3D GPU-Based SPH Simulation of Water Waves Impacting on A Floating Object

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***Abstract*—Smoothed particle hydrodynamics (SPH) is meshless-based numerical method to simulate free-surface flow problems. In this paper, water wave impact on a floating object is studied by implementing SPH method. An open-source DualSPHysics code which is developed based on SPH theory is used to simulate three-dimensional (3D) free-surface flow with floating object. Graphical processing units (GPUs) parallel computing is applied to accelerate computational time of SPH method. The simulation is aimed to investigate the effect of water wave impact on floating object. The water wave is generated by piston-type wave maker in a flume. The frequency of piston is varied from 0.1 Hz to 0.6 Hz to evaluate vertical displacement of floating object. The simulation of free-surface flow and its interaction with floating object mimics a physically realistic phenomenon. It is obtained that the highest vertical displacement of floating object is achieved when piston frequency is 0.3 Hz. The piston frequency of 0.4 Hz – 0.6 Hz yields high impact which makes the floating object is drowned and pushed to shoreline faster than other frequencies.**

Keywords*—*SPH method; water waves; floating object; DualSPHysics; parallel computing; numerical simulation

I. Introduction

Floating object on free-surface has become an interesting problem in ocean and coastal engineering especially in ship hydrodynamics application. In building a new harbor, it is important to consider the effects of the water waves impact on both small and large ships which can be considered as floating objects. In this case, some researchers are usually prefer to perform computer simulation compared to a direct experiment due to expensive effort. The most familiar numerical methods to conduct computer simulation are finite element method (FEM), finite difference method (FDM), finite volume method (FVM), and smoothed particle hydrodynamics (SPH) method. The FEM, FDM, and FVM are mesh/grid-based methods which are very difficult to implement in floating objects simulation. In contrast, SPH is meshfree Lagrangian method which has the capability in simulating floating objects on free-surface.

In SPH method, the water domain is discretized into many small particles. Each SPH particle has certain physical properties such as position, mass, density, velocity, acceleration, and pressure. The motion of each SPH particle is governed by the momentum and continuity equation. Compared to the grid/mesh-based numerical method, the SPH method is easily implemented to the cases with complex geometries even involving floating objects. SPH method has been widely used in solving various science and engineering cases such as tsunami, dam break, flood, wave breaker, and water wave impact on floating objects. Review in SPH method and its application can be found in [1].

Water wave impact on solid structure and floating object has been studied by many researchers. Most of them used SPH method because of its capability. Dalrymple and Rogers [2] successfully modeled breaking waves and wave-structure interaction near beaches while Gomez and Dalrymple [3] analyzed long wave impact on tall structure. Furthermore, Pan et al. [4] studied SPH method to simulate water wave impact on floating offshore structures. Further study on the interaction between fluids and floating objects using the SPH method could be found in [5]–[7]. Recently, Zhang et al. [8] provided a review of recent developments of fluid-structure simulation using SPH method. Unfortunately, in SPH method, to obtain realistic simulation results, it should use thousands and even millions of SPH particles which make long computational time. As consequence, many researchers developed the SPH method with parallel computing.

DualSPHysics is a SPH-based source code to simulate free-surface flow problems [9]. DualSPHyics runs on parallel computing power of graphical processing units (GPUs). In addition, DualSPHysics can also perform parallel computing in multicore central processing units (CPUs). DualSPHysics has been validated using both analytical and experimental data [10], [11]. DualSPHysics has also been widely used to simulate many coastal engineering problems. Suzuki et al. [12] investigated the drag coefficient in vegetation using DualSPHysics. Altomare et al. [13] used DualSPHysics to simulate the wave impact on coastal structure. Ni and Feng [14] simulated overtopping and regular wave run-up using DualSPHysics. Similarly, Panalaran et al. [15] used DualSPHysics to model wave force on cylinder groups. Recently, Crespo et al. [16] used DualSPHysics code to simulate sea waves impact on a floating offshore oscillating water column device. Moreover, Altomore et al. [17] proposed the new wave generation algorithm and active absorption based on DualSPHysics model.

This paper presents numerical simulation of water waves impact on a floating object. In this study, a small boat with certain dimension is considered as a floating object and is placed near shoreline. The simulation is aimed to study vertical displacement of the small boat when hit by the sea wave force. Some applications that require this simulation are floating oscillating water column (OWC) device, design of a ship mooring system, floating breakwater system, design of floating offshore system, ship and harbor design. The numerical simulation is based on SPH method which is implemented in DualSPHysics source code. GPUs parallel computing is used to run the DualSPHysics code. Similar study of interaction between a boat and sea wave is also presented by Crespo et al. [9]. However, in their study, the vertical displacement of the boat is not discussed. This paper is structured as follows. In Section 2, the SPH theory is briefly discussed. The simulation setup and discussion of simulation results are presented in Section 3 and Section 4, respectively. In Section 5, the conclusions and future works of this study are given.

II. SPH Theory

DualSPHysics is build based on smoothed particle hydrodynamics (SPH) theory. In SPH theory, the continuum fluid domain is discretized into set of particles or points where each particle or point has physical properties such as position, density, velocity, pressure, and energy. The physical properties of each SPH particle are calculated based on contribution of neighboring particles. Mathematically, the SPH theory is derived based on integral interpolation concept, i.e. any function f can be represented by integral form [16]:

$$f(\mathbf{r}) = \int_{\Omega} f(\acute{\mathbf{r}})W(\mathbf{r}-\acute{\mathbf{r}}, h)d\acute{\mathbf{r}}, \quad (1)$$

where Ω is the influence domain, $\mathbf{r}$ is vector position, h is smoothing length, and W is weighting function.

Equation (1) can be represented into discrete form by considering set of particles. Let a be a particle in Ω and b is neighboring particles of a within compact support of W, then for particle a, (1) can be expressed as [16]

$$f(\mathbf{r}_a) \approx \sum_b f(\mathbf{r}_b)\frac{m_b}{\rho_b}W(\mathbf{r}_a-\mathbf{r}_b, h), \quad (2)$$

where m and ρ represent mass and density, respectively.

The fluid motion is governed by two equations, i.e. Navier-Stokes and continuity equation. The Navier-Stokes equation or conservation of momentum in continuum field can be expressed as

$$\frac{D\mathbf{v}}{Dt} = -\frac{1}{\rho}\nabla P + \mathbf{g}, \quad (3)$$

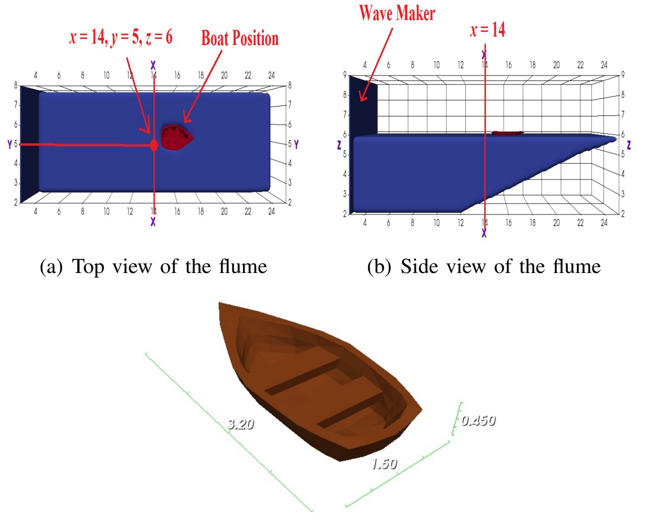
where $\mathbf{v}$, ρ, and P are velocity, density and pressure of the fluid, respectively. Further, $\mathbf{g} = (0, 0, -9.81)$ m/s^2 is gravitational acceleration. In SPH formulation, for particle a, equation (3) can be expressed as [17]

$$\frac{\mathrm{d}\mathbf{v}_a}{\mathrm{d}t} = -\sum_b m_b\left(\frac{P_b+P_a}{\rho_b\rho_a}+\Pi_{ab}\right)\nabla_a W(\mathbf{r}_a-\mathbf{r}_b, h)+\mathbf{g}, \quad (4)$$

where P_b and ρ_b are pressure and density corresponding to particle b. Further, Π_{ab} is artificial viscosity proposed by Monaghan [1].

Conservation of mass is represented as continuity equation which is formulated as

$$\frac{D\rho}{Dt} = -\rho\nabla\cdot\mathbf{v}. \quad (5)$$



(a) Top view of the flume (b) Side view of the flume

(c) Dimension of the boat

Fig. 1. Initial setup of floating boat simulation with 19068 of fluid particles. (a) Top view of flume; (b) Side view of flume; (c) Boat size.

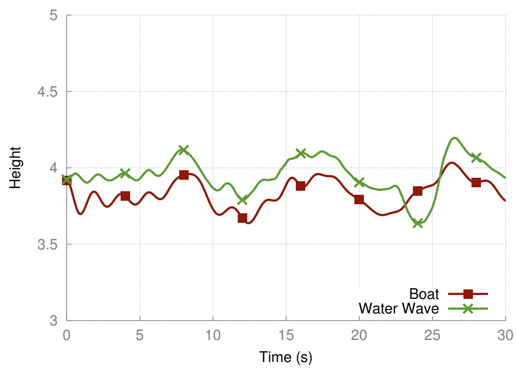


Fig. 2. Water wave elevation located at $(14, 5, 6)$ and boat vertical displacement versus time for piston frequency $\omega = 0.1$ Hz.

By using (2), for particle a, equation (5) can be expressed in SPH formulation as [17]

$$\frac{\mathrm{d}\rho_a}{\mathrm{d}t} = \sum_b m_b(\mathbf{v}_a-\mathbf{v}_b)\cdot\nabla_a W(\mathbf{r}_a-\mathbf{r}_b, h). \quad (6)$$

The relation between pressure and density can be expressed in equation of state. Therefore, pressure of SPH particle can be calculated from the density property of the SPH particle. In this simulation, the fluid is considered as incompressible. As discussed in [19], [20], the equation of state is represented as

$$P = B\left[\left(\frac{\rho}{\rho_0}\right)^{\gamma} - 1\right] \quad (7)$$

where $\rho_0 = 1000$ kg/m^3 is the reference density, $\gamma = 7$ is polytrophic constant, $B = c_0^2\rho_0/\gamma$, and c_0 is the speed of sound at the reference density. More details about SPH formulation can be found in [9].

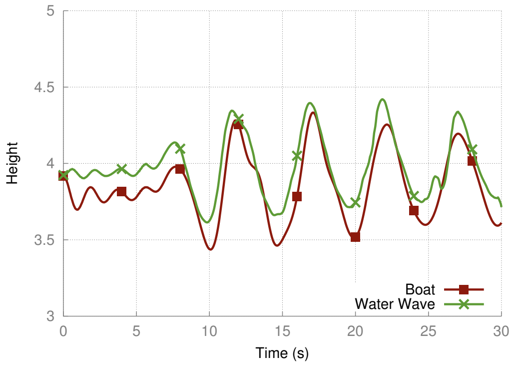


Fig. 3. Water wave elevation located at $(14, 5, 6)$ and boat vertical displacement versus time for piston frequency $\omega = 0.2$ Hz.

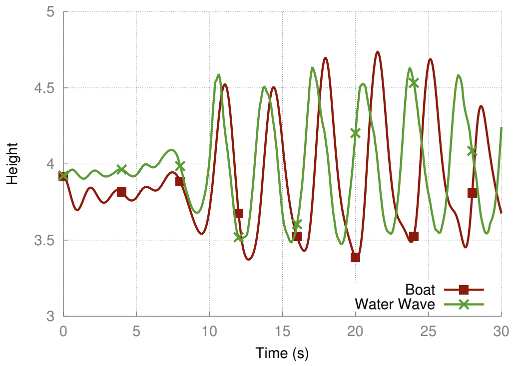


Fig. 4. Water wave elevation located at $(14, 5, 6)$ and boat vertical displacement versus time for piston frequency $\omega = 0.3$ Hz.

III. Simulation Setup

DualSPHysics is designed to simulate real-life engineering and science problems such as dam break, tsunami, floating objects, pump model, and wave maker. The DualSPHysics code is an implementation of SPH method which is written in C++ and CUDA language. The DualSPHysics can run either on the CPUs and GPUs. It has been validated with experimental data and has been proven to be efficient and reliable [9]. In this simulation, the DualSPHysics code is running on GPU with computer specification: Processor Intel Core i3 3rd gen 3217u 1.8 GHz, GPU Nvidia 820m with dedicated VRAM 2

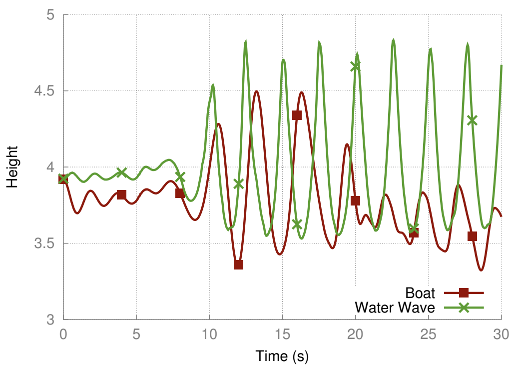


Fig. 5. Water wave elevation located at $(14, 5, 6)$ and boat vertical displacement versus time for piston frequency $\omega = 0.4$ Hz.

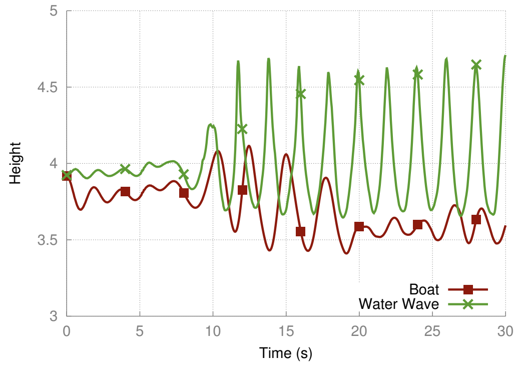


Fig. 6. Water wave elevation located at $(14, 5, 6)$ and boat vertical displacement versus time for piston frequency $\omega = 0.5$ Hz.

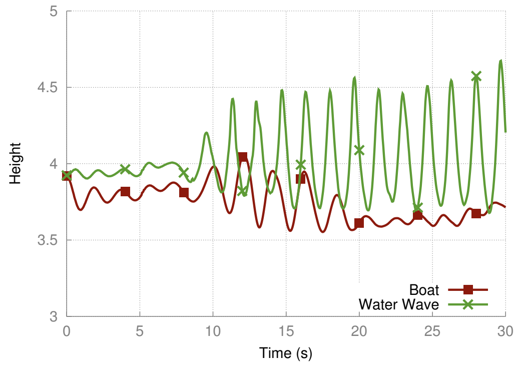
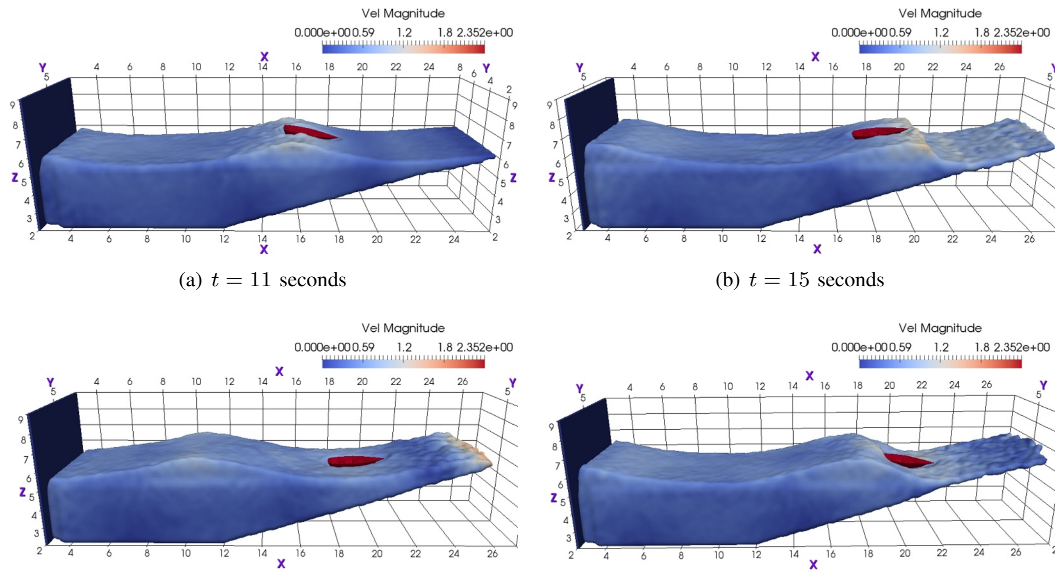


Fig. 7. Water wave elevation located at $(14, 5, 6)$ and boat vertical displacement versus time for piston frequency $\omega = 0.6$ Hz.

GB, and RAM 4 GB. One of the advantages of DualSPHysics is the complex geometry such as a floating object can be build and moved easily over free-surface. A boat with dimension 3.20 m $\times$ 1.5 m $\times$ 0.45 m is considered as a floating object. Here, 19068 of SPH particles are used to simulate a floating boat on free-surface.

The simulation is aimed to investigate the effect of water wave impact on the floating boat. Fig. 1 shows initial setup of the simulation. The water wave is generated by piston-type wave maker which is located on the left of flume. The geometry of flume is made to resemble the coast with the slope is about 18.4°. The dimension of the flume is 23 m $\times$ 7 m $\times$ 4 m. In this simulation, the wave elevation of fluid and vertical displacement of the boat are investigated. As illustrated in Fig. 1, the location to observe water wave elevation is at $(14, 5, 6)$ while the vertical displacement of the boat is measured on a point at the bottom rear of boat. At initial, mean water level is located at $z = 4$ m and the boat is placed at $x = 14$ m on the free-surface of water. The simulation is started by flipping the piston 5 seconds after the boat placed.

The water wave impact on the boat is investigated by varying the piston frequency. In this simulation, the frequency of piston is varied from 0.1 to 0.6 Hz. In each piston frequency, the wave elevation and vertical displacement of boat is evaluated. The visualization of water wave impact on floating object is rendered by an open source software Paraview [18].



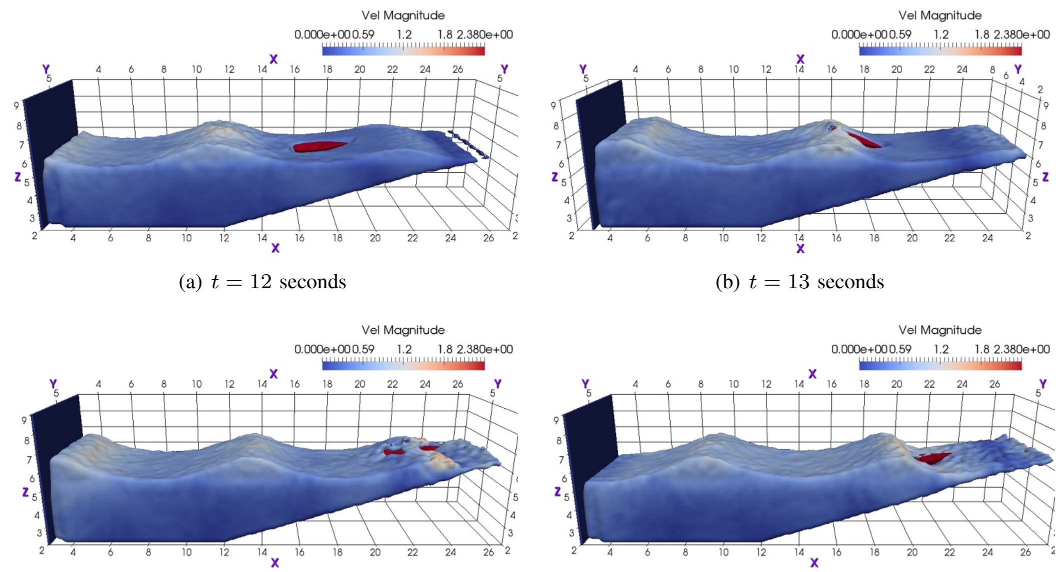
(a) $t = 11$ seconds

(b) $t = 15$ seconds

(c) $t = 20$ seconds

(d) $t = 28$ seconds

Fig. 8. The free surface flow and the position of floating boat simulated by DualSPHysics for piston frequency $\omega = 0.3$ Hz at (a) $t = 11$, (b) $t = 15$, (c) $t = 20$, and (d) $t = 28$ seconds.



(a) $t = 12$ seconds

(b) $t = 13$ seconds

(c) $t = 20$ seconds

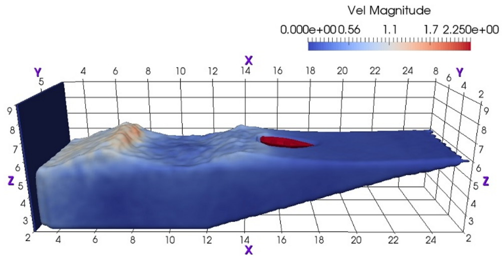
(d) $t = 29$ seconds

Fig. 9. The free surface flow and the position of floating boat simulated by DualSPHysics for piston frequency $\omega = 0.4$ Hz at (a) $t = 12$, (b) $t = 13$, (c) $t = 20$, and (d) $t = 29$ seconds.

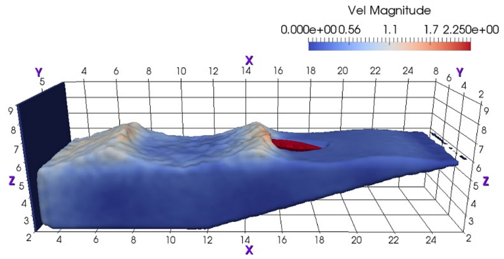
IV. Results and Discussion

In general, the simulation of water wave impact on floating object mimics a physically realistic phenomenon, as shown in Fig. 8 – Fig. 11. Further, Fig. 2 shows wave elevation of water and vertical displacement of boat versus time for $\omega = 0.1$ Hz. From the figure, it can be observed that there is small amplitude of wave generated by the piston within this frequency. As a result, the boat is only experienced small disturbance from this impact. It is obtained that the highest and lowest vertical displacement of the boat are about 0.0335 m and -0.3619 m, respectively. Negative value of vertical displacement means that the position of boat is below mean water level. Furthermore, wave elevation and vertical displacement of boat for $\omega = 0.2$ Hz are shown in Fig 3. It can be seen that the boat position is still stable and following the wave elevation. For $\omega = 0.2$ Hz, the highest and lowest vertical displacement of the boat are about 0.3330 m and -0.5637 m, respectively.

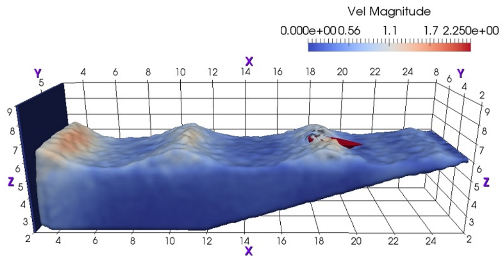
Significant changes to the vertical displacement of boat is depicted by Fig. 4. It can be seen that by using frequency of piston $\omega = 0.3$ Hz, the boat can move up until 0.7355 m above mean water level and move down until 0.6265 m below mean



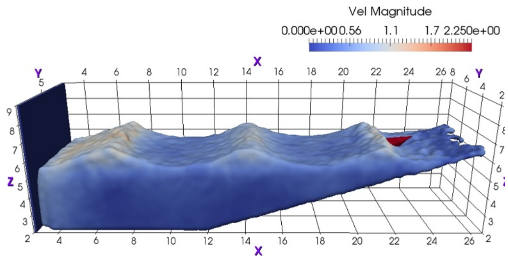
(a) $t = 10$ seconds



(b) $t = 12$ seconds

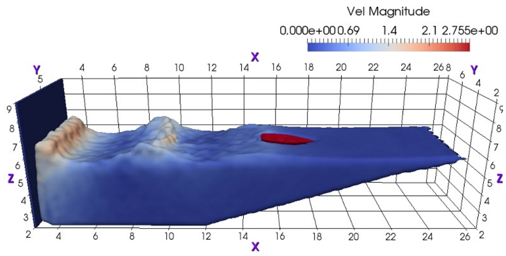


(c) $t = 15$ seconds

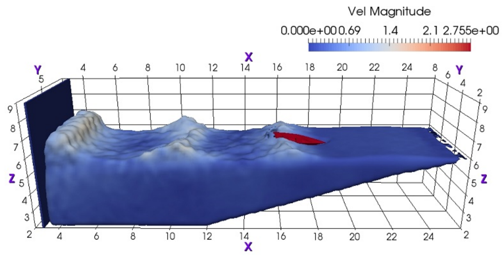


(d) $t = 20$ seconds

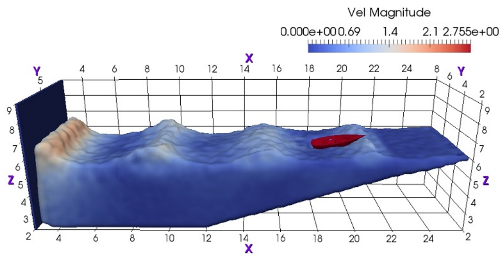
Fig. 10. The free surface flow and the position of floating boat simulated by DualSPHysics for piston frequency $\omega = 0.5$ Hz at (a) $t = 10$, (b) $t = 12$, (c) $t = 15$, and (d) $t = 20$ seconds.



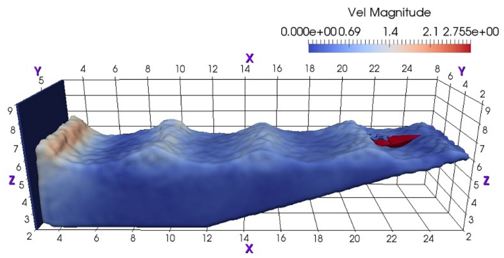
(a) t = 10



(b) t = 12



(c) t = 15



(d) t = 20

Fig. 11. The free-surface flow and the position of floating boat simulated by DualSPHysics for piston frequency $\omega = 0.6$ Hz at (a) $t = 10$, (b) $t = 12$, (c) $t = 15$, and (d) $t = 20$ seconds.

water level. Fig. 8 displays simulation results of water wave impacting on floating boat at $t = 11$, $t = 15$, $t = 20$, and $t = 28$ seconds. It can be observed from the figure that water wave is impacting the boat at $t = 11$ seconds and the boat experiences severe shock at $t = 28$ seconds which makes it is almost drowned.

From Fig. 5, it can be shown that the highest and lowest vertical displacement of boat at piston frequency $\omega = 0.4$ Hz are 0.4966 m and -0.6733 m. The free-surface flow and the position of floating boat at piston frequency $\omega = 0.4$ Hz for several time are illustrated in Fig. 9. This figure reveals that at $t = 13$ seconds, the wave is impacting on the boat which makes some of water is entering the boat. It also can be seen that at $t = 20$ seconds, the boat reaches shoreline so that there is no significant vertical displacement after this time.

Fig. 6 shows wave elevation and vertical displacement of boat for piston frequency $\omega = 0.5$ Hz. By using this frequency, the wave maker produces more wave than piston with frequency below 0.5 Hz. As a result, the water wave is pushing the boat into shoreline faster than other frequency. By Fig. 10, it also can be observed that the boat is sinking after $t = 20$ seconds. Further, piston frequency $\omega = 0.6$ Hz has

TABLE I. VERTICAL DISPLACEMENT OF THE BOAT ABOVE MEAN WATER LEVEL

ω (Hz)	maxVD[a] (m)	minVD[b] (m)	max wave elevation (m)
0.1	0.0335	−0.3619	0.1963
0.2	0.3330	−0.5637	0.4202
0.3	0.7355	−0.6275	0.6311
0.4	0.4966	−0.6773	0.8311
0.5	0.1149	−0.5892	0.7099
0.6	0.0539	−0.4469	0.6734

[a]maxVD = maximum vertical displacement of boat
[b]minVD = minimum vertical displacement of boat

resulted shorter wave length than frequency below 0.6 Hz and it is displayed by Fig. 11. From the figure, it can be seen that the water wave propagates very slow.

The maximum and minimum vertical displacement of the boat compared to the maximum wave elevation are summarized in Table I. It can be seen that the highest of vertical displacement is reached at piston frequency of 0.3 Hz. It also can be observed that the lowest of vertical displacement of the boat is attained when the wave elevation is the highest, i.e. at piston frequency $\omega = 0.4$ Hz. As predicted, the piston with frequency 0.4 Hz, 0.5 Hz and 0.6 Hz yields high impact and pushes the boat to shoreline quickly so that the vertical displacement of the boat does not fluctuate after 20 seconds. In contrast, the boat movement with piston frequency of 0.1 Hz, 0.2 Hz and 0.3 Hz follows the wave elevation so that by these frequencies yield small boat oscillation.

V. CONCLUSION AND FUTURE WORKS

The 3D numerical simulation of water waves impact on a floating object has been successfully conducted. An open-source DualSPHysics code under GPUs parallel computing has been used to run the simulation. Vertical displacement of floating object on free-surface flow has been evaluated by varying the piston-type wave maker frequency. From the numerical results, it can be concluded that the highest vertical displacement of floating object is about 0.7355 m above mean water level which is achieved at piston frequency of 0.3 Hz. Furthermore, by applying piston frequency from 0.4 Hz to 0.6 Hz has made the floating object is drowned and moves faster to shoreline. Although, it has been achieved the reasonable results, the numerical model needs some improvements such as validation with experimental data and compared with other numerical methods.

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