Hydrodynamic interactions between ships during underway replenishment

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Hydrodynamic Interactions Between Ships During Underway Replenishment

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ABSTRACT

This paper describes a numerical code and experiments examining motions in waves for two ships in close proximity, as would occur during underway replenishment of naval vessels. The numerical model uses a linear frequency domain approach and includes hydrodynamic interactions for predicting motions of two ships in waves. Due to a scarcity of data in the open literature, it was necessary to conduct new towing tank experiments of two ships in waves. Comparisons between predictions and experiments are encouraging for two ships travelling with forward speed in head seas. Numerical predictions for realistic seaways indicate that the presence of a larger supply ship can induce large roll motions on a frigate during underway replenishment in head seas.

NOMENCLATURE

$[A^{ab}]$	added mass coupling of ship-a and ship-b
a	wave amplitude
B	ship beam
$[B^{ab}]$	damping coupling of ship-a and ship-b
B_T	towing tank width
$[C^a]$	hydrodynamic stiffness matrix of ship-a
CG	centre of gravity
$\{F^a\}$	wave excitation vector of ship-a
F_n	Froude number
$\overline{GM}$	metacentric height
H	wave height
H_s	significant wave height
$\overline{KG}$	centre of gravity above baseline
L	ship length between perpendiculars
L_f	frigate length between perpendiculars
L_s	supply ship length between perpendiculars
$[M^a]$	mass matrix of ship-a
T_{mid}	midships draft
T_p	peak wave period
T_4	ship natural roll period
x, y, z	global translating axis system
β	incident sea direction relative to ship
ζ_j^a	complex motion amplitude of ship-a
η_j^a	motion displacement of ship-a
λ	wavelength
ω	wave frequency
ω_e	encounter frequency
$\triangle$	ship weight displacement

INTRODUCTION

Underway replenishment is a critical aspect of naval ship operations. Fuel, fresh water, food stuffs, and machinery parts are among the supplies that must be routinely transferred to a ship operating at sea for long durations. Due to the close proximity of ships during underway replenishment, hydrodynamic interactions can affect their maneuvering properties and motions in waves.

To support ongoing operations and anticipated procurement of new supply ships for the Canadian Navy, a numerical model SHIPINT [1] was developed to predict the influence of hydrodynamic interactions on seakeeping performance for ships in close proximity. SHIPINT is a step forward from seakeeping programs, such as DREA's SHIPMO [2], which routinely provide predictions of motions for a single ship in waves. During initial validation of SHIPINT, it was found that little work has been published in the open literature for the case of two ships in close proximity. This paper describes a set of experiments that was conducted to validate the SHIPINT code and to gain new insight into ship interaction phenomena.

NUMERICAL MOTION PREDICTIONS OF TWO SHIPS IN WAVES

This section provides a brief overview of the numerical prediction code, which is described in greater detail by He et al. [1]. The code was developed by extending a program originally developed by Huang and Hsiung [3] for single ships. Both codes are based on linear theory, solving for ship motions in the frequency domain using a three-dimensional approach. The underwater portion of a ship is represented by a series of panels (typically several hundred), and the flow boundary conditions are satisfied by solving for source strengths on the panels. The solution is based on a zero speed, three-dimensional Green function, and approximations are made for forward speed effects.

In comparison to the single ship case, the two ship case is more complex because it has 12 degrees of freedom. Furthermore, hydrodynamic terms such as added mass, damping, and wave diffraction force must account for the presence of two ships in the flow field. The ship interaction code accounts for all of these effects in a rigourous manner.

Figure 1 gives a plan view of the global axis system used for computation. The coordinate system has its origin in the calm waterplane at midships of ship-a. The coordinates x_b, y_b represent the planar location of midships of ship-b relative to ship-a. The incident wave direction β follows the convention of 180 degrees for head seas and 90 degrees for waves from starboard. The z axis has a positive-up direction. The two ships are assumed to have the same steady forward speed, and the coordinate system moves accordingly. Output motions and phase angles for each ship are converted to a local axis system, with its origin at the centre of gravity of the ship in question.

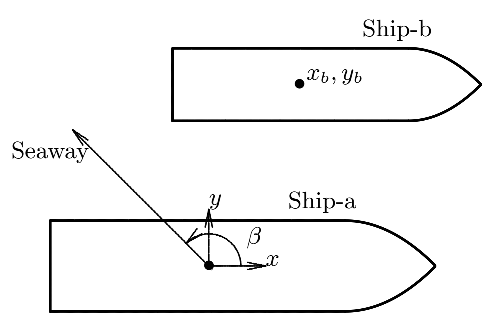

Figure 1: Plan View of Global Axis System

All motions are solved in the frequency domain for the ships in small amplitude regular waves as follows:

$$\eta_j^a(t) \quad = \quad \mathrm{Re}\left\{\zeta_j^a(\omega_e)e^{-i\omega_e t}\right\} \qquad (1)$$

where η_j^a is the displacement of ship a for mode j, Re denotes the real part of the term in brackets, and ζ_j^a is the complex amplitude of motion of ship a for mode j. To obtain motion predictions for random seas, linear superposition can be used.

The equations of motion in the frequency domain are obtained by finding the solution of the following 12 × 12 system of equations:

$$\left(-\omega_e^2 \left[\begin{array}{c|c} M^a + A^{aa} & A^{ab} \\ \hline A^{ba} & M^b + A^{bb} \end{array} \right] - i\omega_e \left[\begin{array}{c|c} B^{aa} & B^{ab} \\ \hline B^{ba} & B^{bb} \end{array} \right] + \left[\begin{array}{c|c} C^a & 0 \\ \hline 0 & C^b \end{array} \right] \right) \left\{ \begin{array}{c} \zeta^a \\ \hline \zeta^b \end{array} \right\} = \left\{ \begin{array}{c} F^a \\ \hline F^b \end{array} \right\} \qquad (2)$$

The above matrices and vectors have been partitioned into portions representing each ship and coupling terms between ships. For ship-a (and similarly for ship-b and interaction terms), M^a are inertial components, A^{aa} are added masses, B^{aa} are damping terms, C^a are hydrostatic stiffness terms, and F^a are wave excitation forces.

To support comparison with planned semi-captive model tests, the SHIPINT program was modified to permit restraint of each of the possible 12 degrees of freedom for the 2 ship system. Setting of an input restraint flag indicates that a restraining force or moment is applied at the centre of gravity for ship-a or ship-b. When applicable, the program outputs restraining forces and moments.

EXPERIMENTS OF TWO SHIPS IN WAVES

Due to scarcity of data in the open literature for seakeeping of two ships in close proximity, it was necessary to perform a dedicated set of model experiments for validation of the SHIPINT code. The model tests would also provide an opportunity for examining unexpected physical phenomena.

During planning stages, the following were considered desirable features for model tests representing underway replenishment in a seaway:

- large-scale models,
- models representative of a Canadian naval frigate and anticipated new supply ship,
- precise control of speed and heading,
- ship speeds of 0 and 12 knots,
- head and bow seas (to 60 degrees off head seas),
- generation of regular and random waves,
- minimal interference from experimental facility walls.

The ideal experimental program would have used large-scale, self-propelled models with sophisticated autopilots in a wide test basin; however, such a test program would have required a budget several times greater than what was available. It was ultimately decided to conduct semi-captive model tests in the towing tank (200 m long × 12 m wide × 7 m water depth) at the Institute for Marine Dynamics (IMD) in St. John's, Newfoundland. Control of speed and heading was accomplished by restraining the models in surge, sway, and yaw. The towing carriage facilitated full-scale ship speeds of 0 and 12 knots for tests in head seas (180 degrees). For tests at oblique headings of 120 and 150 degrees, only tests at zero speed were possible, but these would be useful for validating the oblique sea capability of the program SHIPINT.

Models of Supply Ship and Frigate

When selecting models for the test program, a criterion was that the models be representative of the Canadian Navy's Halifax class (Canadian Patrol Frigate) and an anticipated replacement design for the Canadian Navy's supply ships. In an effort to save costs, an existing 1/25 scale model based on a preliminary design of the Halifax class was selected to be a representative frigate. The frigate model included bilge keels, a single rudder, and propeller shaft brackets for twin propellers. A new 1/25 scale supply ship model was built based on a preliminary design for the Afloat Logistic Sealift Capability (ALSC). The model was fitted with bilge keels and two appendages representative of podded propulsor units. Table 1 gives the full-scale dimensions of the completed models. The given ship length values are taken between perpendiculars, and displacements are given for salt water. The metacentric heights were obtained using inclining tests, and the roll periods were obtained using roll decay tests.

Table 1: Full Scale Ship Dimensions

	Supply ship	Frigate
Length L (m)	187.5	122.0
Beam, B (m)	30.6	14.8
Midships draft, T_{mid} (m)	8.5	4.50
Trim by stern (m)	0.0	0.24
Displacement, $\triangle$ (tonnes)	28177	3975
CG above keel, $\overline{KG}$ (m)	12.43	6.56
Metacentric height, $\overline{GM}$ (m)	1.99	1.37
Roll period in water, T_4 (s)	13.2	9.4

Table 2: Test Program in Regular Waves

Number of runs	Speeds (knots)	Heading (deg)	Longitudinal separation (m)
28	0, 12	180	0, 45
14	0, 12	180	Frigate only
14	0, 12	180	Supply ship only
14	0	150	0, 45
7	0	150	Frigate only
7	0	150	Supply ship only
14	0	120	0, 45
7	0	120	Frigate only
7	0	120	Supply ship only

Experimental Program

Table 2 gives an outline of the experimental program in regular waves, which consisted of each ship being tested alone and the two ships being tested together. Each set of conditions was tested for 7 different wavelengths, with non-dimensional values λ/L_f of 0.25, 0.50, 0.75, 1.00, 1.25, 1.50, and 2.0, where λ is wavelength and L_f is length of the frigate. The wave steepness H/λ was 1/40 for all runs, corresponding to full-scale wave heights ranging from 0.8 m to 6.1 m.

Figures 2 to 4 show plan views of 3 of the experimental configurations. For tests with the two ships together, there was a lateral gap of 30 m between the ships at the point of greatest width. The longitudinal separation is the longitudinal distance between midships of the two vessels. The figures include the side walls of the towing tank, and suggest that tank wall interference could be significant for oblique seas (Figure 4).

Instrumentation

The physical models were mounted on two specially built dynamometers designed to interface with the existing towing tank carriage. Due to the difference in displacement between the two hull forms, the dynamometer designed for the supply ship model is substantially larger than the unit designed to accommodate the frigate model. The arrangement permitted a lateral gap of up to 1.2 m between the models at oblique angles of up to 60 degrees relative to the tank longitudinal centerline. An array of load cells incorporated in the dynamometers was

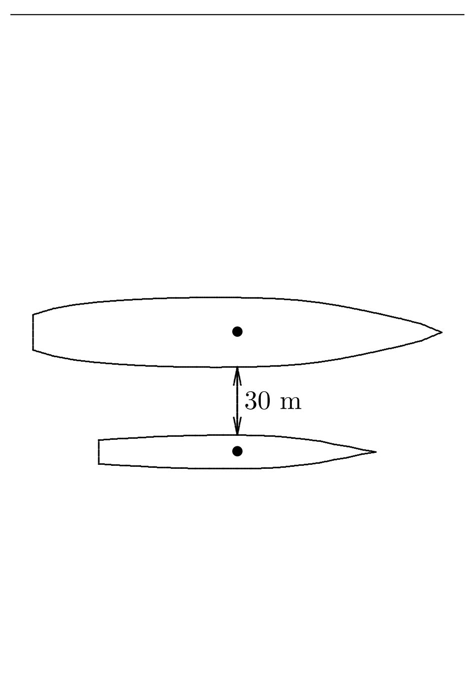

Figure 2: Frigate Alongside Supply Ship, Head Seas

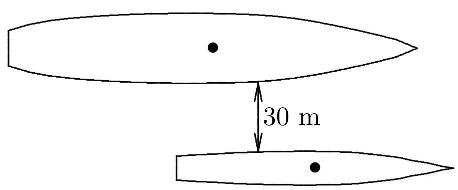

Figure 3: Frigate 45 m Ahead of Supply Ship, Head Seas

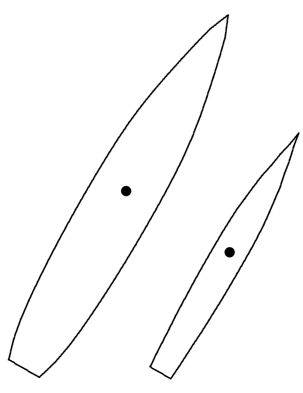

Figure 4: Frigate Alongside of Supply Ship, Bow Seas at 120 degrees

used to measure surge and sway restraining forces and yaw restraining moments. The forces and moments were calibrated using a six by six calibration matrix to accommodate cross talk between channels. The dynamometer tow post was free to heave on low friction linear bearings and terminated in the model on a gimbal at the model center of gravity. Linear displacement transducers fitted parallel to the tow posts were used to measure model heave displacement while rotational displacement transducers incorporated in each gimbal were used to measure model pitch and roll motion. To facilitate the investigation of the wave interaction between the two hulls in a seaway, a series of capacitance type relative motion probes was fitted to both models along the deck edge from bow to stern. Other parameters recorded included carriage speed and wave elevation measured using capacitance wave probes arranged as follows:

- one sensor fixed 30 m from the wave maker,
- one probe fitted at the leading edge of the tow carriage just off the longitudinal centerline,
- probes fitted adjacent to the longitudinal center of gravity of each model - between the model and the tank wall. (Note it was necessary to move these probes as the wave heading angle changed.)

In addition, extensive video records were acquired for each run.

Towing Tank Wall Interference

The finite width of the towing tank led to interference effects due to wave reflection from the tank walls. A review of various references, including proceedings from International Towing Tank Conferences, revealed guidelines for towing tank models in head and following seas; however, no guidelines were found for towing tank models in oblique seas. Bhattacharyya [4] gives a useful summary of interference effects during seakeeping experiments in a towing tank, and includes a graph from Goodrich [5] for determining whether experiments will be free of wall interference effects. For a towing tank model in head seas, wall interference effects increase with the following:

- increasing relative model length L/B_T, where B_T is tank width,
- decreasing model Froude number F_n,
- increasing relative wavelength, λ/L.

For the frigate alongside the supply ship (Figure 2) at a full-scale speed of 12 knots, the supply ship model length is 7.2 m, the nominal tank width is 10.8 m (12 m less 1.2 m between models), and the supply ship Froude number is 0.15. Using the above parameters, Goodrich's method indicates that experiments with the supply ship are free of wall interference effects for relative wavelengths less than 1.5 for a full-scale ship speed of 12 knots or greater. A similar analysis for the frigate indicates that it will be free of of wall interference effects for relative wavelengths less than 3.5 for a full-scale ship speed of 12 knots or greater. For the present experimental program, wall interference effects were likely negligible for head seas tests at a full-scale speed of 12 knots. For the zero speed tests, including all of the oblique seas tests, wall interference effects were likely significant. In an attempt to mitigate the impact of tank wall interference and evaluate the data in a consistent rational manner, each time series was reviewed and only the first 10 to 15 cycles after the initial wave-induced transients had dissipated were analyzed when computing the statistics for the zero forward speed runs.

NUMERICAL AND EXPERIMENTAL RESULTS

The experimental program produced a wealth of data for validating the SHIPINT code. Figures 5 and 6 show measured and predicted motion in head seas for a ship speed of 12 knots, with the frigate alongside the supply ship (Figure 5) and 45 m ahead of the supply ship (Figure 6). These cases are presented here because they are the most representative of operational conditions and are likely free of wall interference effects. Ship motions are presented for each ship alone in the towing tank and for the ships operating together, as would occur during underway replenishment.

The numerical predictions give generally good agreement with the experiments. The presence of the frigate has very little influence on the motions of the supply ship. In contrast, the supply ship has a pronounced influence on the motions of the frigate, particularly for heave and roll at longer wavelengths. For the frigate ahead of the supply ship (Figure 6), the experiments could not be completed for the highest two wavelengths due to excessive motions of the frigate (roll amplitude exceeding 30 degrees).

For the cases of each ship alone in Figures 5 and 6, both the supply ship and frigate exhibit non-zero roll motions in head seas. The non-zero experimental values are due to unavoidable physical asymmetries. The numerical predictions for each ship alone were actually based on computations for both ships together with a separation distance of 2,000 m, thus introducing roll-inducing asymmetries.

The greatest discrepancies between experiments and predictions in Figures 5 and 6 occur for motions of the frigate in longer wavelengths. In these conditions, the frigate motions have large amplitudes, violating linearity assumptions of the numerical predictions.

PREDICTED MOTIONS OF UNRESTRAINED SHIPS IN REALISTIC SEA STATES

The results presented so far are for motions of semi-captive ships in regular waves. Additional computations have been performed for motions of unrestrained ships in random seaways given in Table 3. Figure 7 shows predicted roll, pitch, and yaw motions. For the computations with each ship alone, non-zero roll and yaw motions occur because the computations were actually based on two ships in a seaway with a separation distance of 2,000 m. As was observed for regular seas, the presence of the frigate has a negligible influence on motions of the supply ship. In contrast, the frigate has substantial roll and yaw motions when the supply ship is present.

Table 3: NATO Sea States for Motions in Random Seaways

Sea state	Significant wave height H_s (m)	Peak wave period T_p (m)
3	0.88	7.5
4	1.88	8.8
5	3.25	9.7
6	5.00	12.4
7	7.50	15.0

RECOMMENDATIONS FOR FUTURE WORK

Because of the wall interference effects during experiments, the numerical prediction code requires further validation for oblique seas cases, preferably at both zero and non-zero speeds. Unfortunately,

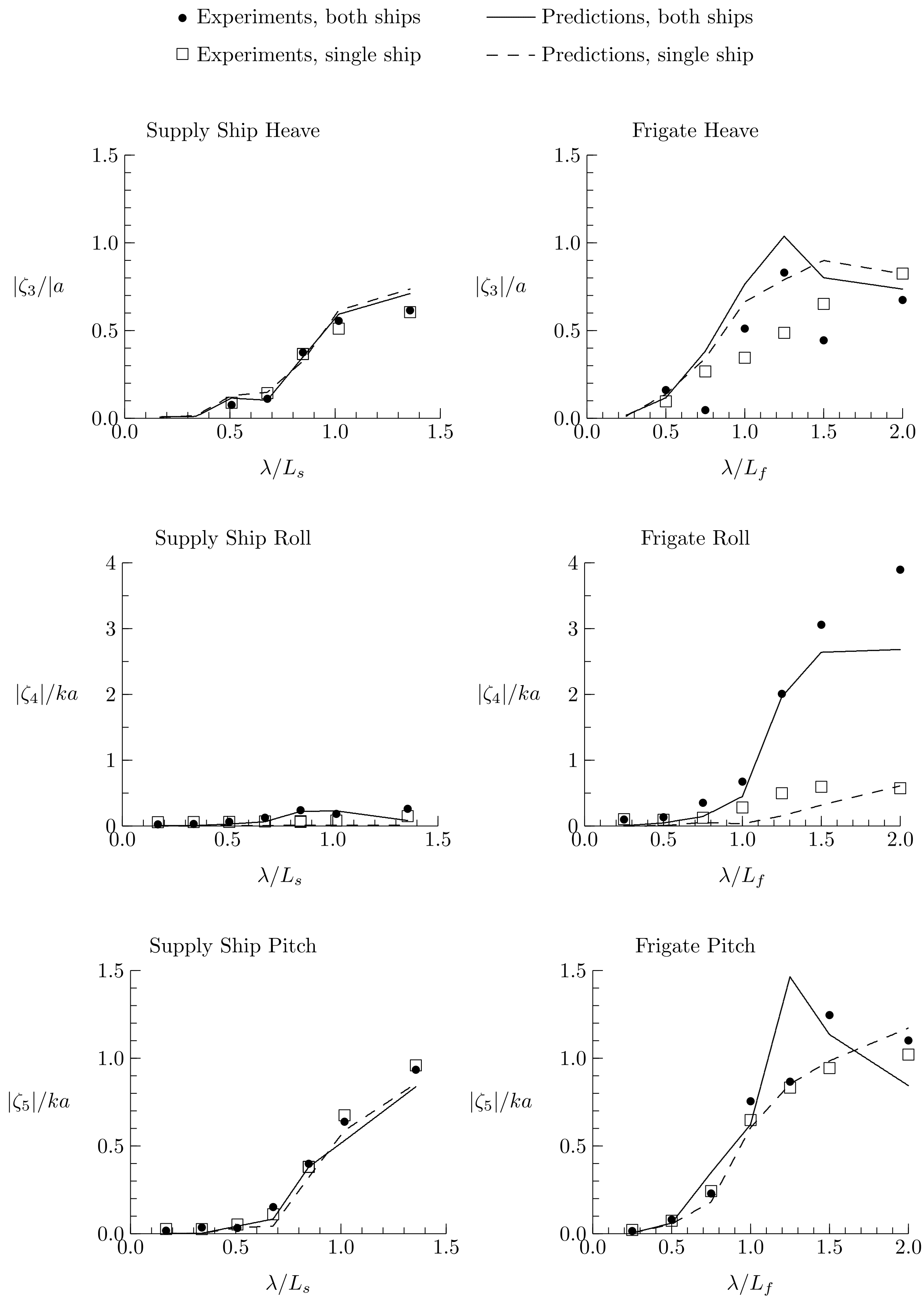

Figure 5: Ship Motions with Frigate Alongside Supply Ship, 12 knots, Head Seas

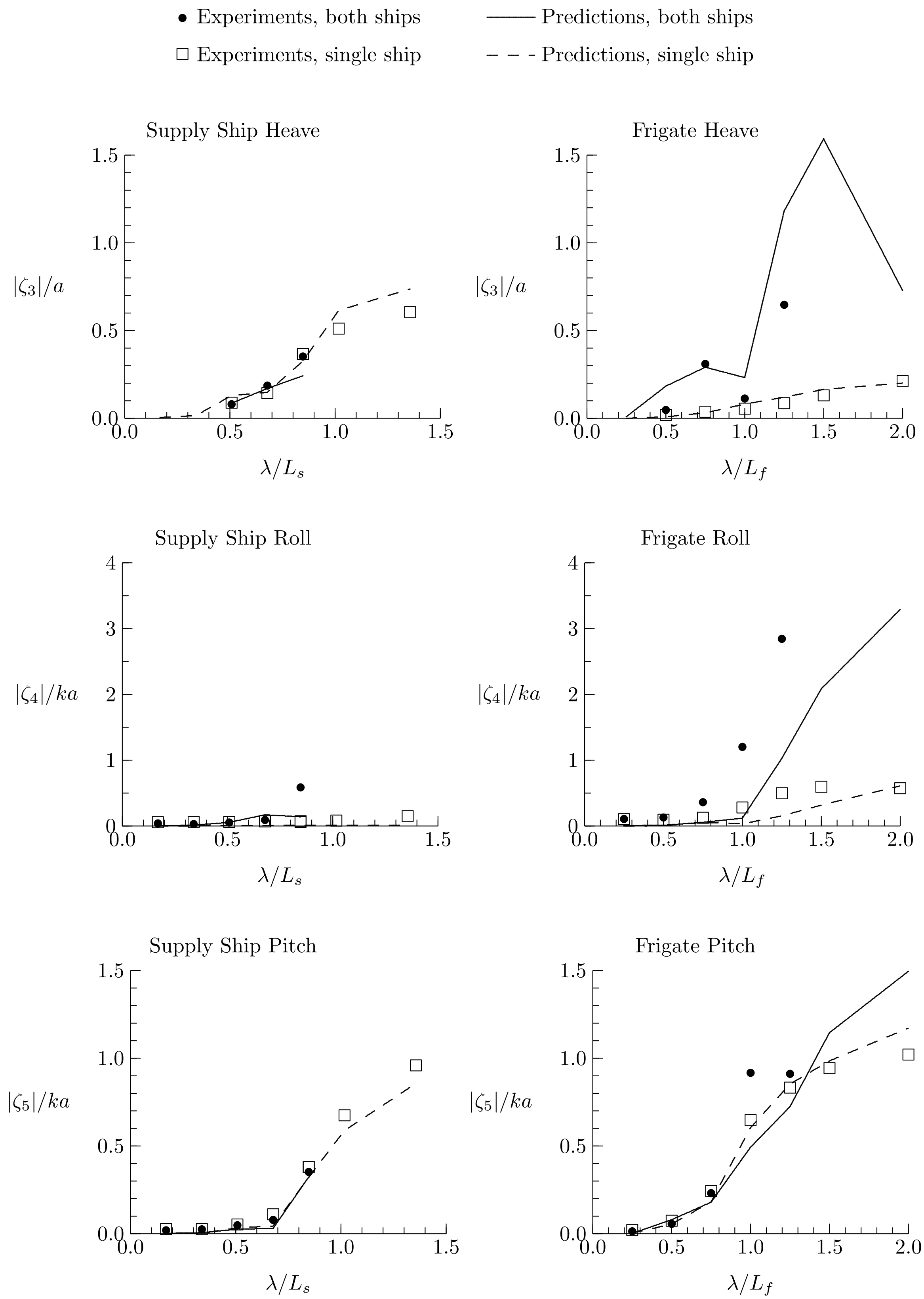

Figure 6: Ship Motions with Frigate 45 m Ahead of Supply Ship, 12 knots, Head Seas

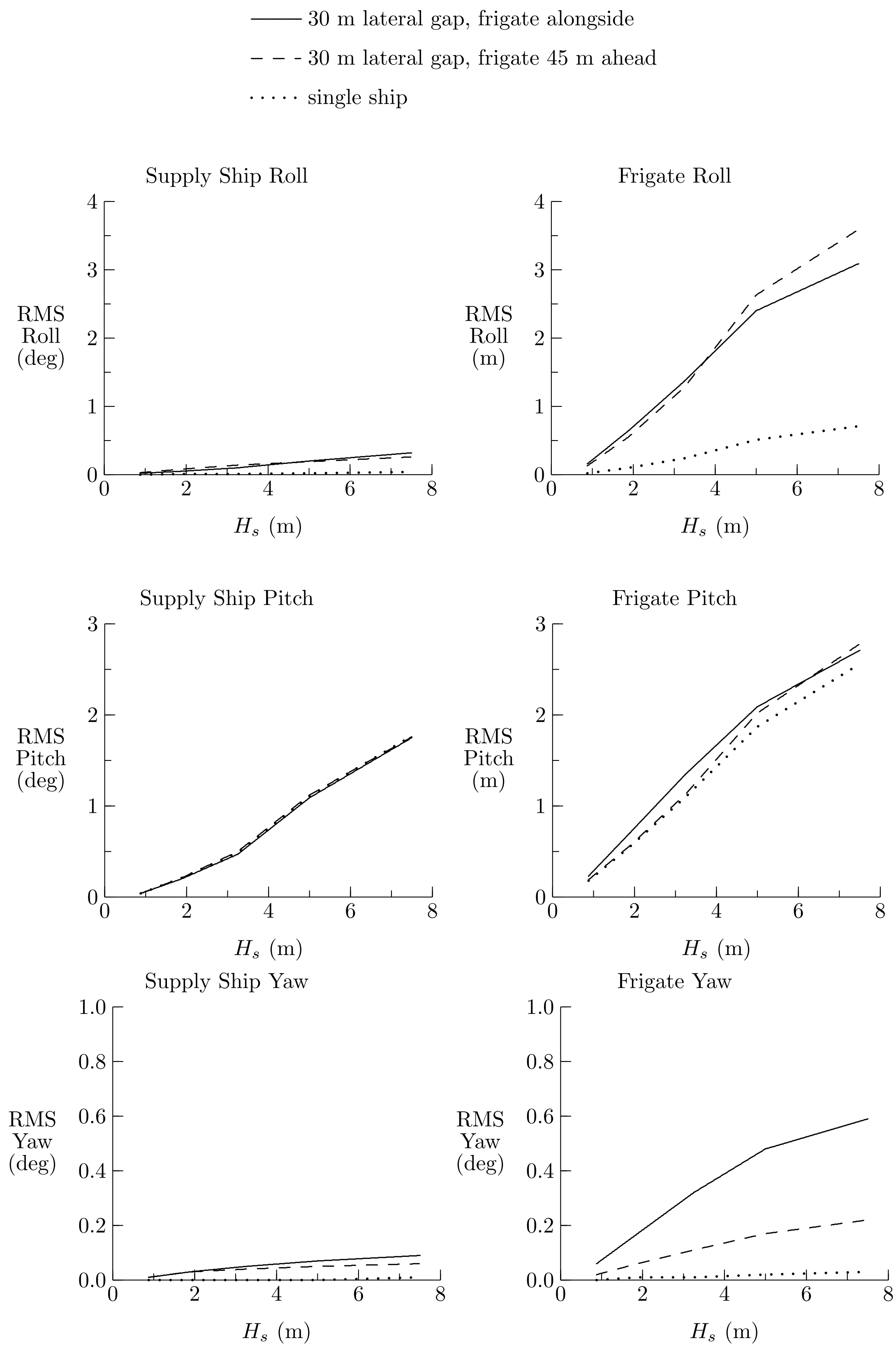

Figure 7: Ship Motions in Random Seaways, 12 knots, Head Seas

such experiments are very difficult and expensive to perform. An alternative approach would be to modify the SHIPINT code to include the towing tank wall boundaries for further comparison with the present experiments. The code modification would be relatively simple and would likely still give acceptable execution times. It is also recommended that further validation work be done using available experimental data for single ships in oblique seas.

CONCLUSIONS

The experimental and numerical results indicate that the presence of a larger vessel can significantly influence the motions in waves of a smaller vessel. Numerical predictions give good agreement with observed motions for two ships travelling with forward speed in head seas. For zero speed tests, which included both head and oblique seas, wall interference effects were likely significant during experiments. Computations for two ships in random seaways suggest that roll motions can be large for a frigate in the vicinity of a larger supply ship during underway replenishment in head seas.

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