SIMULATION OF SHIP DYNAMICS AND STRUCTURAL RESPONSE BASED ON SPH

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I. INTRODUCTION

In the shipping industry, the most popular current simulation method is based on wave potential theory with linear assumptions to solve ship dynamics and structural responses. This method is time-efficient, and for most wave conditions encountered by ships, the prediction accuracy is sufficient. However, ship accidents often involve rare extreme wave conditions which are difficult to handle using traditional wave potential theory. Although considerable work has been conducted to enhance wave potential models by including nonlinear influences induced by free surface or velocity squared terms, it remains challenging to solve green water or slamming load problems, which can lead to sudden extreme loads on ship structures.

Full nonlinear simulation based on Computational Fluid Dynamics (CFD) and the relevant validation for ship dynamics and structural response are necessary. In this research, we aim to demonstrate the applicability of Smoothed Particle Hydrodynamics (SPH) for simulations of ship pitch motion and vertical bending moment (VBM). To increase prediction accuracy, the boundary condition has been enhanced, and comparisons between model test results and both original and new boundary conditions are presented. The results prove that for both pitch motion and VBM, the new boundary condition can predict more robust results.

II. SPH MODEL

The open-source code DualSPHysics [1] is utilized to solve ship pitch motion and VBM under several wave conditions. To improve the simulation performance, we implemented the dummy particle boundary condition proposed by [2] in the original DualSPHysics and conducted two series of simulations based on different boundary conditions: the original Dynamic Boundary Condition (DBC) and the new Dummy Particle Condition (DPC). In DBC, the solid particles on the boundary are solved in the same manner as fluid particles, except for updating the velocity and coordinates of the solid particles, which are determined by the global movement of the boundary. In contrast, in DPC, the pressure of the dummy particles is determined using equation (1), which is specifically designed for kernel integration of fluid pressure near a solid boundary, taking into account the impact of the pressure gradient.

$$P_w = \frac{\sum_f P_f W_{wf} + (\boldsymbol{g} - \boldsymbol{a}_w) \cdot \sum_f \rho_f \boldsymbol{r}_{wf} W_{wf}}{\sum_f W_{wf}} \tag{1}$$

where subscripts *w* and *f* denote the dummy particles and fluid particles, and $\boldsymbol{a}_w$ corresponds to the dummy particle acceleration, which is solved by equation (2).

$$\boldsymbol{a}_w = -\frac{1}{\rho_f} \nabla P_f + \boldsymbol{g} \tag{2}$$

The density of the dummy particles can be derived from the Tait equation.

Fig.1 shows the definition and direction of the internal force of the ship segment. The unknown parameters in Fig. 1, the horizontal internal force component F_{xi}, the vertical internal force component F_{zi} and the vertical bending moment M_i can be solved by equation (3) as:

$$\begin{gathered}
F_x^i = (a_x - a_{pitch} r_z^i) m^i - F_{ex}^i + F_x^{i-1} \\
F_z^i = (a_z + a_{pitch} r_x^i + g) m^i - F_{ez}^i + F_z^{i-1} \\
M^i = (a_{pitch}) I^i - M_e^i - F_x^{i-1} r_{s1\_z}^i + F_z^{i-1} r_{s1\_x}^i + M^{i-1} \\
+ F_x^{i1} r_{s2\_z}^i - F_z^i r_{s2\_x}^i
\end{gathered} \tag{3}$$

where, the superscript *i* denotes the segment id, the a_x, a_z and a_{pitch} are the ship acceleration in surge, heave, and pitch direction. m^i, I^i are the mass and moment of inertia of the segment. More detailed discussion about the calculation of VBM can be found in [3].

III. 3D SIMULATION FOR SHIP MOTION AND VERTICAL BENDING MOMENT

The numerical simulations is validated using experimental data from [4], which utilized a 1/65 scale model of a 6750 TEU container ship. Table 1 presents the main dimensions of this scale model.

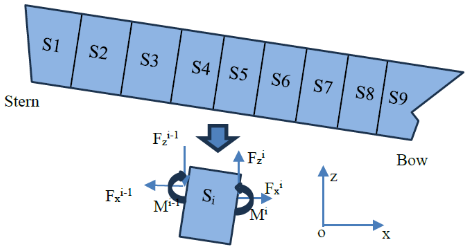

Figure 1. Definition of the internal force of ship segment

TABLE 1. MAIN DIMENSIONS OF THE TARGET SHIP

	Ship	**Model Ship**
Lpp (Length between Perpendiculars, m)	286.6	4.41
B (Breadth, m)	40	0.615
T (Draft, m)	11.98	0.184
Displacement (ton)	85724.7	0.3121
KG (Vertical center of gravity, m)	16.562	0.253
K_{yy} (Radius of gyration, m)	70.655	1.087

The experimental setup included four mooring lines attached to the model ship (Fig. 2) to counteract wave drift effects. In the SPH simulation, we represented these mooring lines as linear springs using the Chrono model. Fig. 3 shows the complete numerical model generated by SPH. We constructed a numerical water tank measuring 12m × 3.6m × 2m (length × width × depth), with a 1.5m damping zone at its end to minimize wave reflection effects. Further details of the SPH model implementation can be found in our previous work [5].

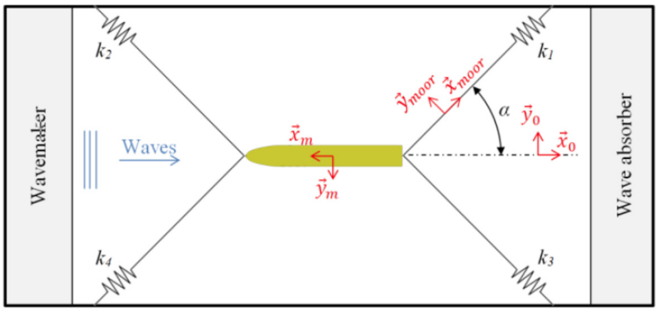

Figure 2. Arrangement of the model test

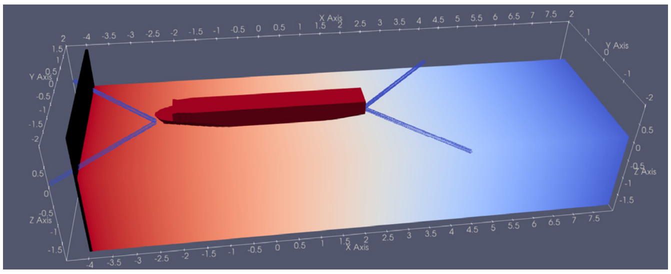

Figure 3. Numerical model based on SPH

For validation, the regular waves approaching from the head direction (180 degrees) is generated while the ship remained stationary. Following the experimental setup, five distinct wave conditions (detailed in Table 2) are selected to evaluate SPH performance.

TABLE 2. REGULAR WAVE CONDITIONS

Wave ID	**Wave Height (m)**	**Wave Period (s)**	**Wave Stiffness**
Wave_1	0.09	1.68	2.1%
Wave_2	0.17	1.67	3.8%
Wave_3	0.23	1.66	5.2%
Wave_4	0.38	1.62	8.7%
Wave_5	0.46	1.59	10.5%

To investigate different fluid-solid interaction approaches, two numerical models based on DBC and DPC are built. Besides, two different particle dimensions are employed to assess how particle size affects the robustness of both boundary conditions.

IV. RESULTS

Fig. 4 shows the comparison of the amplitude of the pitch. The horizontal axis corresponds to the wave height. In addition to the SPH simulation results, which include the results based on DPC and DBC with two different particle sizes (0.015m and 0.03m), the experimental data (labeled as "exp") and the simulation results based on nonlinear potential theory, referred to as BEM, are also included. It can be seen that for the case with a water height of less than 0.3m, the nonlinear potential theory has a good correlation with the model test data, while the SPH tends to underestimate the pitch. However, the DPC underestimates less compared to the DBC. The influence of particle size is also relatively larger in DBC compared to DPC. When the wave height increases to 0.38m and 0.46m, which belong to the 3rd and 4th order Stokes wave regions, the nonlinear potential theory clearly overestimates the pitch, while the DPC shows the best correlation with the model test data. Similarly, the accuracy of DBC is more dependent on the particle size. Fig. 5 provides the time history of pitch for wave condition Wave_5, when the wave height is the largest.

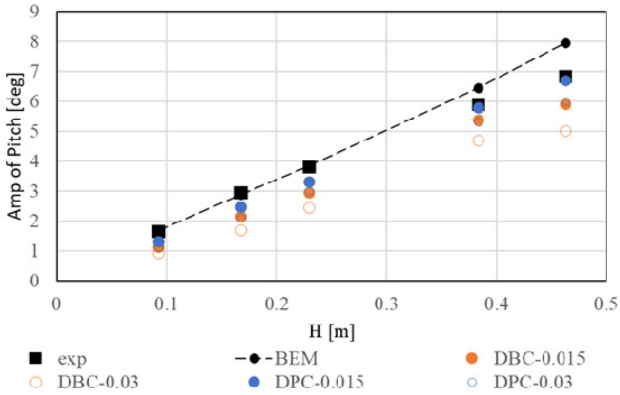

Figure 4. Comparison of pitch amplitude

Fig. 6 presents a comparison of the VBM amplitudes. For small waves, when wave height is larger than 0.3m, SPH models using both DBC and DPC exhibit better correlation with model tests compared to the pitch. In severe wave conditions (wave height > 0.3m), the DPC model demonstrates higher accuracy than the DBC model. Furthermore, as the particle size increases, the accuracy of the DBC model diminishes more rapidly than that of the DPC model. It is important to note that both SPH models underestimate the VBM in the most extreme wave cases. While the influence of the elastic hull is not considered in either the model tests or the SPH simulations, the connections between segments of the ship model exhibit some elasticity. This elasticity contributes to a high-frequency VBM component that becomes significant in high waves and cannot be neglected. Removing this high-frequency component influence should improve the correlation between model test data and SPH results. Fig. 7 illustrates the time history of VBM for wave condition Wave_5. The high-frequency component in model test is clearly observed. Although the peak-to-peak amplitude of the nonlinear potential model matches the model test, the mean value is lower. In contrast, the SPH results, particularly for the DPC model, accurately predict not only the peak-to-peak amplitude but also the mean value, aligning closely with the model test data. Additionally, the simulated wave profile exhibits better agreement with the model test data.

V. CONCLUSIONS

In this research, the ship pitch and vertical bending moment are simulated using SPH method. Five regular wave conditions with different wave heights are used to investigate the influence of wave height on the SPH simulation performance. Two boundary conditions are used to demonstrate the effects of the boundary conditions. Regarding pitch motion, the SPH underestimates the pitch when the wave height is small, where the potential theory always performs well. As the wave height increases, the performance of the SPH improves significantly. For the vertical bending moment, the SPH shows acceptable accuracy for both low and high wave conditions. For high wave conditions, the SPH successfully generates a VBM similar to that of the model test, including both linear and nonlinear components. Regarding the boundary conditions, the DPC demonstrates better accuracy for both pitch and VBM. Additionally, the accuracy of the DBC shows a larger dependency on the particle size. Overall, for ship simulations under extreme wave conditions, when traditional potential flow theory becomes inapplicable, SPH shows promise as a reliable and alternative simulation technique. The feasibility of employing SPH for ship simulations under irregular waves requires further investigation and will be explored in future work.

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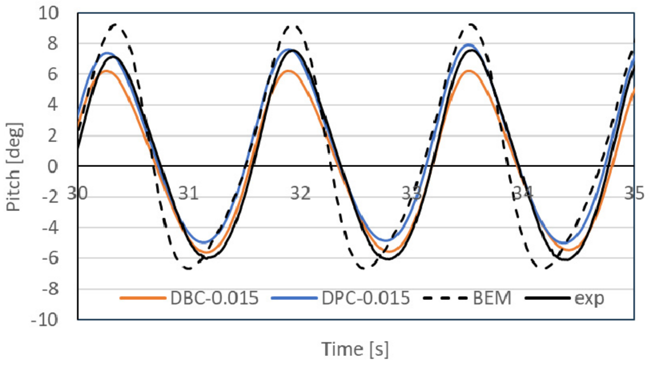

Figure 5. Comparison of time history for pitch (DP=0.015m)

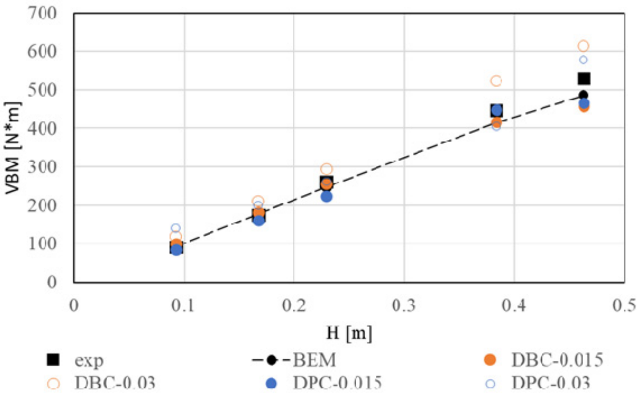

Figure 6. Comparison of VBM amplitude

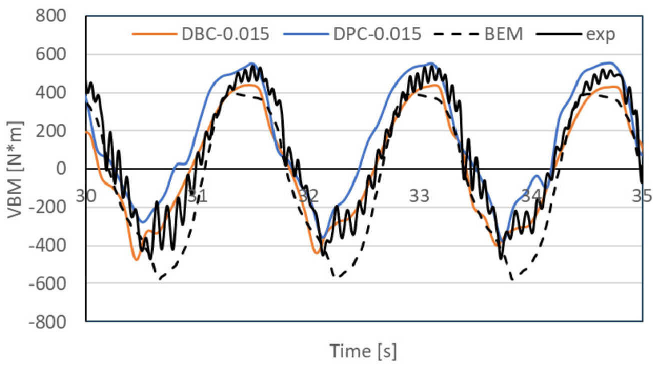

Figure 7. Comparison of time history for VBM (DP=0.015m)