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Numerical studies on effects of slosh coupling on ship motions and derived slosh loads

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ABSTRACT

This work presents development of a ship motion algorithm coupled with slosh loads and studies the effect of the coupling on both slosh loads and ship motions for different conditions. A hybrid approach by combining a potential flow based solution scheme for the external fluid flow and a viscous flow solver for the internal sloshing flow is adopted for the computation. The potential flow solution for the ship motion problem is achieved by using boundary element method (BEM) based on transient Green's function technique, while the viscous flow solution for the sloshing problem is achieved using finite volume method (FVM) based on viscous multiphase interface capturing volume of fluid (VoF) technique. Validation of the developed method is made against experiments and numerical computations available in literature. The severity of the coupling effect for various filling conditions is studied, and it is observed that coupling is more severe at low filling conditions resulting in a significant damping of roll RAO near the resonance and a shift in the peak. Damping in the roll response in turn results in a low sloshing loads. For a few filling conditions, however, the coupling effect produces higher roll response leading to higher slosh loads. Consideration of non-linearities in ship motions associated with Froude–Krylov and restoring forces, and the effect of sway-roll coupling in the ship motions on sloshing are studied and found that these aspects of ship motions can have non-negligible influence on the slosh loads. Long duration simulation studies reveal that there can be significant differences in the computed tank wall pressures between the coupled and uncoupled cases.

1. Introduction

Sloshing in partially filled tanks has a significant effect on the global ship motions, typically in sway and roll. In turn, sloshing loads are governed by the excitation motions of the tank. It is thus necessary that the coupling effect of sloshing is taken into account in computing the ship motion responses. This in turn leads to the requirement of a robust numerical tool that can model the effects of sloshing on ship motions and vice-versa. Such a tool will be particularly useful for the design of containment systems of liquefied natural gas (LNG) carriers, LNG floating production storage and offloading (FPSO) units and LNG terminals. Ship motions are conventionally solved using 2D strip theory or 3D panel based methods in the frequency or time domain, and these potential-flow based methods continue to remain as work horses for industry. On the other hand, sloshing phenomenon is a highly non-linear free surface flow, often involving folding and breaking of the free surface. Thus viscous flow based CFD solvers (such as FDM, FVM and SPH) are better tools compared to potential flow methods for evaluating slosh-induced loads. In spite of recent advancements in CFD and computational resources over the past couple of decades, solving the combined problem of sloshing coupled with seakeeping by a viscous CFD method is still computationally very expensive. It is thus useful to employ a hybrid solution strategy by taking advantage of a computationally less expensive potential flow based ship hydrodynamics solver and a fully non-linear viscous flow based sloshing solver for the solution of this coupled problem.

Development of hybrid solution approaches by combining sloshing loads and ship motions based on different schemes has been ongoing for past several decades. One of the earliest such work could be found in Mikelis and Journee [1] in which the slosh induced moment computed from a two-dimensional finite difference method (FDM) was coupled to the ship roll equation of motion, and the numerical predictions were compared against model experiments. Molin et al. [2] presented a frequency domain potential flow model assuming linearity in the modal sloshing approach to predict the combined dynamics of a floating body coupled with liquid cargo motions. They also conducted model experiments of a barge equipped with two rectangular tanks for comparative evaluation of their numerical results. Subsequently, Molin

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et al. [3] extended their work to study the effect of roof impacts on the coupling between wave response and sloshing, and performed further experiments on the same barge model. In the work of Kim [4], the coupling was achieved through integration of a linear time domain panel method based seakeeping solution with a FDM based sloshing solution. The seakeeping solution was achieved using a 3D transient Green function based panel method. Later, in Kim et al. [5] and Kim et al. [6], a linear impulse response function (IRF) based seakeeping solution was coupled with finite-difference method to study the coupling effects. The IRF method uses precomputed frequency-domain solution for the external hydrodynamic (radiation–diffraction) problem, which is generally achieved using strip theory or frequency domain 3D Green's function based method. Kim [4] and Kim et al. [5,6] have studied the anti-roll tank effect on a modified S175 hull equipped with an anti roll tank (ART) with or without pillars, and compared their results with experiments of Bai and Rhee [7] for a geometrically similar supply vessel. They have also studied the influence of fill ratio and wave steepness on coupling effects. Nam et al. [8] also used IRF along with FDM, to study the coupling behaviour of a modified S175 hull equipped with ART and a LNG FPSO equipped with two prismatic tanks. They have performed model experiments using LNG FPSO with three degrees of freedom for various filling combinations in tank, to validate their coupling algorithm. The experiments of Nam et al. [8] were further used by Gou et al. [9] and Jiang et al. [10]. Gou et al. [9] performed a comparison of frequency-domain and time-domain solutions. The frequency-domain solution was based on a combination of wave Green function method for external ship motions and a Rankine panel method for sloshing, while the time-domain method was based on Rankine panel method for both ship motions and sloshing. Jiang et al. [10] adopted a viscous two-phase flow model of OpenFOAM, based on interface capturing volume of fluid (VoF) method for coupling sloshing flow with external ship motions. The ship motions were computed using IRF method, where a higher-order boundary element method (HOBEM) was used for frequency-domain pre-calculations. They studied the influence of coupling on ship motions and slosh induced loads for various filling combinations and incident wave amplitudes. Zhao et al. [11–13] present experiments and numerical model to couple nonlinear sloshing flow and linear ship motions. Their method is 2D, and BEM is used for both internal slosh motion and external ship motion. They study slosh coupling effects on an idealized 2D FLNG section with partially filled tank for different modes of hull motions (sway, heave, roll) and also provide comparisons with result from an experiment designed specially for replicating their 2D computational set-up. An essentially similar method but for the 3D case and 6 DoF ship motions is recently presented in Zhao et al. [14]. In some other recent works, Cercos-Pita et al. [15] presented a method where a Weakly-Compressible Smoothed-Particle Hydrodynamics (SPH) solver AQUAgpush in used for the internal tank flow. For the ship motion computations, they use an IRF method in which the incident wave and hydrostatic forces are fully nonlinear, but the radiation and diffraction forces are based on linear potential flow pre-computations. Although diffraction forces are stated to be instantaneous, no further details are available. They present roll motion results with and without a tank for a Series 60 vessel in regular beam waves at different wave steepness. Servan-Camas et al. [16] also use a SPH solver for the interval tank flow, which is coupled with a time domain Finite Element Method (FEM) based linear radiation–diffraction solver for the ship motion. In Zhuang and Wan [17], a full viscous CFD method for both ship motions and internal slosh flow appear to have been applied to study sloshing in a simplified LNG hull with two prismatic tanks.

From the above survey of literature, it is seen that solution for the coupled problem of sloshing and ship motions have been presented in several works using different approaches. In some of these the seakeeping solution is obtained using linear time domain boundary element method (BEM) based on transient Green's function method. Many other works use an impulse response function (IRF) based approach, where pre-calculated linear radiation–diffraction solution in frequency domain is used for determining ship motions in time domain. Majority of the available works are found to employ variants of BEM based scheme for determining the seakeeping responses except Servan-Camas et al. [16] who apply a finite element method (FEM). For the coupling studies most of the works assume the external ship motion problem to be linear while some of the recent work consider nonlinearities with different levels of approximations. For instance, Cercos-Pita et al. [15] consider nonlinear ship motions, but from the limited description of the seakeeping solver available in their publication, the solution appears to be approximately nonlinear. For the internal tank sloshing solvers, initial works reported in literature have been mostly based on finite difference methods (FDM), but the choice for this field solver appears to be gradually migrating towards finite volume methods (FVM). Few of the works have also reported application of potential flow based methods, but clearly these potential flow methods are limited by their inability to model violent sloshing involving multi-valued and breaking of the free-surface. In recent times, application of a smoothed-particle hydrodynamics (SPH) method is also found to be applied for the internal sloshing problem (e.g. Servan-Camas et al. [16]).

In the present work, the coupling between sloshing and ship motions is achieved through a hybrid approach by combining an approximately nonlinear potential flow solution scheme for the ship motions and a fully nonlinear viscous flow solution scheme for the internal sloshing flow. The nonlinearities considered in the seakeeping solver include the exact Froude–Krylov and hydrostatic force nonlinearities, but the interaction hydrodynamics of radiation and diffraction remain linearized. This level of nonlinear seakeeping calculations is often referred to as level-II nonlinear (or so called weakly nonlinear, see [18]). The method used for the ship motion solution here is based on a formulation using transient Green function and the solution is in the time domain, similar to the LAMP code [19]. An advantage of the choice of this method is that it enables consideration of successively higher levels of nonlinearities (see e.g. [20]) for the forward speed ship motion problem. In this respect this solver can be considered more versatile compared to the IRF based method, albeit at the expense of more computational complexity and effort. Although the present work is confined to level II nonlinearity, higher levels of nonlinearities can be considered in our future work. However, before considering these higher levels, one needs to first establish whether nonlinearities in ship motions have any significant effect on the sloshing loads. We also presently confine our application to the zero speed case, although the method is capable of considering forward speed of the ship. The viscous flow solution for the sloshing problem is achieved using a finite volume method (FVM) based on viscous multiphase interface capturing volume of fluid (VoF) technique, which is available in open-source CFD toolbox OpenFOAM. In our previous works [21–23], we presented numerical studies on slosh coupled ship motions based on linear seakeeping solution combined with nonlinear sloshing solution confined to three degrees of freedom. In Saripilli and Sen [21] the two components, the ship motion computation (linear) and slosh load computations under prescribed tank motions, have been validated independently and some preliminary application of coupling was presented. In later works (Sen and Saripilli [22], Saripilli and Sen [23]), a more detailed numerical studies on slosh coupled ship motion validation and influence of coupling on impact pressure were presented.

The present work is a continuation of our previous work towards developing a robust method for the coupled slosh and ship motion algorithm. After briefly describing the two independent solvers, we present the details of the coupling algorithm by focussing on computational efficiency of the method and the strategies used to that end. Extensive validation of the developed algorithm against known experimental data and other numerical computations available in literature are then presented, extending our previous validation studies considerably. The main objective of this work is however to study the effect of nonlinearities in the seakeeping computation on the slosh loads