Ship-Ship Interactions in Calm Water and Waves. Part 2:URANS

Validation in Replenishment and Overtaking Conditions

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ABSTRACT

Part 2 of this two-part paper presentsURANS ship-shipvalidation results against the experimental data studied in Part 1. The simulation matrixis designed based on the Part 1 results to focus on most significant effects, as well as to complement the datato further explain the physics involved.Calm water validation results show that the error values are comparable to the previous single-ship URANS studies. Single-ship (Hope only and Bobo only) calm water hull pressure distributions are compared to ship-ship solutions, providing insight into the physics of the induced effects based on the regions of decreased or increased hull pressure. Regular wave resultsachieve error values comparable to those for previous single-ship URANS validation studies. Also compared to the previous use of the same data for different simulation tools other than URANS, the current results achieve

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5 significantly lower error values.Ship-ship results in waves are compared to single-ship
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8 simulations, showing that the presence of the second ship induces resonant effects for most
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10 of the variables, and induces increased amplitudes for forces and moments at high
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12 frequencies. An overtaking validation simulation in regular head waves is carried out,
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14 which shows URANS capability with reasonably good agreement to the experiment.
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22 **Keywords:**URANS Validation;Viscous CFD;Ship-Ship Interaction;Multi-Body;
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1. Introduction

In Part 1, an overview was provided for experimental and empirical methods used in the literature for ship-ship interactions, and a recent extensive experimental data (Van't Veer & Van Engelenburg, 2006) were analyzed and used to study the interactions in calm water and waves. In the current Part 2, URANS validation studies are carried out based on the experimental data in Part 1, and the results are compared to the previous use of the same data for different simulation tools other than URANS (Silver et al., 2008).

System-based methods are mainly used for free running simulations of shallow calm water overtaking and encountering maneuvers and side-by-side replenishments in waves. Gronarz (2006) presented simulation results for a large container ship overtaking a small ship where a collision is predicted. Chitrapu et al. (2007) used a time domain method for seakeeping and maneuvering and compared their results with the RAOs from Hope and Bobo experiment. They also extended for 6 DOF autopilot simulations in oblique wind, waves and current, maneuvering effects, mooring lines, and fenders.

Skejic & Faltinsen (2007) used a unified seakeeping and maneuvering method based on generalized slender body theory for maneuvering and strip theory for seakeeping and studied the autopilot behavior for two ships overtaking in calm water and replenishing while advancing in regular oblique waves. Collision scenarios are predicted for both conditions.

Potential flow solvers are used for interactions in both calm water and waves. Jiankang et al. (2001) used a wave equation model and Galerkin finite element method

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5 with moving grids to study calm water interactions of two identical S60 ships moving side-
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7 by-side in shallow water (depth to length ratio of 0.17). Compared to single-ship, the wave
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9 resistance decreased and an attractive side force was produced. Decreasing spacing and
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11 increasing speed intensified the interactions. De koningGans et al. (2007) studied calm
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13 water overtaking under hull drift using 3D panel method with a wake model for effects of
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15 lift force. O’Cathain et al. (2008) presented a time domain approach for multi-body of wave
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17 energy devices in regular waves using Newton-Euler equations of motion for rigid-body
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19 dynamics and linear potential theory for hydrodynamic forces. McTaggart et al. (2003)
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21 used 3D frequency domain computations based on a panel method for seakeeping of two
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23 ships in replenishment condition in regular and random head waves. Towing tank
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25 experiments were conducted in regular waves and used for validation. For cases where
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27 trapping waves (Mciver & Newman, 2003) are present in the gap between two floating
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29 structures, the standing transverse waves and the forces associated with them can become
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31 unrealistically large in potential flow solvers, since the viscous damping is not included
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33 (e.g. Chen & Fang, 2001; Lewandowski, 2008).
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43 The Hope and Bobo experiments are used to evaluate six computational tools of
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45 different methods other than URANS including system-based methods, time or frequency
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47 domain zero speed free surface Green’s function, and time domain Rankine panel method
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49 (Silver et al., 2008). The conditions were limited to replenishment in waves and no calm
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51 water or overtaking cases were studied. A summary of the results are presented in this
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53 paper and compared to the current URANS simulations.
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Very limited CFD simulations of ship-ship interactions are available. Chen et al. (2003) used chimera URANS for shallow constrained calm water simulations and compared the results with overtaking and encountering experiments by Dand (1981) with good agreement. The simulation conditions were then extended to effects of a passing ship on a moored vessel, berthing operations, and floating pier and multi-vessel interactions including mooring and fender effects. Sadat-Hosseini et al. (2011) used CFDShip-Iowa URANS solver for side-by-side shallow calm water validation studies against the benchmark data provided by Lataire et al. (2009). The propellers are modeled by prescribed body forces applied on thin cylinders using the open water curves and the thickness of the propellers. Wu et al. (2013) improved the simulations by including interactive non-axisymmetric body force propeller modeling and studied the problem in more depth by including single-ship and deep water simulations and analyzing the effects on global and local flow variables. CFD simulations of ship-ship interactions in waves are so far not addressed in the literature.

The objectives of this Part 2 paper are to perform detailed URANS validation studies for ship-ship simulations in deep calm water and waves based on and extending the previous single-ship URANS validation studies, and to further study the ship-ship interactions using the CFD simulations specially designed to complement the data and explain the physics behind the interactions. URANS computations are carried out using CFDShip-Iowa V4.5 (Huang et al., 2008), which employs dynamic overset grids for motions including multi-body capability. URANS test matrix is selected based on studies of the experimental data (Part 1) and potential flow (PF) results (Silver et al., 2008) to allow

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5 studies of ship-ship interactions, assessments of URANS capability including comparison
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7 with previous PF-based studies, and investigations of the flow including free surface and
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9 hull pressure distributions and comparison with single-ship computations. Procedures for
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11 assessment of validation results are based on and extend the previous G2010 single-ship
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13 studies (Stern et al., 2014). Experimental data uncertainty studies and simulation
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15 verification are lacking and only qualitative validation is carried out by comparing the
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17 simulation results with the experimental data.
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26 **2. Computational Methods**

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CFDShip-Iowa V4.5 is an incompressible URANS/DES solver designed for ship hydrodynamics (Huanget al., 2008). Single-phase level-set approach is used for free surface, blended $k-\varepsilon/k-\omega$ for turbulence model, and curvilinear dynamic overset grids for 6DOF ship motions. Incompressibility is enforced by a strong pressure/velocity coupling, achieved using either PISO or projection algorithms. The fluid flow equations are solved in an inertial coordinate system, either fixed to a ship or other frame moving at constant-speed or in the earth system. The rigid body equations are solved in the ship system, and forces and moments are projected to perform the integration of the rigid body equations of motion, which are solved iteratively with fluid flow equations. For details of the 6DOF motion capabilities including multiple bodies refer to Carrica et al. (2007). Initial and boundary conditions are imposed to generate the waves inside the computational domain. Other modeling capabilities include semi-coupled two-phase air/water modeling, moving

control surfaces, advanced controllers, propulsion models, environmental waves and winds, bubbly flow, and fluid-structure interaction.

3. Simulation Conditions

3.1 Grids and Computational Domain

In the CFD coordinate system, positive x direction is from the bow of the ships aftward, and positive y is toward starboard. CFD results are transformed to experimental coordinate system for comparison of the results. The overset grid systems for each ship include double-O boundary layer grid, skeg, rudder, and bilge keel. Refinement grids are included in the calm water simulations. The Cartesian background grid extends enough to the sides and behind the ships to capture the free surface and wake flows. The boundary layer grids are designed to achieve $y^+ < 1$ at all Fr for both ships. Free surface grids are designed to include sufficient points per surface elevations and per wavelengths. The total grid size is 6.5 M without the refinement blocks and 11.9 M with refinements. Figure 1 shows the grids for ships, their refinements, and background. The domain size varies for simulations in different wave headings to capture the diffracted waves. The smallest computational domain for calm water and 180° waves extends to $-0.75 < x/L_B < 3.65$, $-0.8 < y/L_B < 1.5$, and $-1.0 < z/L_B < 0.3$.

3.2 Selection of Calm Water and Wave Conditions

The conditions are selected based on the analysis of the experimental data in Part 1 to include the critical conditions and complement the experimental data, as well as the previous PF-based tool evaluation studies (Silver et al., 2008). Eight regular wave conditions were included in the PF-based tool studies, as summarized in Table 1. The cases selected for current URANS studies are indicated in bold. At the higher speed ($Fr_H=0.16$), head waves (180°) are selected, as well as 120° waves for which Part 1 results showed most significant sheltering effects. At the low speed and small spacing, 135° waves are selected, again since include significant ship-ship interactions due to sheltering in oblique waves.

Table 2 shows all the simulation conditions for the current URANS studies along with the reasons for their selection. Single-ship (Hope only and Bobo only) conditions, which were missing in the experiments, are included in calm water and in head waves (180°), to be compared with ship-ship results for better understanding of the interactions. Calm water simulations are at the highest speed and the smaller spacing where the results in Part 1 showed largest induced forces and moments. Side-by-side simulations in waves include the selected conditions from the PF-based evaluation studies, as well as simulations in b-m configuration and 120° wave heading for which the results in Part 1 showed most significant sheltering effects. Each set of regular wave studies include six simulations at different wavelengths/wave frequencies, as was summarized in Part 1, Table 3.

An overtaking simulation is carried out to assess URANS capability. The selected condition corresponds to the smaller spacing with Hope overtakes Bobo at $f_e=0.75$ Hz

($\lambda/L_H=0.88$ and $\lambda/L_B=1.36$), for which an examination of the experimental data showed most significant interactions. The simulation is carried out in a relative inertial reference frame moving with average speed of the two ships, such that the faster ship moves forward and the slower ship moves backward inside the computational domain, thus minimizing the required domain size.

4. Post Processing Procedures

Analysis of time histories in calm water and waves follow the procedures presented in Part 1 (Section 3.1). Seakeeping analysis including procedures for calculating regular wave RAOs follow Mousaviraad et al. (2010). Procedures for calculating and averaging/categorizing the comparison error values are discussed herein, which are based on and extend the procedures in G2010 (Stern et al., 2010).

4.1 Definition of Comparison Error Values

Calm water error value $E\%D$ is defined as:

$$E\%D = 100 \times (D - S)/D \quad (1)$$

where D is the experimental data value and S is the simulation value.

Regular wave error value $E\%DR$ is defined as:

$$E\%DR = 100 \times |D - S|/DR \quad (2)$$

where DR values are the differences between minimum and maximum values over the frequency range for amplitudes, and 360° for phases.

4.2 Averaging and Categorizing for Assessment of Comparison Error Values

For CFD simulations of seakeeping in regular waves with ship motions, the results include 6 variables, i.e. X , Y , K , N , z , and θ . Performing Fourier analysis introduces at least three variables to be considered, i.e. 0th harmonic amplitude, 1st harmonic amplitude, and 1st harmonic phase. Each set of simulations in the current study include 6 different wavelengths, and the results are obtained both for Hope and Bobo, resulting in 216 variables. For the current simulation matrix with 6 sets of ship-ship simulations (Table 2), 1296 values need to be evaluated for validation studies. Therefore averaging and categorizing the error values, as used and found suitable and reliable for single-ship URANS studies in the SIMMAN 2008 workshop (Stern et al., 2011) and the Gothenburg 2010 workshop (Stern et al., 2014), are employed to reduce the results and reach overall conclusions for CFD comparison error values. This also allows comparison of the current results to the previous single-ship studies. Note that while it may not seem natural to average between different variables, the averages are obtained for the error values and not the values themselves.

Categorization into 1st and higher order terms is based on the proposition used previously for single-ship calm water maneuvering (Stern et al, 2011) and seakeeping in

regular waves (Stern et al., 2014) that CFD prediction assessments should separate capability for 1st order vs. higher order terms. Consideration is given to 0th harmonic, streaming, and 1st harmonic amplitude and phase, while 2nd and higher harmonics are not included. For the resistance problem in calm water, the steady resistance is considered 1st order while sinkage and trim are higher order, i.e. the contribution of sinkage and trim to the free surface elevation is higher order. For wave cases, resistance 0th harmonic is considered 1st order and 0th harmonic heave and pitch are higher order using the same reasoning as in calm water. According to linear potential flow, the 1st harmonic amplitudes of resistance, heave, and pitch are proportional to wave amplitude and are therefore 1st order. The streaming parameters are proportional to square root of wave amplitude and are considered higher order. For the current study, the 0th and 1st harmonics of Y , K , and N are considered higher order since include strong interference effects from the other ship.

5. Calm Water Results

5.1 Calm Water Validation

As per Table 2, the calm water ship-ship simulation is carried out in m-m configuration (See Figure 1 in Part 1 for definition) at $Fr_H=0.16$ and 0.37 m spacing. Calm water validation results are shown in Table 3. Note that the σ and τ values are very small, resulting in large $E\%D$ values. Motions are generally under-predicted by CFD, with average $E=33\%D$. Resistance is under-predicted for Hope by 22% D , while for Bobo the error value is very small, at about 0.75% D . Y is over-predicted for both ships at similar

error values of about $23\%D$. K is under-predicted for Hope by $12\%D$ and for Bobo by $20\%D$. N is under-predicted for Hope by $19\%D$, while for Bobo it is over-predicted by $6\%D$. Consistent with G2010, 1st order terms are predicted better at about $11\%D$ while higher order terms are predicted at $24\%D$. The overall average error is $21.39\%D$, comparable to G2010 which was $24\%D$ for $Fr < 0.2$ and $6.8\%D$ for $Fr > 0.2$ (current simulations are at $Fr_H = 0.16$ and $Fr_B = 0.19$).

5.2 Single-Ship Results and Comparison to Ship-Ship Computations

Single-ship calm water CFD results show that both ships sink down and trim bow-down. The difference between the single-ship and ship-ship computations are reported in Table 4. When moving side-by-side in m-m configuration, both ships sink further down, Hope trims further bow-down, and Bobo trims bow-down but at smaller trim angle than single-ship (bow-up effect). Resistance is decreased by 4% for Hope and increased by 10% for Bobo.

Hull pressure distributions for the ship-ship and single-ship computations are subtracted and shown in Figure 2 as percent difference in pressure values. Maximum differences are $\pm 10\%$ for Hope and $\pm 7\%$ for Bobo. Pressure is decreased over a large area at the bottoms of both ships creating the suction forces that cause the sink-down effect. For Hope, there are areas of increased pressure at the fore and the aft. The pressure increase is higher at the aft than the fore, causing the increased trim (bow-down) and decreased resistance. For Bobo, there is an area of increased pressure at the fore, causing the

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5 decreased trim and increased resistance. For both ships, there are areas of increased
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7 pressure over the side closer to the other ship, causing the repelling Y forces and the roll
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9 away moments. The yaw moment in Hope is induced by areas of increased pressure at the
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11 bow and decreased pressure aft of the amidships on the side closer to Bobo. For Bobo the
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13 area of decreased pressure fore of the amidships on the side closer to Hope and the
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15 asymmetric pressure increase at the bow being more significant on the side further from
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17 Hope (not shown in Figure 2) are responsible for the yaw moment.
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26 27 **6. Regular Wave Results**

28 29 30 **6.1 Regular Wave Validation**

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33 Regular wave validation results are shown for RAOs and phases in Figures 3, 4,
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35 and 5. Both the current URANS study and experiments include only six wave frequencies,
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37 providing discontinuous responses. It was not possible, considering the computational
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39 expenses and the number of test conditions to be considered, to obtain continuous curves
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41 using URANS. The same approach is used in previous CFD seakeeping studies, including
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43 in G2010 (Stern et al., 2010). The PF-based tools evaluation study by Silver et al. (2008)
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45 includes continuous curves for Hope and Bobo. However, those curves are not included
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47 herein because as will be discussed in Section 6.2 they have large error values and are not
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49 helpful for CFD validation. The connecting lines are used for CFD points to distinguish
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51 between different conditions, while experiments are shown by symbols only. The results
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53 show reasonably good agreement with the experiments for all simulations.
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The comparison error values for all forces, moments and motions averaged over the 6 encounter frequencies for each set of simulations are reported in Table 5. The error values are generally largest for the 0th amplitudes compared to 1st amplitudes and phases, except for X where 1st amplitudes have the largest error. The error values are larger for Hope than Bobo in m-m configuration where Bobo is sheltered, while in b-m configuration the errors are larger for Bobo. The low speed and small spacing simulations in 135° heading are validated with comparable results to other conditions (average $E=19\%DR$), although more challenging and more computationally expensive in terms of grid size, time-step, and run length.

Considering the categorized values, the average errors are larger for forces/moments (19% DR) than for motions (16% DR). 1st order terms are predicted with smaller error than higher order terms for all sets of simulations, as expected. The average error values are 11% DR for 1st order and 23% DR for higher order terms with overall average of 17% DR . These are comparable to G2010 single-ship regular wave error values which were 18% DR for 1st order terms, 31% DR for higher order terms, and 23% DR overall.

6.2 Comparison with PF-Based Computational Tools

The average error values are summarized in Table 6, categorized by computational methods. The values are averaged for the five conditions included both incurrent URANS and the PF-based tool evaluation studies, as per Table 1. Only 1st harmonic amplitudes and phases are considered since 0th amplitudes were not predicted by the PF-based tools. For all

tools, the error values are larger for forces/moments than motions. The error values for current URANS results are smallest for all force/moment and motion components and for both ships, with overall average error of 10%*DR*, compared to 45%*DR* for system-based methods, 31%*DR* for time and frequency domain Green's function codes, and 15%*DR* for time domain Rankine panel method codes.

Although Table 6 shows the error values averaged over all 5 conditions indicated in bold in Table 1, a thorough examination of the results (not shown herein) revealed that the URANS error values are always the smallest for all variables and in all simulation conditions.

6.3 Single-Ship Results and Comparison to Ship-Ship Computations

Single-ship streaming values from CFD computations are shown in Table 7 as percentage of calm water values. For X , the 0th amplitudes in waves are larger than calm water resistance, on average 51% for Hope and 10% for Bobo. The 0th amplitudes of z are smaller for both ships than calm water sinkage, i.e. the ships sink further down in waves by less than 2% on average. The 0th amplitudes of θ are larger for both ships than calm water trim, i.e. the ships trim further bow-down in waves by average 32% for Hope and 22% for Bobo. Overall, streaming effects are largest for X (30%) followed by θ (27%), while for z the streaming effects are very small (2%). The streaming values are much larger for Hope than Bobo.

Single-ship (S_∞) RAOs and phases for simulations in head waves (180°) at $Fr_H=0.16$ are included in Figure 3. Single-ship RAOs do not peak and decrease with encounter frequency, perhaps since the current Fr is much smaller than Fr_c . For Hope, heave and pitch RAOs do not reach 1.0 in the simulation range since the maximum λ/L_H is 1.38. For Bobo, λ/L_B reaches up to 2.12 and RAOs approach 1.0 at small encounter frequencies. Both heave and pitch RAOs are larger for Bobo than Hope. At f_e larger than 1.2 Hz ($\lambda/L_H < 0.45$; $\lambda/L_B < 0.7$), RAOs are very small (near zero) for both ships.

The effects of presence of the second ship on amplitudes and phases of z , θ , and X are also evident in Figure 3. The most important effect is significantly increased heave RAOs in the resonance region for both ships, which intensifies by reducing spacing from 0.74 m to 0.37 m, while no peak was observed in the resonance region for single-ship RAOs. This is perhaps due to resonance in the radiated waves of each ship further exciting the other ship at its near resonant frequency, since the natural frequencies are close for Hope and Bobo (around 1.0 Hz). The second effect is slightly decreased pitch RAOs for Bobo at the very small frequency (very long wave, $\lambda/L_B=2.12$), again more significant at the smaller spacing. Perhaps even longer waves will be required for pitch RAO of Bobo to reach 1.0 in the presence of Hope. X amplitudes decrease for both ships at frequencies lower than the resonant frequency and increase at the resonant and higher frequencies. The peak of X amplitude in the resonance region is more significant for Bobo than Hope.

The effects of presence of the second ship on 0th amplitudes and 1st amplitudes and phases of X , z , and θ averaged over the wave frequencies are summarized in Table 8 for both 0.74 m and 0.37 m spacing. Averaging over wave frequencies is carried out for non-

absolute values to show increase or decrease. Y , K , and N are zero for single-ship and therefore not included. Compared to single-ship results, the 0th amplitudes of X at 0.37 m spacing decrease by about 4% for Hope and increase by about 9% for Bobo, comparable to the calm water resistance effects (Table 4). At 0.74 m spacing, the effects are less significant, 3% decrease for Hope and 5% increase for Bobo. The 0th amplitudes of z increase for both ships at both spacing, i.e. the ships sink further down compared to single-ship simulations. At 0.37 m spacing the effects on 0th amplitudes of z are 26% for Hope and 30% for Bobo, again very close to the calm water effects (Table 4). The 0th amplitudes of pitch increase for Hope (bow-down effect) and decrease for Bobo (bow-up effect), consistent with calm water. At 0.37 m spacing the 0th amplitudes of pitch are affected by 43% for Bobo, similar to the calm water value (50%), and by 79% for Hope, smaller than the calm water value (119%). Overall, the effects of the second ship in head waves are most significant on θ followed by z and then X for both ships and at both spacing. At both spacing, Hope is affected more significantly than Bobo. For both ships, the effects are larger at 0.37 m spacing compared to 0.74 m spacing.

Figure 6 shows a snapshot of the dynamic free surface and hull pressure distributions during a ship-ship head wave simulation. Note the complex wave system in the gap between the ships and the induced pressure distributions on the hulls.

7. Overtaking Results

The overtaking simulation in regular head waves imposed specific challenges due to the additional degree of freedom, domain size design, determination of the initial phase of the incoming waves relative to each of the ships, etc. Validation were also more critical than side-by-side simulations since the measured experimental data showed non-regularity in the incoming waves and the speeds of the ships as they pass by each other. Nevertheless, very good results are obtained as shown in Figure 7 for time histories of heave and pitch motions of both ships. The CFD results follow the experiments slightly better for Hope than Bobo. This perhaps is because the interaction effects are more significant on Bobo, and therefore more difficult to predict and more sensitive to differences in experimental and CFD conditions. Figure 8 shows snapshots of the ships and free surface during the overtaking simulation.

The interaction effects during the overtaking event are discussed here for all variables (motions, forces, and moments), while only heave and pitch motions are shown in Figure 7. Amplitudes of heave motions decrease for both ships as they pass by each other, being more significant for Bobo. Heave interaction effects occur for Hope when it is still in the wake of Bobo, and for Bobo as the ships approach amidships-to-amidships and again after Hope passes and Bobo is in its wake. Amplitudes of pitch motions also decrease for both ships, although only slightly for Hope. Pitch interactions occur for Hope when it is in the wake of Bobo and again when approaching amidships-to-amidships, and for Bobo when in the wake of Hope. There also seems to be an increase in pitch amplitudes of Bobo when Hope is in its wake right before overtaking. Amplitudes of

X decrease for Hope during overtaking and slightly increase right after overtaking when Bobo is in its wake. For Bobo, X amplitudes decrease before the overtaking when Hope is in its wake, increase during overtaking, and slightly decrease after overtaking when in the wake of Hope. Amplitudes of Y increase significantly for Bobo during overtaking and decrease afterwards. A similar trend is observed for Hope but for a shorter duration. K and N also increase during overtaking and decrease when the overtaking ship has passed, with the interaction effects being less significant on Hope than Bobo.

8. Conclusions and Future Work

Part 2 of this two-part paper presents URANS ship-ship validation results in deep calm water and waves against the experimental data studied in Part 1. URANS validation simulation conditions are selected based on the results of Part 1 and the previous use of the data for evaluation of PF-based computational tools. The simulation matrix also includes single-ship (Hope only and Bobo only) computations to complement the experimental matrix and provide further explanations of the physics involved through studies of the global and local flow variables. URANS computations are carried out using CFDShip-Iowa V4.5 which uses dynamic overset grids and multi-body rigid motion solver for multi-body ship motions. Validation procedures follow the previous G2010 single-ship studies.

Validation results in calm water show that Y forces are over-predicted by CFD while other variables are under-predicted. Consistent with previous single-ship studies, 1st order terms are predicted better at about $E=11\%D$ while higher order terms are predicted at

24%*D*. The overall comparison error value for URANS simulations in calm water is about 21%*D*, comparable to G2010 for single-ship, which was 24% for $Fr < 0.2$ computations and 6.8% for $Fr > 0.2$ (current values are $Fr_H = 0.16$ and $Fr_B = 0.12$).

Calm water interactions are studied through comparison of ship-ship in m-m configuration with single-ship simulations. Both ships sink further down when move side-by-side. Bow-down trim is induced on Hope and bow-up on Bobo. Resistance is decreased by 4% for Hope and increased by 10% for Bobo. The hull pressure distributions in ship-ship and single-ship computations are subtracted to quantify the effects of the second ship on each of the ships. The results showed decreased bottom pressure for both ships inducing a suction force responsible for the sink-down effect. Increased pressure areas are predicted for Hope over the aft, causing the bow-down trim and decreased resistance, while for Bobo an increased pressure area in the bow induces the bow-up trim and increased resistance. Increased pressure areas for both ships over the side closer to the other ship cause the repelling *Y* forces and the roll away moments. The yaw moment is induced in Hope by areas of high pressure at the bow and low pressure aft of the amidships on the side closer to Bobo. For Bobo, the yaw moment is induced by an area of low pressure fore of the amidships on the side closer to Hope and an area of high pressure at the bow on the other side.

Regular wave validation studies include extensive simulation conditions in different configuration, spacing, speed, and heading conditions, each at six different wave frequencies. The average error values are 11%*DR* for 1st order and 23%*DR* for higher order terms with overall average of 17%*DR*. These are again comparable to G2010 single-ship

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5 results which were 18%*DR* for 1st order terms, 31%*DR* for higher order terms, and 23%*DR*
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7 overall.
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11 The Hope and Bobo experimental data were previously used for evaluation of
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13 different PF-based simulation tools. In comparison, current URANS results achieve
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15 smallest error values for all motion, force, and moment components and for both ships.
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17 The total average error values are 10%*DR* for current URANS, followed by Rankine panel
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19 methods with 15%*DR*, Green's function with 31%*DR*, and system-based methods with
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21 45%*DR*. Current results show great promise for URANS as a powerful and reliable tool for
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23 ship-ship interaction studies.
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29 Ship-ship regular head wave results in m-m configuration are compared to single-
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31 ship CFD simulations. Compared to single-ship, heave RAOs increase and peak for both
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33 ships in the resonance region, while the effects on pitch RAOs are insignificant. The 1st
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35 amplitudes of *X* decrease at frequencies lower than the resonant frequency and increase at
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37 the resonant and higher frequencies for both ships.
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42 For the overtaking simulation in regular head waves, URANS time histories are
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44 validated with close agreement to the experimental data. The interaction effects are most
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46 significant during the overtaking and include decreased motions and increased *Y*, *K*, and *N*.
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48 These effects are more significant on Bobo than Hope.
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53 Future work will need to include CFD verification and validation (V&V) studies.
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55 Simulation conditions need to extend for ship-ship interactions in shallow and confined
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57 water, stronger interactions in trapping wave conditions and at coincidence Froude
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5 number, and different geometries with different length ratios. Next step will need to extend
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8 to validation of free-running simulations with propulsor and controllers for resistance and
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11 propulsion, seakeeping, course keeping, and maneuvering in calm water and regular and
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13 irregular seas for deep and shallow conditions.
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Table 1: List of regular wave conditions included in the previous PF-based tool evaluation studies (Silver et al., 2008). **Bold:** conditions included in current URANS studies

Configuration	Spacing (m)	Speed			Heading (deg)	No. of Runs
		(m/s)	Fr_H	Fr_B		
m-m	0.37; 0.74	1.23	0.16	0.19	120; 150; 180	6×6
m-m	0.067	0.38	0.05	0.06	135; 180	2×6

Table 2: URANS simulation conditions

Configuration	Spacing (S)			Speed			Heading	No. of Simulations	Main Reason for Selection
	S(m)	S/L_H	S/L_B	speed ratio (H/B)	Fr_H	Fr_B			
H; B	∞			1.0	0.16	0.19	Calm Water	2	Single-ship
m-m	0.37	0.059	0.091					1	Largest Y, K, and N
H; B	∞			1.0	0.16	0.19	180°	2×6	Single-ship
m-m	0.74	0.12	0.18					6	Comparison with PF-based studies
	0.37	0.059	0.091					6	
	0.74	0.12	0.18					6	
	0.37	0.059	0.091					6	
b-m	0.37	0.059	0.091				120°	6	Sheltering
m-m	0.067	0.0107	0.0165		0.05	0.06	135°	6	Low speed & small spacing + Comparison with PF-based studies
overtaking	0.37	0.059	0.091	1.6	0.16	0.12	180°	1	Overtaking Capability

Table 3: Calm water validation results

	$E\%D$						Average of absolute values				
	σ	τ	X	Y	K	N	Forces/moments	motions	1 st order	Higher order	Avg.
Hope	41.55	31.61	22.17	-21.96	12.37	18.97	18.87	36.58	22.17	25.29	24.77
Bobo	27.15	30.30	0.75	-23.66	20.42	-5.79	12.66	28.73	0.75	21.46	18.01
Average	34.35	30.96	11.46	22.81	16.40	12.38	15.76	32.65	11.46	23.38	21.39

Table 4: Single-ship calm water CFD results compared to ship-ship computations

Percent difference	σ_H	σ_B	τ_H	τ_B	X_H	X_B
$\frac{S_{0.37}-S_{\infty}}{S_{x_c}}\times 100$	23.78	29.46	119.12	-50.55	-3.88	9.98
Average of absolute values	55.73				6.93	
	31.33					

Table 5: Regular wave validation results

		E%DR															
		Hope						Bobo						Average			
		X	Y	K	N	z	θ	X	Y	K	N	z	θ	forces/ moments	motions	1 st order	higher order
Terms	0th	13.53	99.90	20.45	37.22	38.06	69.92	2.42	33.68	23.26	14.66	29.07	35.06	30.64	43.03	11.16	27.13
	1st Amp	36.70	24.92	30.06	30.07	13.34	2.08	33.50	23.18	25.58	7.43	12.76	4.73	26.43	8.23		
	1st Phase	11.17	13.38	12.53	10.68	4.20	8.28	3.44	5.03	7.52	5.12	3.58	6.54	8.61	5.65		
	Avg.	20.47	46.07	21.01	25.99	18.54	26.76	13.12	20.63	18.79	9.07	15.14	15.44	21.89	18.97		
		28.39			22.65			15.40			15.29						
25.52						15.35						19.14					
m-m S _{0.74} 180	0th	13.72	90.07	14.47	41.77	31.02	14.72	1.98	50.42	112.00	4.30	21.64	9.05	41.09	19.10	9.14	24.28
	1st Amp	33.14	20.35	22.12	14.21	5.05	1.07	35.59	14.64	27.41	9.33	5.45	2.27	22.10	3.46		
	1st Phase	5.09	4.59	8.41	3.22	3.64	7.23	4.16	5.29	10.00	5.20	1.72	7.79	5.74	5.09		
	Avg.	17.32	38.34	15.00	19.73	13.24	7.67	13.91	23.45	49.81	6.27	9.60	6.37	22.98	9.22		
		22.60			10.45			23.36			7.99						
16.53						15.67						16.71					
m-m S _{0.74} 120	0th	10.42	13.83	141.33	70.75	18.50	11.09	1.45	29.40	11.92	7.66	10.58	24.25	35.85	16.11	11.21	20.00
	1st Amp	59.17	15.05	14.26	9.56	4.70	3.75	31.84	16.99	19.17	6.61	5.15	11.80	21.58	6.35		
	1st Phase	6.98	4.86	2.04	2.15	3.28	1.48	10.40	1.93	5.04	2.91	1.76	4.69	4.54	2.80		
	Avg.	25.53	11.25	52.54	27.49	8.82	5.44	14.56	16.11	12.04	5.73	5.83	13.58	20.66	8.42		
		29.20			7.13			12.11			9.71						
18.17						10.91						15.6					
m-m S _{0.37} 120	0th	11.04	31.84	54.11	46.59	18.80	38.93	2.27	35.12	19.04	8.18	8.91	14.46	26.03	20.27	10.02	18.24
	1st Amp	46.63	18.89	15.64	12.52	7.74	3.92	28.14	15.50	23.67	6.01	7.52	4.69	20.87	5.97		
	1st Phase	8.63	5.76	6.82	2.02	3.29	4.30	6.54	7.13	6.90	4.38	2.45	3.08	6.02	3.28		
	Avg.	22.10	18.83	25.52	20.38	9.94	15.72	12.32	19.25	16.54	6.19	6.29	7.41	17.64	9.84		
		21.71			12.83			13.57			6.85						
17.27						10.21						14.13					
b-m S _{0.37} 120	0th	10.64	32.55	45.41	54.90	29.92	23.44	2.64	10.54	35.55	30.94	14.32	91.16	27.90	39.71	10.16	20.85
	1st Amp	52.87	12.42	11.16	9.97	5.50	3.62	24.53	10.99	14.87	9.17	9.37	5.64	18.25	6.03		
	1st Phase	3.27	2.10	2.33	1.03	3.07	2.99	10.85	2.69	11.43	1.73	5.31	1.89	4.43	3.31		
	Avg.	22.26	15.69	19.63	21.97	12.83	10.02	12.67	8.07	20.62	13.95	9.66	32.90	16.86	16.35		
		19.89			11.42			13.83			21.28						
15.66						17.56						15.5					
m-m S _{0.067} 135	0th	16.33	16.58	27.94	19.75	43.09	145.59	15.90	5.85	19.00	14.17	39.33	74.03	16.94	75.51	12.54	25.30
	1st Amp	18.30	18.43	19.92	13.55	6.62	5.40	22.52	27.91	16.79	17.69	19.23	15.41	19.39	11.67		
	1st Phase	12.82	8.05	3.48	6.34	7.33	7.43	14.88	5.25	8.59	5.17	6.31	7.09	8.07	7.04		
	Avg.	15.82	14.35	17.11	13.21	19.02	52.81	17.77	13.00	14.79	12.34	21.62	32.18	14.80	31.41		
		15.12			35.91			14.48			26.90						
25.52						20.69						18.92					
Average	0th	12.62	47.46	50.62	45.16	29.90	50.61	4.44	27.50	36.80	13.32	20.64	41.33	29.74	35.62	10.71	22.63
	1st Amp	41.14	18.34	18.86	14.98	7.16	3.31	29.35	18.20	21.25	9.37	9.91	7.43	21.44	6.95		
	1st Phase	7.99	6.46	5.94	4.24	4.14	5.28	8.38	4.55	8.25	4.09	3.52	5.18	6.24	4.53		
	Avg.	20.58	24.09	25.14	21.46	13.73	19.74	14.06	16.75	22.10	8.93	11.36	17.98	19.14	15.70		
		22.82			16.73			15.46			14.67						
19.78						15.06						16.67					

Table 6: Comparison of different computational tools for validation of 1st harmonic values in regular waves for the five simulation conditions indicated in Table 5.

Simulation Type	Tools	Terms	<i>E%DR</i>													
			Hope							Bobo						
			<i>X</i>	<i>Y</i>	<i>K</i>	<i>N</i>	<i>z</i>	θ	<i>X</i>	<i>Y</i>	<i>K</i>	<i>N</i>	<i>z</i>	θ	forces/ moments	motions
System-Based	MVS MVTDS	1st Amp	46.31	133.49	34.02	131.96	36.84	51.06	59.91	159.53	68.23	54.51	35.72	58.09	85.99	45.43
		1st Phase	26.06	25.46	23.38	27.24	25.49	25.96	26.37	24.49	27.11	26.70	23.00	23.95	25.85	24.60
		Avg.	36.18	79.47	28.70	79.60	31.17	38.51	43.14	92.01	47.67	40.60	29.36	41.02	55.92	35.01
			55.99							55.86						
			45.41							45.52						
Green's Function	AQWA ShipMo3D	1st Amp	26.52	44.60	92.19	89.42	6.96	8.53	32.32	42.35	117.36	191.75	10.97	15.32	79.56	10.44
		1st Phase	20.10	18.41	21.53	21.60	9.93	10.84	21.00	24.54	23.08	23.41	9.68	10.98	21.71	10.36
		Avg.	23.31	31.50	56.86	55.51	8.44	9.68	26.66	33.44	70.22	107.58	10.33	13.15	50.63	10.40
			41.79							59.48						
			25.43							35.61						
Rankine Panel Method	LAMP AEGIR	1st Amp	35.85	23.79	16.55	11.01	5.87	6.24	41.22	19.33	22.99	13.58	9.71	6.30	23.04	7.03
		1st Phase	15.84	19.91	15.88	20.23	7.31	11.74	14.64	21.42	23.71	20.93	8.15	11.63	19.07	9.71
		Avg.	25.84	21.85	16.21	15.62	6.59	8.99	27.93	20.38	23.35	17.26	8.93	8.97	21.05	8.37
			19.88							22.23						
			13.84							15.59						
URANS	CFDShip-Iowa	1st Amp	38.79	19.53	20.40	15.98	7.49	3.25	30.32	19.65	22.52	9.41	10.02	7.78	22.08	7.14
		1st Phase	8.94	7.33	6.66	4.88	4.35	5.74	7.89	4.93	7.61	4.56	3.16	5.84	6.60	4.77
		Avg.	23.86	13.43	13.53	10.43	5.92	4.49	19.10	12.29	15.07	6.98	6.59	6.81	14.34	5.95
			15.31							13.36						
			10.26							10.03						

Table 7: Single-ship streaming results $\left(\left| \frac{S_{waves} - S_{calm}}{S_{calm}} \right| \times 100 \right)$ for CFD simulations in head waves

Hope			Bobo			Average		
X	z	θ	X	z	θ	X	z	θ
50.64	1.49	32.49	10.19	1.66	22.21	30.41	1.57	27.35
	16.99			11.94			14.46	
33.81			11.06			22.44		

Table 8: Single-ship regular head wave CFD results compared to ship-ship computations in m-m configuration

		Hope			Bobo		
		X	z	θ	X	z	θ
$(S_{0.74} - S_{\infty})/S_{\infty}$	0 th	-2.91	17.76	68.82	5.10	17.93	-11.06
	1 st Amp	7.84	-6.08	11.88	-8.66	9.51	-3.41
	1 st Phase	15.71	-5.19	-2.01	1.97	-1.23	15.56
	Average of absolute values	8.82	9.68	27.57	5.24	9.56	10.01
		15.36			8.27		
$(S_{0.37} - S_{\infty})/S_{\infty}$	0 th	-3.56	25.69	78.76	8.83	30.28	-42.59
	1 st Amp	-24.39	31.30	13.93	-5.15	24.57	22.18
	1 st Phase	-9.85	-6.68	-8.98	0.57	-0.32	11.10
	Average of absolute values	12.60	21.22	33.89	4.85	18.39	25.29
		22.57			16.18		

Figure 1: Overset grid design and free surface at an instance during the calm water computation

Figure 2: Percent difference of hull pressure distributions between ship-ship and single-ship CFD solutions in calm water normalized by maximum single-ship pressure magnitude

Figure3: 1st amplitudes and phases of motions and X fore for CFD and experiments (EFD) in m-m configuration and 180° waves at $Fr_H=0.16$ including single-ship results

Figure 4: RAOs and phases for CFD and experiments(EFD) in 120° waves at $Fr_H=0.16$

Figure 5: RAOs and phases for CFD and experiments(EFD) in m-m configuration at low speed ($Fr_H=0.05$) and small spacing (0.067 m) in 135° waves

Figure 6: Free surface and non-dimensional hull pressure distributions at an instance during the regular head wave simulation at $f_e=0.96\text{Hz}$; m-m; $S_{0.37}$; $Fr_H=0.16$

Figure 7: Heave and pitch motions for CFD and experiments (EFD) during the overtaking simulation in waves for $S_{0.37}$; $Fr_H=0.16$, $Fr_B=0.12$; in 180° waves at $f_e=0.75\text{ Hz}$ ($\lambda/L_H=0.88$ and $\lambda/L_B=1.36$)

Figure 8: Snapshots of theovtaking simulation in waves