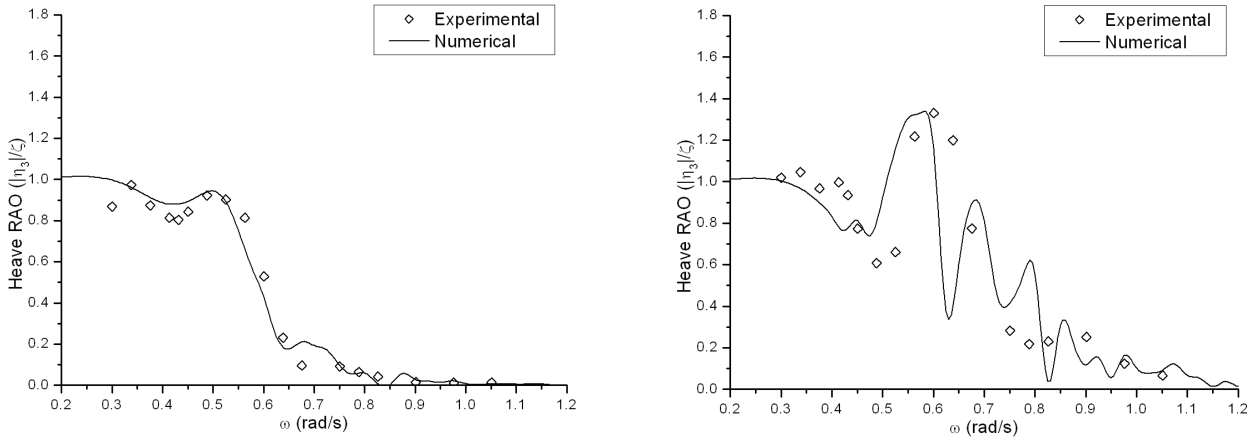
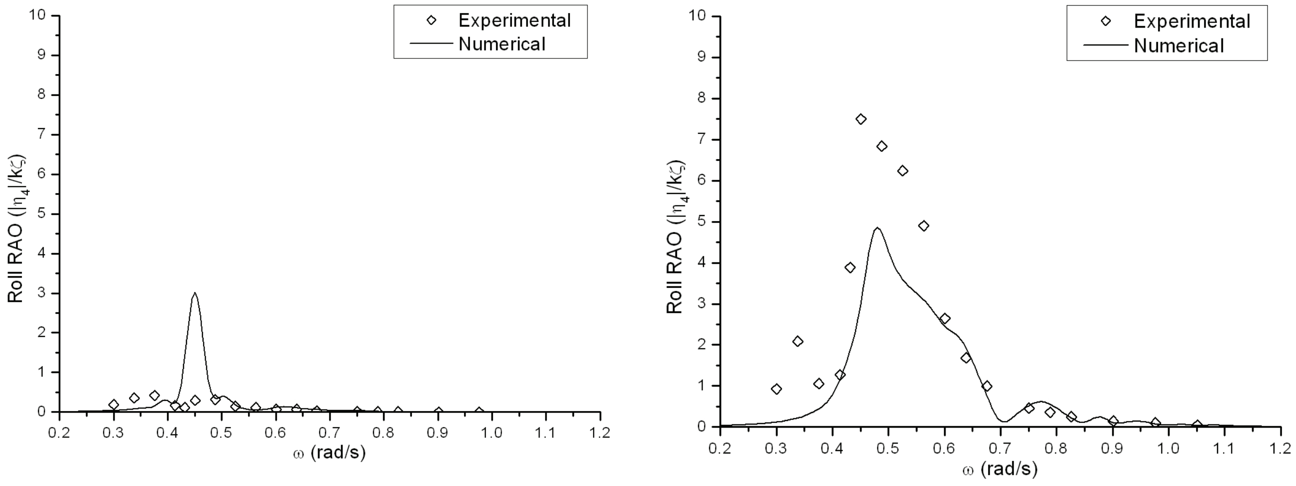


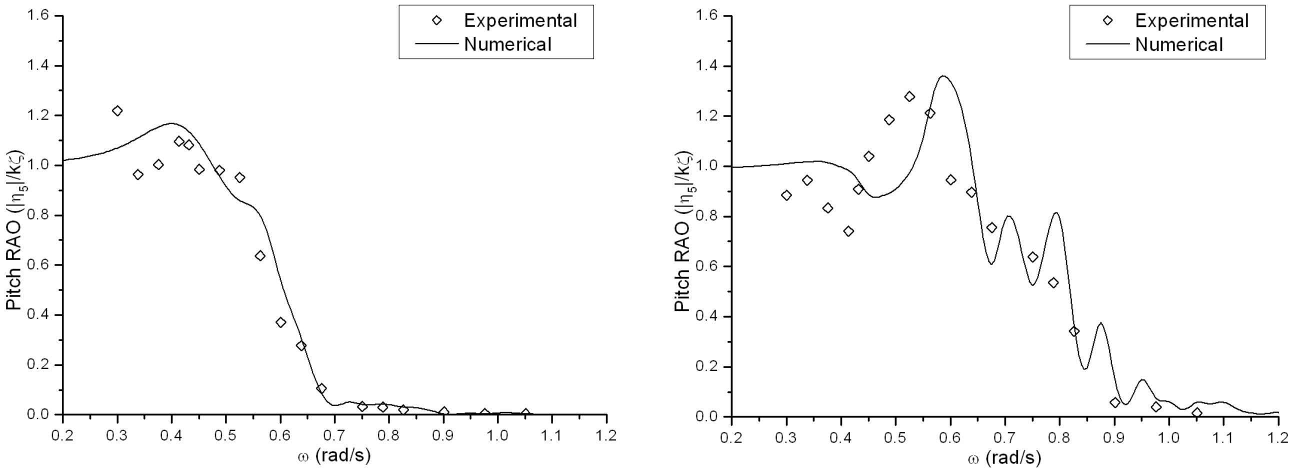
a) Supply Tanker Heave RAO

d) Frigate Heave RAO



b) Supply Tanker Roll RAO

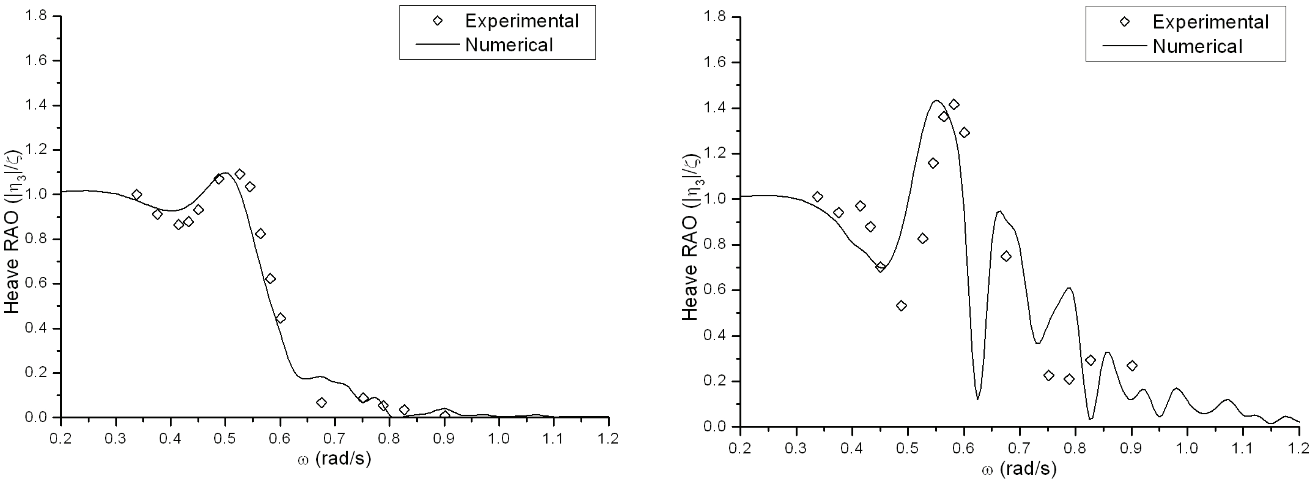
e) Frigate Roll RAO



c) Supply Tanker Pitch RAO

f) Frigate Pitch RAO

Figure 4: Numerical and experimental Supply Tanker and Frigate heave, pitch and roll RAOs (Condition 1)



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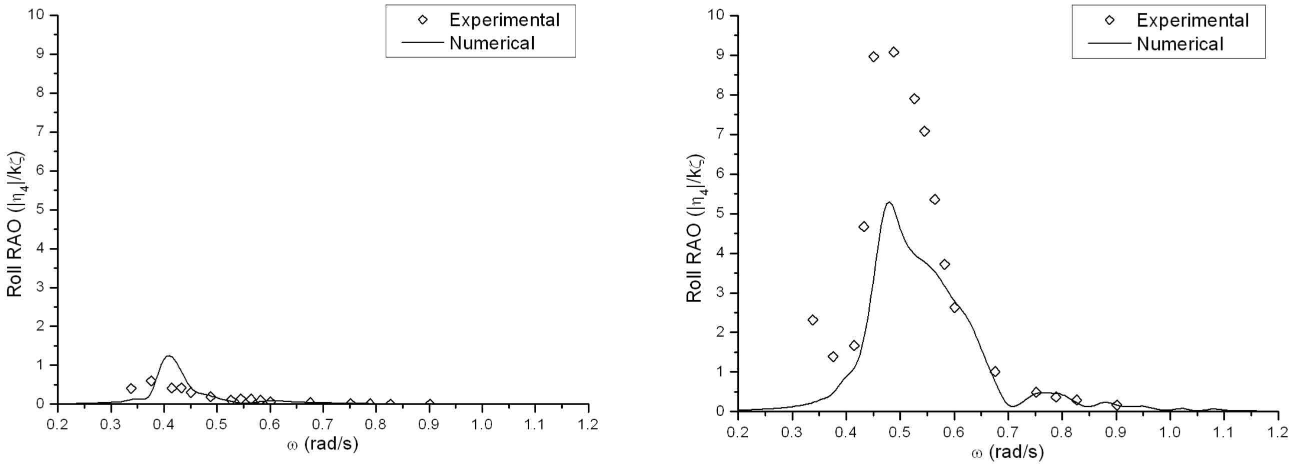
d) Frigate Heave RAO



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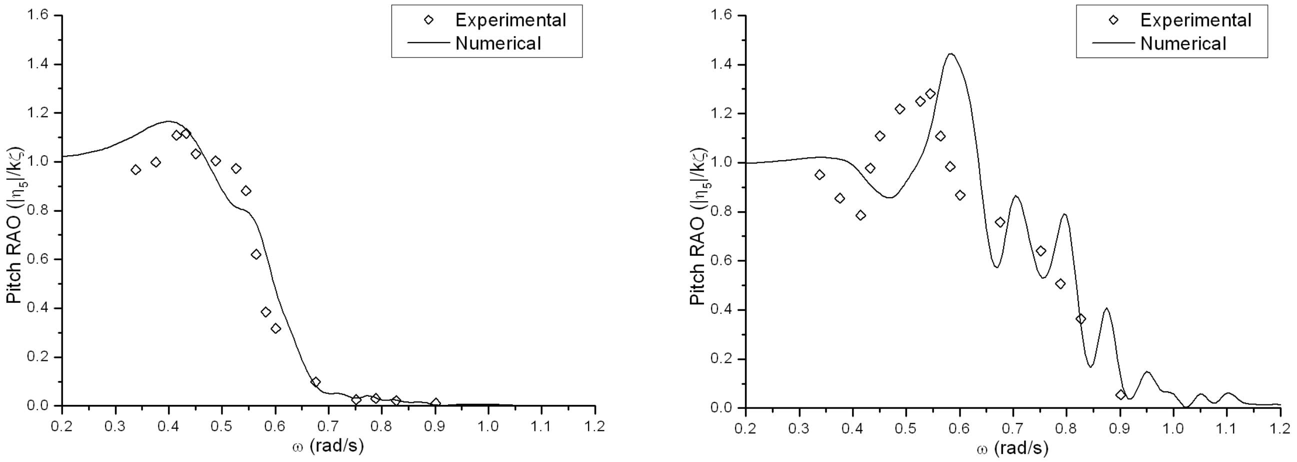
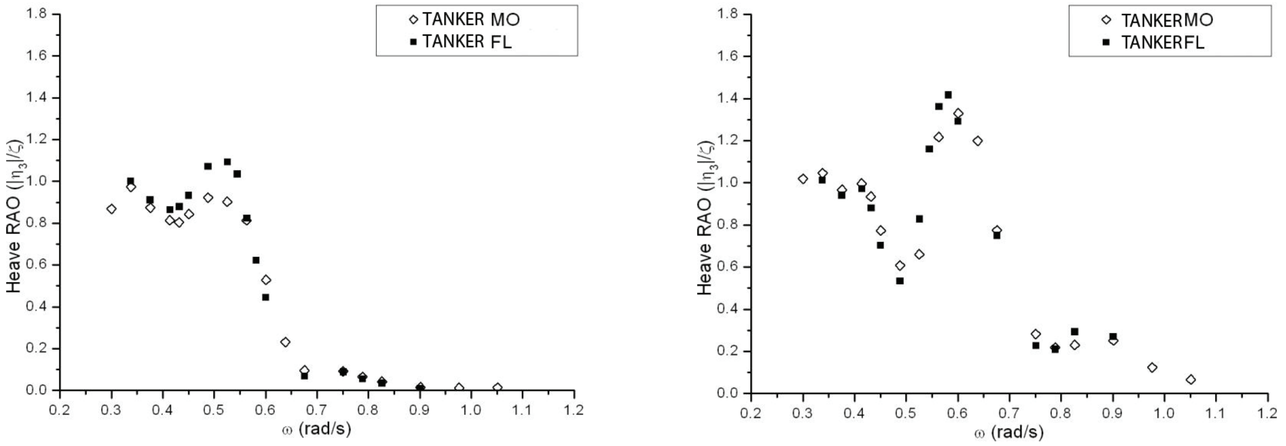
e) Frigate Roll RAO



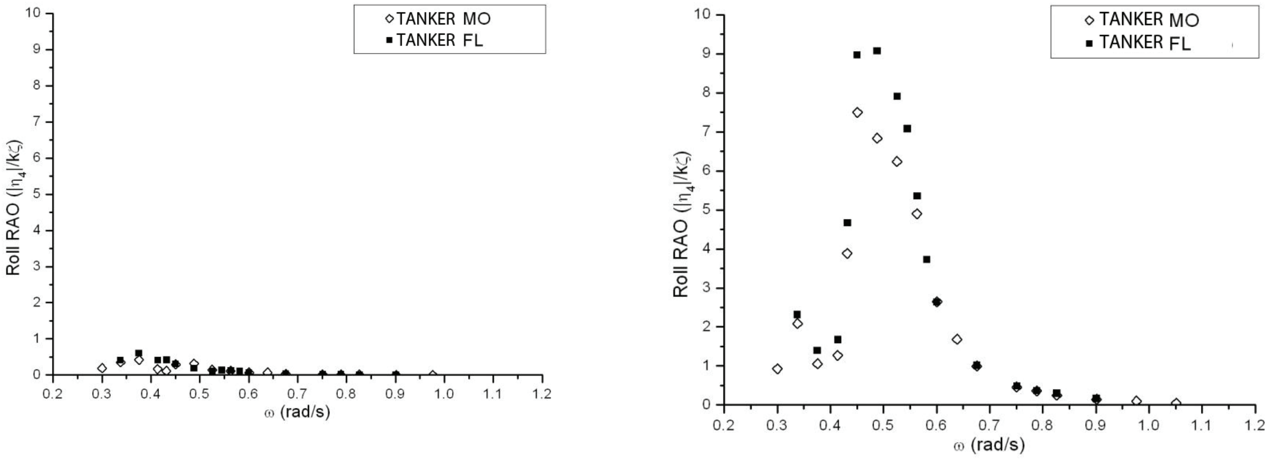
c) Supply Tanker Pitch RAO

f) Frigate Pitch RAO

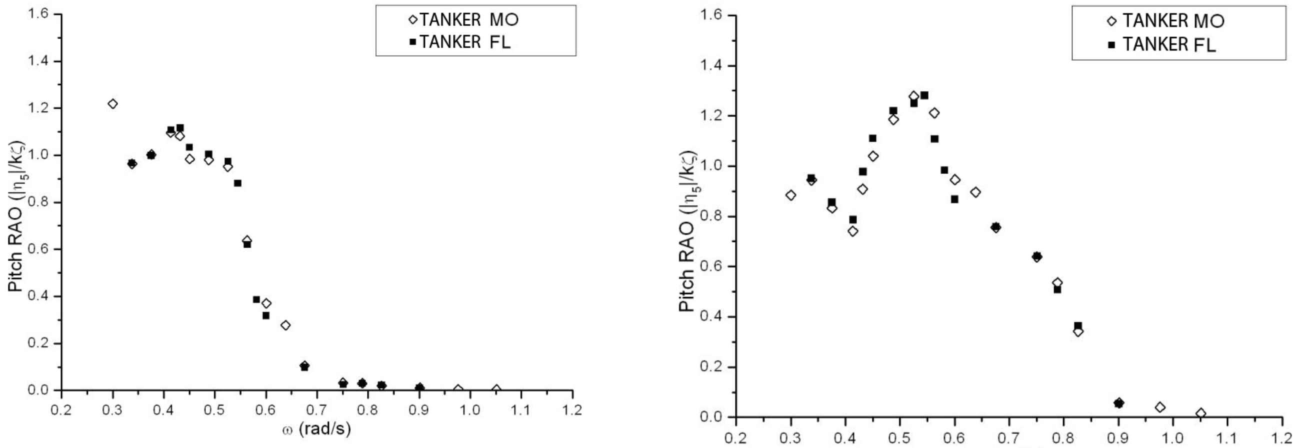
Figure 5: Numerical and experimental Supply Tanker and Frigate heave, pitch and roll RAOs (Condition 2)



a) Supply Tanker Heave RAO d) Frigate Heave RAO

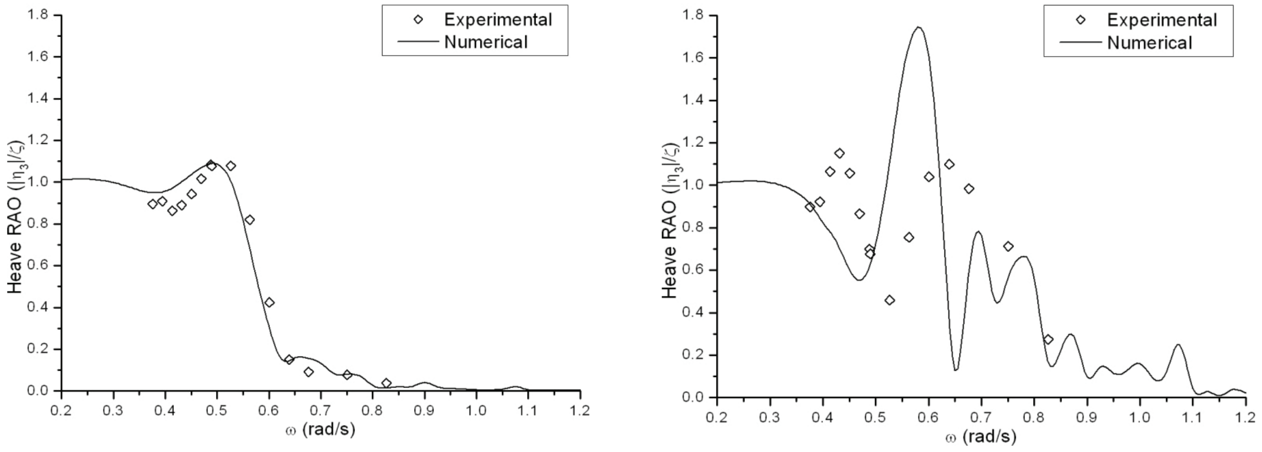


b) Supply Tanker Roll RAO e) Frigate Roll RAO



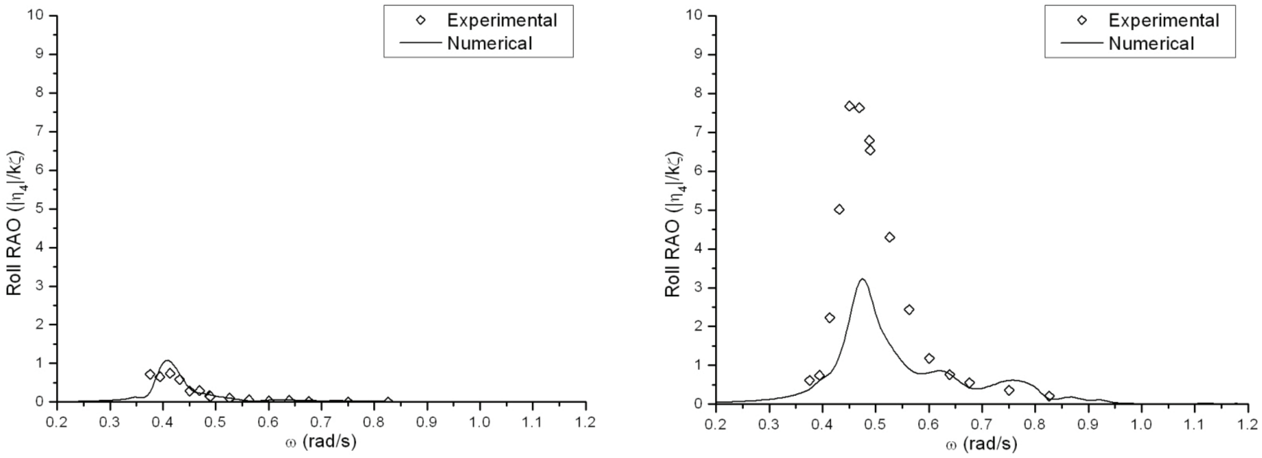
c) Supply Tanker Pitch RAO f) Frigate Pitch RAO

Figure 6: Effect of supply tanker displacement on motions; heave, pitch and roll RAOs (Conditions 1 & 2)



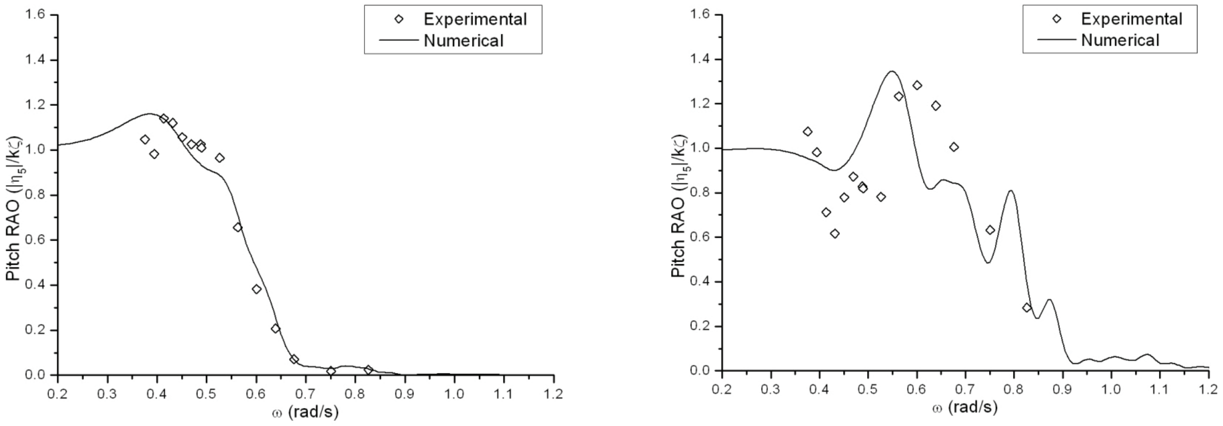
a) Supply Tanker Heave RAO

d) Frigate Heave RAO



b) Supply Tanker Roll RAO

e) Frigate Roll RAO



c) Supply Tanker Pitch RAO

f) Frigate Pitch RAO

Figure 7: Numerical and experimental Supply Tanker and Frigate heave, pitch and roll RAOs (Condition 3)

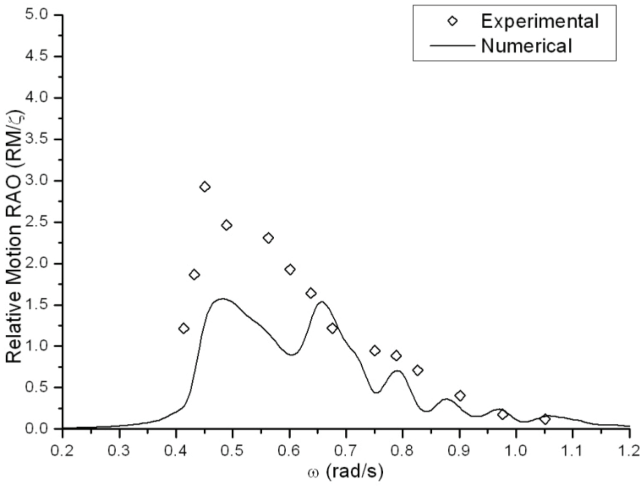


Figure 8: Relative motions Condition 1 (transverse 72.52m, longitudinal 11.13m, Supply Tanker MO)

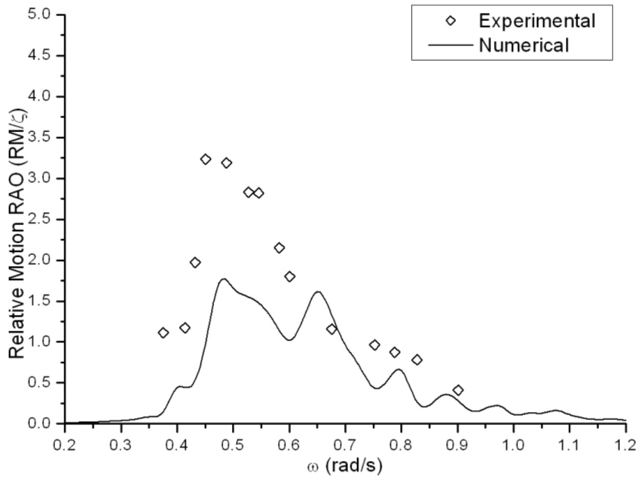


Figure 9: Relative motions Condition 2 (transverse 72.52m, longitudinal 11.13m, Supply Tanker FL)

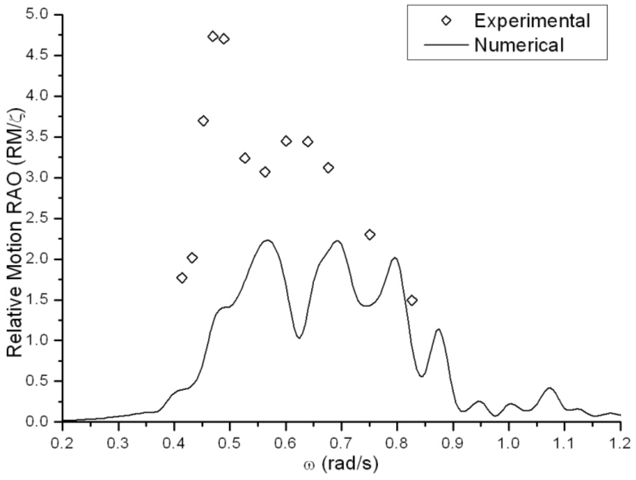


Figure 10: Relative motions Condition 3 (transverse 72.52m, longitudinal 45.78m, Supply Tanker FL)

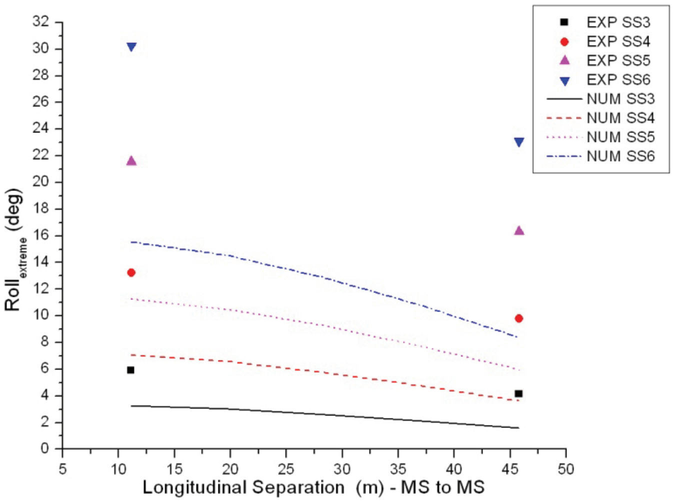


Figure 11: Expected extreme roll angles of the frigate with 1 percent exceedence probability in 3 hours in irregular sea state – influence of longitudinal separation

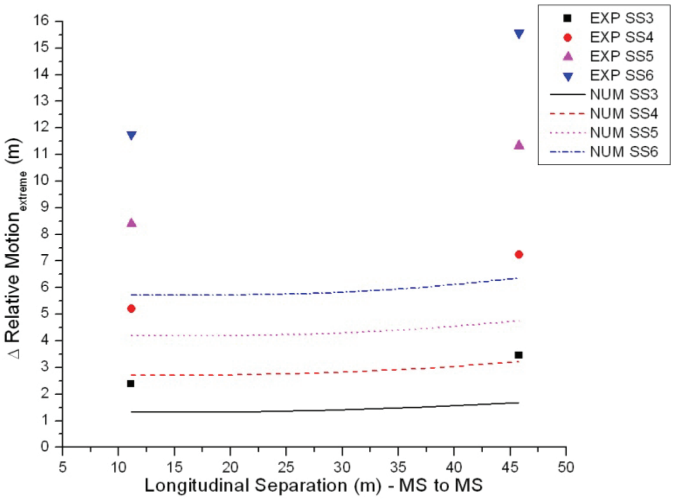


Figure 12: Expected extreme change of relative motion with 1 percent exceedence probability in 3 hours in irregular sea state – influence of longitudinal separation