Numerical simulation of green water on S-175 containership

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ABSTRACT

The green water phenomenon of the S-175 containership in different head waves was simulated by our own solver naoe-FOAM-SJTU. The whole process of a green water event was observed and the nonlinear motion response in head waves under different conditions was achieved. The comparison between numerical results and experimental data were quantified. Good agreement shows the naoe-FOAM-SJTU solver is applicable and reliable to study green water problem.

KEY WORDS: Green water on deck; naoe-FOAM-SJTU solver, S-175 ship model.

INTRODUCTION

Green water is a phenomenon when ships encounter waves, plenty water surpasses freeboard and flushes onto the deck. Severe water on deck could not only cause active speed loss and course changing of ships, but also damage equipment and superstructures on the deck. For this reason, the green water phenomenon is of great importance during ship design process and many researchers have done lots of studies on this phenomenon through model tests, theoretical research and numerical simulations.

Buchner[1] conducted a FPSO model test in MARIN basin, and discussed the influence of wave height, wave period, current velocity and the shape of breakwaters on the ship motion and the impact loading on superstructures. Fonseca[2] carried out a series of model tests to study how the bow of a containership affects the green water. Model tests were carried out using S-175 containership in head regular and irregular waves of large amplitude. They measured the relative motions, the structural loads, the height of water and the impact pressure on the deck. The effect of the horizontal impact pressure and total force on the bow was discussed. Tanizawa et al.[3] reported that depending on the wavelength, the interaction between ship bow and waves could result in reflected water by the bow and the major shipment of water onto the deck. One of the important conclusions was that the air entrapment during the impact could account for the fluctuation in the impact pressure curves they recorded.

Theoretical research is another way to study green water phenomenon. This method always takes some simplification of physical problems. Hoffman and Maclean[4] used linear strip theory to get the relative motion of ship and wave, then modified the response amplitude operator (RAO's) of the wave-body relative motion based on swell-up coefficient acquired from model test. Using swell-up coefficient can effectively improve the accuracy to predict the green water phenomenon. Most theoretical methods are based on potential flow theory. These methods can deal with special stage of green water phenomenon, but can not acquire necessary accuracy when ship is in large amplitude nonlinear motion.

Green water phenomenon is a strong nonlinear ship-wave interaction, and traditional model tests and theoretical researches could only describe some of green water processes due to their oversimplification of physical problems. With the rapid development of computation technology, computational fluid dynamics (CFD) has shown great advantages to deal with green water problems, and makes it possible to study physical mechanism of green water. Stansberg et al.[5] compared the experimental results from a green water test using a stationary FPSO model with CFD simulation results. It was found that CFD based on VOF technique could predict the water propagation on deck and the impact load on a vertical surface very well. Zhu[6] studied both 2D and 3D green water phenomenon of FPSO by commercial software FLUENT. He took advantages of both the virtues of potential flow theory and CFD technique to simulate green water phenomenon. In the 3D case, they considered the effect of heave and pitch motion on green water and their results agree well with experimental ones. This validated the effectiveness of their approach to predict and analyze impact loads on floating structures due to green water. Zhang et al.[7] studied both 2D and 3D green water phenomenon using Moving Particle Semi-implicit Method (MPS), and found that particle method can effectively deal with the complicated free surface deformation.

In this paper, our in-house CFD solver naoe-FOAM-SJTU is used to study green water phenomenon of the S-175 containership model. The ship is considered advancing in head waves with different wavelengths (λ/L_{pp}=1.0,1.2,1.4). The wave height is 0.15 m and the Froude number is 0.25. The ship model is free to sinkage and trim. The predicted RAO's of motions are compared with experiment data. The green water phenomenon can be observed in all the wave conditions. The whole process of a green water event can be simulated using our naoe-FOAM-SJTU solver, which shows that the current approach can be an alternative tool to study the green water phenomenon.

NUMERICAL METHODS

Green water phenomenon is mainly the affected by two mechanisms: wave propagation and ship motion. Green water and its impact on superstructures may cause damage on a ship. So it is essential to accurately simulate the process of green water phenomenon. Based on the open source tool packages, OpenFOAM, a CFD solver named naoe-FOAM-SJTU has been developed. This solver is designed for computing viscous flows of ships and ocean structures[8, 9, 10, 11]. The CFD code naoe-FOAM-SJTU solves Navier-Stokes equations for unsteady turbulent flows with VOF method capturing free surface[12, 13]. The wave making and damping module is developed to generate desired incident waves and avoid the influence of wave reflection from the outlet boundary.

Governing Equations

In this paper, an incompressible Reynolds-Average Navier-Stokes (RANS) equation are used to address the unsteady incompressible viscous flow. It is shown as followings:

$$\nabla \cdot \mathbf{U} = 0 \tag{1}$$

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla(\rho(\mathbf{U} - \mathbf{U}_g)\mathbf{U}) = -\nabla p_d - \mathbf{g}\cdot\mathbf{x}\nabla\rho + \nabla\cdot(\mu_{eff}\nabla\mathbf{U}) + (\nabla\mathbf{U})\cdot\nabla\mu_{eff} + f_\sigma \tag{2}$$

Where U and U_g are the velocity field and the velocity of grid nodes, respectively. $p_d = p - \rho\mathbf{g}\cdot\mathbf{x}$ is the dynamic pressure and p is the total pressure, ρ is the mixed density with water and air. $\mu_{eff} = \rho(\nu - \nu_t)$ is the effective dynamic viscosity, in which ν and ν_t are kinematic viscosity and eddy viscosity, respectively. f_σ is the surface tension caused by the free surface. f_s is the source term introduced because of wave damping.

Interface Capturing

The free surface is captured by the VOF method with artificial bounded compression techniques. The same set of equations are used to solve air and water during simulation, and the different phases are marked using volume fraction α.

$$\begin{cases} \alpha = 0 & \text{air} \\ 0 < \alpha < 1 & \text{interface} \\ \alpha = 1 & \text{water} \end{cases} \tag{3}$$

α obeys the following transport equation:

$$\frac{\partial \alpha}{\partial t} + \nabla\cdot(\alpha\mathbf{U}) + \nabla\cdot[\alpha(1-\alpha)\boldsymbol{U_r}] = 0 \tag{4}$$

Instead of using free surface reconstruction method to acquire free surface, we add a pseudo compressibility term in VOF transport equation, which can get good accuracy, stability and efficiency of the simulation.

Wave Generation and Damping

Our naoe-FOAM-SJTU solver includes a wave generation and damping module. We use the following equations in the wave generation module to generate waves at the inlet of the computational domain[14]:

$$\xi(x,t) = a\cos(kx - \omega_e t) \tag{5}$$

$$U(x,y,z,t) = U_0 + a\omega e^{kz}\cos(kx - \omega_e t) \tag{6}$$

$$W(x, y, z, t) = a\omega e^{kz} \sin(kx - \omega_e t) \tag{7}$$

Where ζ is transient wave elevation, a, ω and k are wave amplitude, wave frequency and wave number, respectively. U_0 is ship speed.

Ship Motions

In naoe-FOAM-SJTU solver, a 6DOF module is developed to predict the ship motions. This method includes two coordinate systems: one is earth fixed system and the other is ship fixed system. At the initial condition, the two systems are parallel. With movement of ship, the solver calculates the forces and moments in the earth-fixed system and then transforms them to ship-fixed system. The motions of ship are implemented by employing a moving-mesh technique. The topology of the mesh does not change while the ship is moving, but only the spacing between nodes changes by stretching and squeezing and cell shape deforms. Shen et el.[9] has validated the ability of our naoe-FOAM-SJTU solver in dealing with large amplitude motion of ship.

GEOMETRY AND CONDITIONS

Geometry

In the present work, the S-175 containership model is applied to study the green water problems. It is a benchmark case to study sea-keeping capability with adequate experimental data. The block coefficient of the ship is 0.5716 and the scale factor is 1:70. A vertical baffle was added at the bow to simulate the influence of green water on the superstructures. The geometry of the S-175 model is shown in Fig. 1. Main particulars of S-175 containership at both full scale and model scale are shown in Table 1.

Fig. 1 geometry of S-175 model

Table 1 Main particulars of S-175

Main particulars	Full-scale	Model
L_{pp} (m)	175.0	2.5
B (m)	25.4	0.363
D (m)	15.4	0.22
d (m)	9.5	0.136
Δ (m)	24138.5	0.07213
GM (m)	1.0	0.014
C_b	0.5716	0.5716
K_{yy}/L_{pp}	0.24	0.24
K_{xx}/B	0.328	0.328

Case Conditions

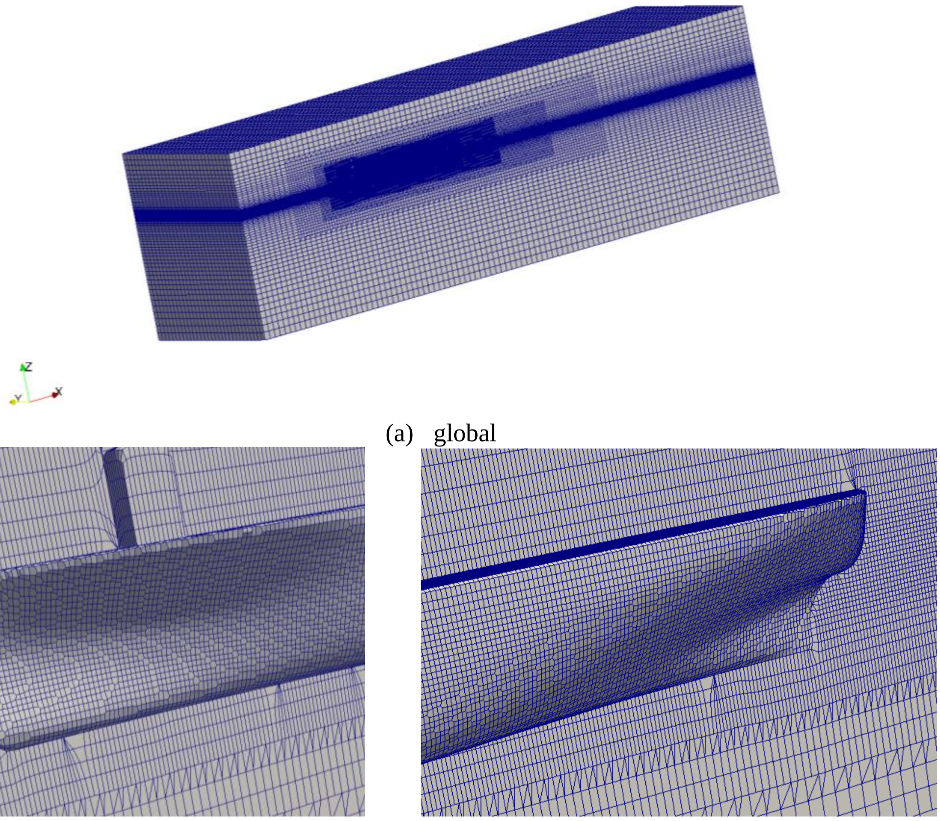
The simulation in our study is S-175 advancing in regular head waves. Three different wavelengths with the same height were chosen to investigate the influence of wavelength on green water phenomenon. The wave height is 0.15 m and the wavelengths are 2.5 m, 3.0 m and 3.5 m, respectively. The approaching speed is 1.2381 m/s, with corresponding Froude number F_r= 0.25. The case conditions are shown in Table 2. Considering the ship is advancing in head waves, the heave and pitch motions are mainly discussed. Our CFD simulation results were compared with experiment data of Tao[15].

Table 2 Case condition

F_r	Wavelength (λ/L_{pp})	Wave height H(m)	Wave steepness *ak*
0.25	1.0	0.15	0.06
	1.2	0.15	0.05
	1.4	0.15	0.043

Mesh Generation

An automatic mesh-generation tool snappyHexMesh is applied to generate the meshes for our computation. The tool generates mesh on an original Cartesian background mesh, splitting hexahedral cells into split-hex cells. The mesh quality is quite important when simulating large amplitude motion of ship. To improve the mesh quality, we used a topoSet tool to refine the background mesh which generated by the blockMesh tool (seeing in Fig. 2(a)). As the ship is symmetry, half of the hull is adopted to reduce computation time and the symmetry plane boundary condition is set as symmetry. The computational domain extends $-1.0L_{pp} < x < 4.0L_{pp}$, $0 < y < 1.5L_{pp}$, $-1.0L_{pp} < z < 0.5L_{pp}$. Fig. 2 shows computational domain. The total cell number is 1.05 million. In order to ensure that the incident wave will not dissipate during propagation, 20 grids were meshed in one wave height. To avoid wave reflection from the outlet boundary, we use a sponge layer setup at the outlet of the computational domain. The sponge length is equal to ship length. In the cases, the wave height is relatively large which can cause the large amplitude motion of the ship. This large amplitude motion may result in large deformation of mesh. So it is not easy to stabilize the solution. To make it easy to converge in each time step, the interface Courant number was controlled to be under 0.3. The time step is 0.0005 s in each case.



(a) global

(b) bow (c) stern

Fig. 2 computational domain

RESULTS AND DISCUSSION

Effect of Green Water on Ship Motion

Many researchers indicated that the green water did affect the ship motions, and heave and pitch are most influential types of motion to green water phenomenon. As a result, only these two degrees of freedom were released. In order to investigate the motions of ship quantitatively and compare them with experimental data, most ship motion theories introduce the transfer functions or the RAO's to find out the motion amplitudes. RAO's can be acquired by experiment or simulation. For heave and pitch motion, it can be defined as:

$$K_1 = 2Z_a / H \tag{8}$$

$$K_2 = 2\phi_a / kH \tag{9}$$

where K_1, K_2 are the RAO's of heave and pitch motion, Z_a, ϕ_a are the amplitudes of heave and pitch motion, H is the wave height and k is wave number. The RAO's of heave and pitch motion of our simulation are compared with experiment and nonlinear theoretical method by Tao[15]. He solved the ship motion equations using numerical integration technique in time domain. In his computer program, a three-point predictor-corrector technique was employed to integrate the equations. Fig. 3 and Fig. 4 show the RAO's of heave and pitch motion. As shown in Fig. 3, when λ/L_{pp} = 1, our CFD result approaches the theoretical result, but both results are larger than the experiment result. This is because that the green water has a certain inhibitory effect on ship heave motion. And the motion amplitudes reduced by green water in the experimental case. Both methods overestimated heave motion by about 22.6%. Pham[16] indicated that non-linear buoyancy due to above water hull form and non-linear damping could play considerable part in this behavior. But in Fig. 4, there is a good agreement between experimental data and CFD method predicted RAO's for pitch motions at each wavelength. The theoretical results show less accuracy in each case. When λ/L_{pp} = 1.2, the CFD result also shows agreement with the theoretical one. The CFD method over-predicted the heave RAO's by about 25%. When λ/L_{pp} = 1.4, the theoretical result can predict the transfer function of heave motion better than our CFD method. Our CFD result shows much larger result than the experiment data. It over-predicted the heave RAO's by 24.5%.

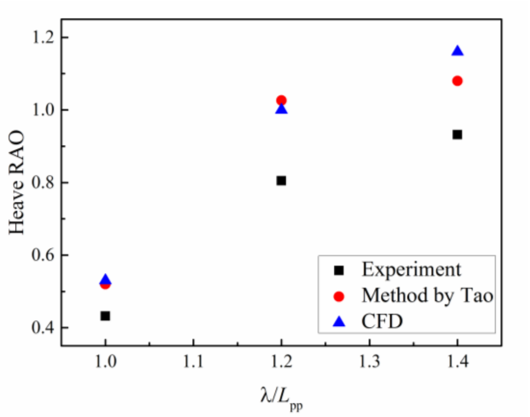


Fig. 3 Heave RAO's of S-175 at F_r=0.25

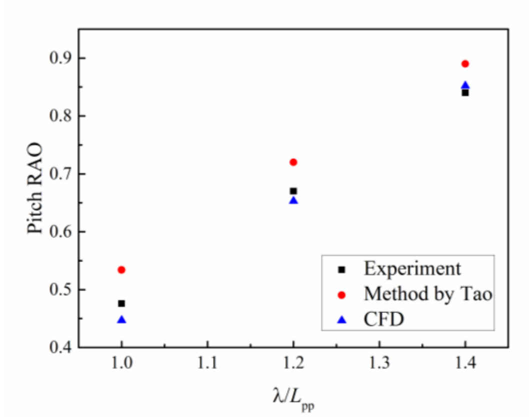


Fig. 4 Pitch RAO's of S-175 at F_r=0.25

Time History of the Heave and Pitch Motions

Time history of the heave and pitch motions for each wavelength obtained from our CFD simulation are shown in Fig. 5 and Fig. 6. We can find that although the same wave height was employed in each case, the ship shows different motion amplitudes. At smaller wavelength, the wave steepness was larger but the ship motions were smaller. At larger wavelength, the motion was larger but the waves were less steep. For heave motion, the value of the positive amplitude is equal to negative amplitude for each case. While for pitch motion, the positive amplitude and negative amplitudes are of different magnitude. This phenomenon is due to the change of hydrodynamic coefficients and the nonlinear restoring force which results from significant changes in cross-section areas.

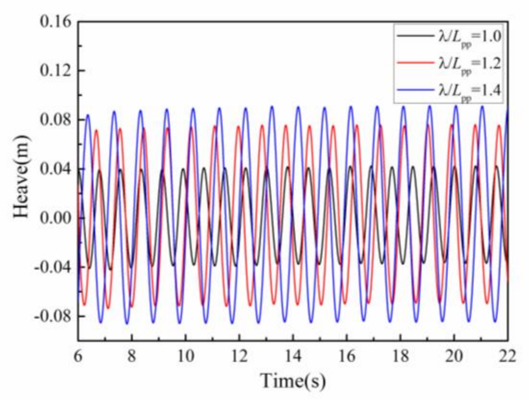


Fig. 5 Heave time history

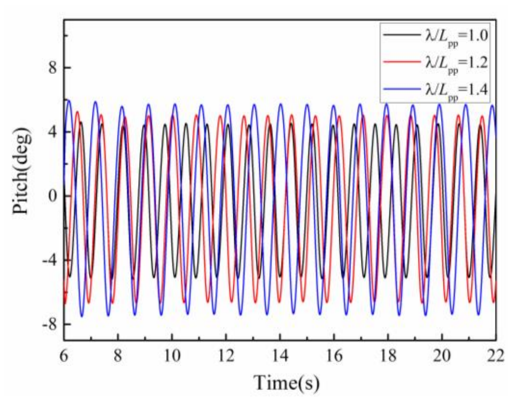


Fig. 6 Pitch time history

Water Evolution in Green Water on Deck

As shown in Fig. 7, the water moves towards the bow due to the effect of trim by bow. Then pitch motion makes the upcoming wave begin to run up and cross the freeboard under the ship-wave interaction. When the ship pitches deeper into the water, water around the bow will cross the freeboard from the direction normal to the deck edge (shown in Fig 7(d)). Due to the bulwark and the relative motions between the bow and the surrounding water, the inflows of green water normally had a vertical velocity component. Therefore, green water flows tended to take off the deck edge before plunging back on deck. This process can result in an air gap or air entrapment immediately behind the deck edge or the bulwark[16]. As the water landed back on the deck due to gravity, it causes green water to happen. Because of the horizontal relative motion between ship and wave, the water moves along the deck and falls down on the deck due to gravity. When the ship starts to pitch out of the water, the water moves towards centerline plane and impacts on superstructures.

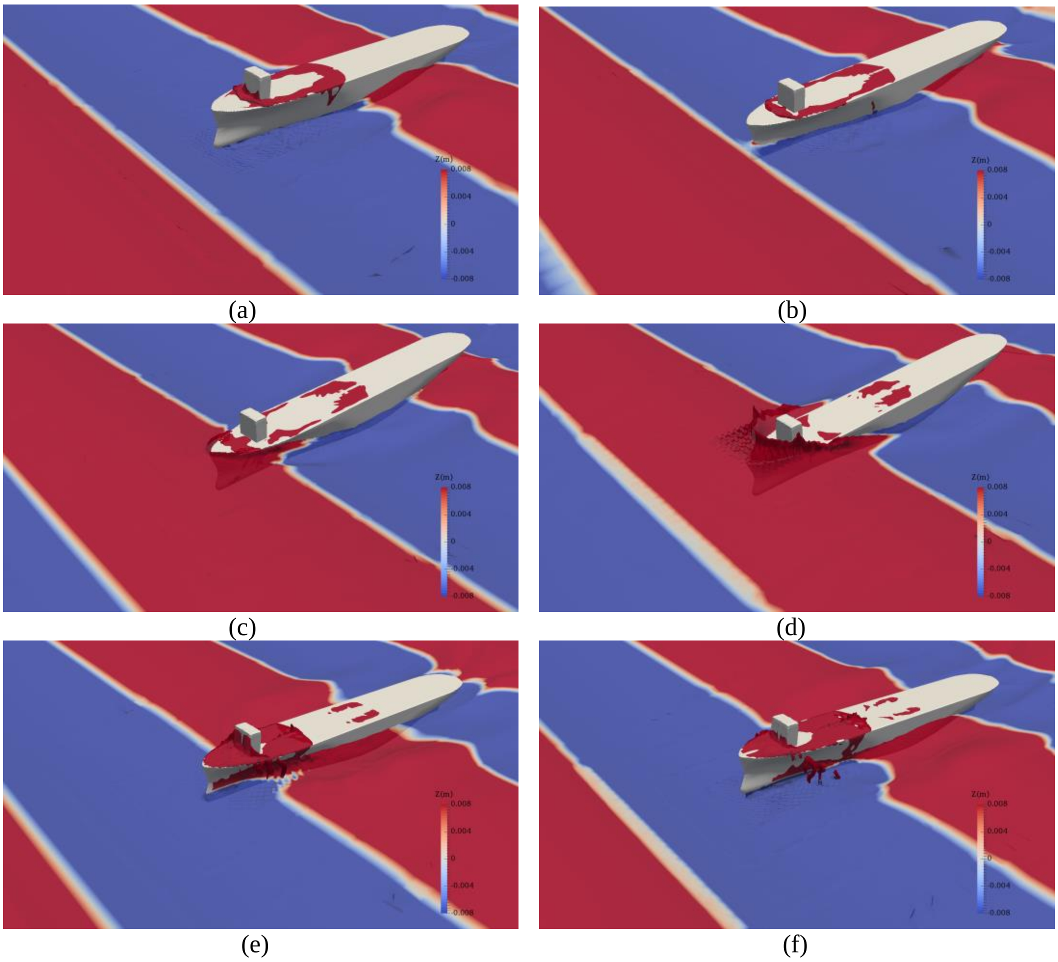


Fig. 7 Water evolution in green water on deck at $\lambda/L_{pp} = 1$

CONCLUSIONS

In this paper, numerical simulation of the green water phenomenon of the S-175 containership in regular waves are performed by our own solver naoe-FOAM-SJTU. Three incident wave conditions with different lengths (λ/L_{pp}=1.0,1.2,1.4) are conducted to investigate the green water phenomenon. The predicted RAO's of motion are compared with experiment data. The ship motions show strong nonlinear behaviors, and green water phenomenon occurs at each case. It can be found that the pitch motion predicted by our CFD method is consistent with the experimental data. But heave motion is over predicted. This illustrates that the heave motion amplitudes may be reduced by green water in the experimental case. For pitch motion, the positive amplitude and negative amplitudes are of different magnitude. This may due to the change of the nonlinear restoring force. The whole process of a green water event can be simulated using our naoe-FOAM-SJTU solver. The results show that that the current approach can be an alternative tool to study the green water phenomenon.

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