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Numerical Studies of Coupling Effect of Sloshing on 3D Ship Motions

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The present work describes the development of an approach to study the problem of ship motions coupled with internal sloshing effects. A hybrid solution algorithm is developed that integrates a three-dimensional potential flow solver for ship motions into a viscous flow solver for sloshing loads. A three-dimensional time-domain forward-speed boundary element method (BEM), based on the transient Green's function technique, is employed to capture the external ship hydrodynamics, while the open source finite volume method (FVM)-based solver, OpenFOAM, which incorporates an incompressible multiphase viscous flow model into an interface-capturing volume of fluid (VOF) technique, is employed to capture the internal sloshing hydrodynamics. After the individual solvers are validated against the experiments and other computations available in the literature, the solution from the coupled solver is discussed, and the influence of the coupling effects of sloshing loads on ship motions is brought out.

INTRODUCTION

Sloshing is caused or initiated by ship motions under the action of waves that in turn affect ship motions. This coupling effect of sloshing on ship motions depends on the resonant characteristics of the sloshing flow in the tanks. The modified motions in turn affect the sloshing loads that are essential to evaluate the strength of the containment system. Conventionally, sloshing loads are determined by model experiments or computational fluid dynamics (CFD) simulations, where the precomputed ship motions obtained from a seakeeping analysis without consideration of the sloshing effects are used. This may lead to overestimation or underestimation of the loads.

To determine the effect of sloshing on ship motions and vice versa, a robust numerical tool capable of capturing the coupling effects is necessary. Several numerical studies have been attempted in the past in which potential flow and viscous flow solvers have been coupled. Kim (2002) used the 3D transient Green's function-based method for computing ship motions and a fused deposition modeling (FDM)-based single phase solver for sloshing. Rognebakke and Faltinsen (2003) used a low-order boundary element method (BEM) for ship motions and a 2D simplified nonlinear multimodal approach for internal tank sloshing. Kim et al. (2004) used an impulse response function (IRF) method in conjunction with an FDM-based single phase solver and a smoothed-particle hydrodynamics (SPH)-based solver for the internal sloshing loads. The last two studies focused on the effect of sloshing in anti-rolling tanks. Peric et al. (2009) applied a full Unsteady Reynolds-Averaged Navier Stokes (URANS) computation to study the coupling effect of sloshing on ship motions. Nam et al. (2009) applied an IRF-based method for computing ship motions and used FDM-based computations for computing sloshing forces. Lin et al. (2009) used a frequency-domain Green's function method (GFM) for computing ship motions and a finite volume method (FVM)-based multiphase flow volume of fluid (VOF) solver for sloshing loads. Lee and Kim (2010) investigated the interaction between ship motion and inner tank sloshing by combining 3D diffraction radiation panel method for ship motions and Navier-Stokes solution based on FDM. Wang and Arai (2010) used linear strip theory-based coefficients in their IRF method for ship motions and an FDM-based solver for sloshing computations. Huang et al. (2012) applied a Non-Uniform Rational Basis Spline (NURBS)-based time-domain body nonlinear higher order boundary element method (HOBEM) for both internal sloshing and ship motions. The application of IRF-based methods to ship motions, coupled with the open source FVM-based Reynolds-Averaged Navier Stokes (RANS) solver, OpenFOAM, for sloshing in various forms, has been adopted by Li et al. (2012), Huang et al. (2013), and Jiang et al. (2014, 2015). As can be seen, in most developments the ship motion part is determined by the use of an IRF-based time-domain formulation in which the needed frequency-dependent coefficients are determined by the use of either a 3D frequency-domain Green's function-based scheme or strip theory. As regards sloshing, different versions of viscous solvers are used.

The present work describes the development of a robust algorithm for the coupled sloshing problem by combining a 3D time-domain Green's function-based method for ship motions with the open source FVM-based multiphase interphase-capturing volume of fluid (VOF) solver, OpenFOAM, for sloshing. The paper initially presents the validation of the two solvers independently, followed by the application of the coupled algorithm to study the influence of sloshing on global ship motions.

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KEY WORDS: Sloshing, ship motion, coupled analysis, transient Green's function method, finite volume method.