International Journal of Offshore and Polar Engineering (ISSN 1053-5381)

Vol. 23, No. 3, September 2013, pp. 186–196

http://www.isope.org/publications

Numerical Analysis of Large-Amplitude Ship Motions Using FV-based Cartesian Grid Method

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A finite-volume (FV)-based method on a non-uniform Cartesian grid with staggered arrangement of variables is applied to simulate and analyze large-amplitude ship motions. The wave-body interaction problem is considered as a multi-phase problem with water, air, and solid phases. Each phase is identified by a volume-fraction function in each cell. In order to capture the interface between air and water, the tangent of hyperbola for interface capturing (THINC) scheme is used with weighed line interface calculation (WLIC) method. The volume fraction of a solid body embedded in a Cartesian grid system is calculated by a level-set based algorithm, and the body boundary condition is imposed by a volume-weighted formula. Wave excitation force and moment and hydrodynamic coefficients are validated for a Wigley III hull. Numerical simulations for the ship motion in linear waves also have been carried out to validate the newly developed code. The computational results for the Wigley III hull with different forward speeds are compared with experimental data. To demonstrate the applicability of the method for highly nonlinear wave-body interactions such as green water on the deck, numerical analysis of the large-amplitude ship motion of an S175 containership is conducted.

INTRODUCTION

As modern ships become larger and faster, the prediction of extreme wave loads on ships is becoming an important issue. Potential-based codes (Kim et al., 2007; Kim and Kim, 2011) have been widely applied to simulate various seakeeping problems, and they have provided useful results for engineering purposes. However, potential-based methods have some limitations, especially in simulating strongly nonlinear wave-body interaction problems. Among the alternative approaches, computational fluid dynamics (CFD) based on the Navier-Stokes or Euler equations are becoming popular due to the dramatic increase of computational resources. Also, current numerical methods, such as volume-of-fluid (VOF) or level-set method, provide reliable results even for the violent flow problem, in which the topology of the free-surface boundary is largely distorted, fragmented and merged. The major difficulty in the numerical simulation of strongly nonlinear wave-body interaction problems using a field equation solver is that a rigid body can move arbitrarily without coincidence of grid line and the body boundary, so that some special treatments are needed, such as re-mesh, moving mesh or embedding techniques.

A few representative groups have been studying numerical methods to solve field equations for strongly nonlinear wave-body interaction problems. Orihara and Miyata (2003) solved ship motions in regular head wave conditions and evaluated the added resistance of ships in waves using a CFD simulation method called WISDAM-X. The Reynolds-averaged Navier-Stokes (RANS) equation was solved by the finite-volume method with an overlapping grid system. Dommermuth et al. (2007) simulated breaking waves around ships and prescribed solving the motion problem by Numerical Flow Analysis (NFA) code based on a combination of Cartesian grid methods and volume-of-fluid methods. A ship hull was represented on a Cartesian grid by immersed boundary generated from surface-panelized ship hull data. Yang et al. (2007) and Yang and Stern (2009) developed their new series of program called CFDShip-Iowa version 6, which also used immersed boundary method with level-set/ghost fluid method for solid-fluid and fluid-fluid interface treatments, respectively. Lagrangian dynamic Smagorinsky subgrid-scale model was adopted for large-eddy simulations. They solved bubble dynamics, water entry and exit, landslide-generated waves and ship resistance problems with wall-layer models. Hu and Kashiwagi (2007) developed a CFD-code named Research Institute for Applied Mechanics, Computation Method for Extremely Nonlinear hydrodynamics (RIAM-CMEN), which adopted a constrained interpolation profile (CIP)-based Cartesian grid method. In the CIP-based formulation, the wave-body interaction problem is considered as a multi-phase problem. Different phases are recognized by a density function that has a definition similar to the volume fraction function in the VOF method. To calculate the volume fraction of solid phase, virtual particles were used. They compared the THINC scheme and the CIP scheme as an interface capturing method and showed the possibility that a CIP-based method could be applied to simulate strongly nonlinear wave-body interaction problems for modified Wigley models. Visonneau et al. (2010) solved the trim and sink of a frigate advancing in regular head waves using the free-surface capturing viscous solver ISIS-CFD. They used an unstructured hexahedral grid and an analytical weighting mesh deformation approach to treat the moving body problem. Monroy et al. (2009) validated a spectral wave explicit Navier-Stokes equation (SWENSE) method to solve ship motion problems in irregular head waves. In the SWENSE method, incident wave terms are calculated by a potential flow model, and diffracted wave fields are solved based on the RANSE equation under a structured body-fitted grid system.

In this paper, using a time integration method similar to that of Hu and Kashiwagi (2007), an FV-based Cartesian grid method is applied to simulate strongly nonlinear ship motion problems. First-order fractional method is applied for velocity-pressure coupling. THINC method with WLIC is used as a fluid interface capturing scheme. To deal with complex ship geometry and motion, a level-set-based method is adopted. A solid body is represented by a signed distance function to calculate the volume fraction of

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Received July 24, 2012; revised manuscript received by the editors April 3, 2013. The original version was submitted directly to the Journal.
KEY WORDS: Large-amplitude ship motion, Cartesian grid, THINC, WLIC, volume fraction.