Ocean Engineering 148 (2018) 500–515

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

CFD verification and validation of green sea loads

Inno Gatin [a], Vuko Vukčević [a], Hrvoje Jasak [a,b,*], Jeonghwa Seo [c], Shin Hyung Rhee [c]

[a] University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, Zagreb, Croatia
[b] Wikki Ltd, 459 Southbank House, SE1 7SJ, London, United Kingdom
[c] Research Institute of Marine Systems Engineering, Seoul National University, Gwanak-ro 1, Gwanak-gu, Seoul, 08826, South Korea

ARTICLE INFO

Keywords:
Green sea loads
Regular waves
CFD
Naval Hydro pack
VOF

ABSTRACT

An extensive verification and validation for green sea load simulations is presented. The calculations are performed using the Naval Hydro pack, a library based on foam–extend, which is an open source Computational Fluid Dynamics software. The geometric Volume of Fluid method is used for interface advection, while the Ghost Fluid Method is employed to discretise the free surface boundary conditions at the interface. Pressure measured at the deck of a fixed structure is compared to experimental data for nine regular waves. Verification is performed using four refinement levels in order to reliably assess numerical uncertainties. A detailed uncertainty analysis comprises both numerical and experimental data. Comparable uncertainties are exhibited in simulations and experiments, with good agreement of results.

1. Introduction

In the field of offshore and marine engineering, wave loading poses a wide range of different challenges which are important in the design process. One of the more difficult wave–related problems to describe and reliably estimate is the green sea load. Green sea, or water on deck, is a consequence of a highly nonlinear interaction between the floating structure and the free surface waves, which comprise incident, diffracted and radiated waves. The complex origin of the phenomenon renders the prediction of green sea occurrence challenging. Apart from that, violent two phase flow develops once the water is on the deck, which is difficult to predict via simplified flow theories. Green sea effect cause both local and global structural loads which can endanger the structural integrity, and therefore must be taken into account in the design process.

Given the complexity of the problem, experimental and numerical means are currently utilised to calculate green sea loads. According to Tamarel et al. (Temarel et al., 2016), both experimental and numerical methods available today are not mature to reliably assess green sea loads. Hence, further research is needed to establish confidence in both fields. As a result, a wide variety of methods have been developed and applied in recent years. Greco et al. (2012) used the numerical solver developed by Greco and Lugni (2012) to calculate wave loads on a patrol ship, including green sea loads with comparison to experiments. Lu et al. (2012) developed a time domain numerical method based on Finite Volume (FV) method used for green sea load simulations. Xu (2013) used Smoothed Particle Hydrodynamics to simulate breaking waves plunging onto a deck. Zhao et al. (2014) studied the influence of structure motion on the pressure loads due to green sea effects using a FV based method. Kim et al. (2013) used a linear method for assessing the ship motion, and a nonlinear viscous method to calculate green sea loads on a container vessel. Ruggeri et al. (2013) used WAMIT software based on the potential flow model and a viscous FV code StarCCM+ to devise guidelines for green sea load calculations. Joga et al. (2014) compared two viscous FV codes with experimental results of water ingress into open ship holds during green sea events. Pakozdi et al. (2014) coupled a potential flow based method and a viscous model to conduct simulations of green sea events. Zhu et al. (2009) conducted numerical simulations of green sea events for a Floating Production, Storage and Offloading (FPSO) vessel.

In this work, a detailed validation study of green sea loads on a static structure is conducted. Experimental results published by Lee et al. (2012) are used for the comparison. Nine regular wave cases are investigated, including the uncertainty analysis of numerical and experimental results. Naval Hydro software pack is used for numerical simulations, which is an extension of the collocated FV based CFD open source software foam–extend (Weller et al., 1998; Jasak, 2009). The Naval Hydro package is specialised for viscous, two phase, large scale flows. Nonlinear stream function regular wave theory by Rienecker and Fenton (1981) is used for wave generation. The potential wave flow and CFD are coupled

---

[*] Corresponding author. University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Ivana Lučića 5, Zagreb, Croatia.
E-mail addresses: inno.gatin@fsb.hr (I. Gatin), vuko.vukcevic@fsb.hr (V. Vukčević), h.jasak@wikki.co.uk, hrvoje.jasak@fsb.hr (H. Jasak), thamjang@snu.ac.kr (J. Seo), shr@snu.ac.kr (S.H. Rhee).

https://doi.org/10.1016/j.oceaneng.2017.10.026
Received 5 June 2017; Received in revised form 29 August 2017; Accepted 16 October 2017

in a one–way fashion using implicit relaxation zones (Jasak et al., 2015) by imposing the wave solution at the boundaries of the domain and gradually transitioning to the nonlinear CFD solution towards the middle of the domain. The interface is captured using the Volume of Fluid (VOF) method where a novel geometric approach developed by Roenby et al. (2016) is employed, called isoAdvector. Free surface boundary conditions are discretised using the Ghost Fluid Method (GFM) (Vukčević, 2016), providing a infinitesimally sharp pressure and density gradient distribution at the interface.

The aim of this paper is to assess the accuracy and feasibility of a modern naval hydrodynamics CFD software for predicting green sea loads. In order to reduce the possible sources of error to a minimum, a simple static geometry is analysed with publicly available experimental results (Lee et al., 2012). Since numerical simulations of wave induced motions and loads have been validated using the Naval Hydro package in the past (Vukčević, 2016; Vukčević et al., 2015, 2016; Jasak et al., 2014), green sea load validation is the missing piece for conducting complete numerical simulations with moving bodies where green sea loads are calculated.

This paper is organised as follows: in the second chapter the numerical method is outlined. The third chapter gives basic information about experimental measurements that are used for comparison. In the fourth chapter the numerical simulations of green sea loads are described in detail, including the simulation set–up, uncertainty analysis procedure and comparison of the results with the experiments. Finally, a brief conclusion is given.

2. Numerical model

In this section the numerical model used in this work is presented. Governing equations describing two–phase, incompressible and viscous flow are:

$$\nabla\cdot\mathbf{u} = 0, \tag{1}$$

$$\frac{\partial\mathbf{u}}{\partial t} + \nabla\cdot(\mathbf{u}\mathbf{u}) - \nabla\cdot(\nu\nabla\mathbf{u}) = -\frac{1}{\rho}\nabla p_d, \tag{2}$$

where $\mathbf{u}$ denotes the velocity field, ν stands for the kinematic viscosity of the corresponding phase, ρ is the density, while p_d stands for dynamic pressure:

$$p_d = p - \rho\mathbf{g}\cdot\mathbf{x}. \tag{3}$$

Here, p is the absolute pressure, $\mathbf{g}$ is the gravitational acceleration, while $\mathbf{x}$ denotes the radii vector. Note that the momentum equation has been divided through by the density, assuming a two–phase free surface system of incompressible immiscible fluids. Eq. (1) and Eq. (2) are discretised in collocated FV fashion yielding the pressure and momentum equation (Vukčević et al., 2017), respectively. The equations are solved implicitly. Eq. (2) is valid for both phases, where the discontinuity of dynamic pressure and density at the interface is taken into account with the GFM (Vukčević, 2016; Vukčević et al., 2017). The dynamic pressure and density jump conditions are a consequence of normal stress balance at the free surface. The tangential stress balance is modelled approximately, while the surface tension is neglected. The two jump conditions arising from the normal stress balance are:

$$p_d^- - p_d^+ = -\left(\rho^- + \rho^+\right)\mathbf{g}\cdot\mathbf{x}\ , \tag{4}$$

$$\frac{1}{\rho^-}\nabla p_d^- - \frac{1}{\rho^+}\nabla p_d^+ = 0. \tag{5}$$

Superscripts ”+” and ”−” denote the water and air phase, respectively. Eq. (4) states that the jump of dynamic pressure across the interface is proportional to the jump in density, while Eq. (5) states that the jump of specific dynamic pressure gradient is zero. The jump conditions are introduced into the discretisation via specialised discretisation schemes, ensuring that Eq. (4) and Eq. (5) are satisfied. The reader is referred to Vukčević et al. (2017) for details.

In order to advect the interface, a geometric VOF method called isoAvector (Roenby et al., 2016) is used. Standard advection equation is used in order to transport the volume fraction variable α:

$$\frac{\partial\alpha}{\partial T} + \nabla\cdot(\alpha\mathbf{u}) = 0. \tag{6}$$

Written for a finite control volume P, and discretised in time using the first order accurate Euler method, Eq. (6) states:

$$\int_{V_P}\alpha_P(t+\Delta t) - \alpha_P(t)dV = -\int_t^{t+\Delta t}\oint_{S_P}\alpha\,\mathbf{n}\,\mathbf{u}dS\,d\tau, \tag{7}$$

where V_P is the volume of the control volume P, S_P is the closed boundary surface of the control volume, $\mathbf{n}$ is the unit normal vector of the boundary surface, while τ denotes the time integration variable. For a surface boundary discretised with a finite number of faces, the closed surface integral is replaced with a sum of surface integrals across the faces:

$$V_P(\alpha_P(t+\Delta t) - \alpha_P(t)) = -\sum_f\int_t^{t+\Delta t}\int_{S_f}\alpha\,\mathbf{n}_f\,\mathbf{u}dS_f\,d\tau, \tag{8}$$

where f denotes the face index. The volume integral of the temporal term is discretised assuming a second order accurate FV method (Jasak, 1996). Instead of evaluating the temporal and surface integrals in Eq. (8) by employing conventional discretisation schemes, in the isoAdvector method they are integrated explicitly directly from the information about the moving iso–surface of the volume fraction, representing the interface, through a polyhedral cell. In this way, sub–grid resolution is achieved for interface advection. This results in a sharp interface and bounded volume fraction field. The reader is directed to (Roenby et al., 2016) for more details on the isoAdvector method.

2.1. Wave modelling

Regular waves are imposed into the CFD domain via implicit relaxation zones (Jasak et al., 2015). Relaxation zones are regions in the computational domain where the theoretical wave solution is imposed by smoothly transitioning to the calculated CFD solution. The same method is used to dampen the waves at the outlet, where the CFD solution is gradually replaced by the imposed solution, the incident wave in this case. A stream function wave model (Rienecker and Fenton, 1981) is used which is fully nonlinear, permitting a shorter CFD domain since the wave nonlinearities are resolved outside of the CFD domain.

3. Green sea experiments

The experimental tests were performed in the towing tank of Seoul National University, with the details and results published in (Lee et al., 2012). A simplified model of a FPSO vessel is used, where three different bow shape configurations are tested. The computations in this work are performed for one of the geometries, called Rect0 in the original paper (Lee et al., 2012). The structure is static in order to reduce the number of possible sources of error when comparing the results. Ten pressure gauges are positioned at the deck of the model. The geometry of the model and position of pressure gauges are shown in Fig. 1. A vertical wall is positioned at the deck to simulate the breakwater. Pressure data is measured for nine incident wave cases, with wave parameters shown in Table 1. Pressure gauges are labelled as indicated in Fig. 1 in a separate figure for clarity.

In (Lee et al., 2012) detailed experimental results are presented for pressure peaks of individual gauges. The reported values are average