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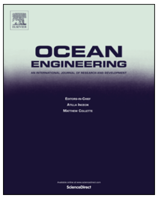

Coupled simulation of nonlinear ship motions and a free surface tank

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ABSTRACT

This paper investigates the coupled nonlinear dynamics of a vessel with a free surface tank onboard. To this end, a 6-DOF ship motions simulation code is coupled with a CFD solver addressing the behaviour of the fluid in the tank. The nonlinear ship motions code is of the blended (hybrid) type, intended for the simulation of free running vessels in waves. The nonlinear CFD solver is a GPU-based 3D Weakly-Compressible Smoothed-Particle Hydrodynamic (WCSPH) solver. Numerical results are presented for the nonlinear roll motion of a vessel with and without a free surface tank in regular beam waves with different steepnesses. Nonlinear phenomena are identified and discussed.

1. Introduction

Tanks characterised by the presence of a free surface are almost invariably present onboard vessels, with different scopes: fuel tanks, ballast tanks, cargo tanks, anti-rolling devices, etc. While taking exactly into account their effect on static restoring is, nowadays, a matter of routine stability calculations, the same cannot be said when ship dynamics and fluid cargo dynamics are to be accounted for in a coupled way. Due to the complexity of the involved phenomena, a coupled dynamic approach is particularly challenging when nonlinear effects are to be considered in both ship motions and fluid dynamics in the free surface tanks.

Different approaches have been used in the past to simulate the behaviour of a vessel in presence of liquid tanks onboard. Fully linear approaches for ship motions, internal hydrodynamics and external hydrodynamics, have been developed by Malenica et al. (2003) and Kim and Shin. (2008). Such approaches are very suitable for design purposes in mild sea conditions. However, when sloshing within the tanks becomes violent and/or ship motions become large, the linearity assumption become too restrictive and the underlying models fail to reproduce the actual fluid and ship dynamics. As a result, nonlinearities need to be introduced, and different authors, recognising this need in certain conditions, have tackled the problem with approaches having different levels of sophistication.

In case ship motions can be considered small enough to be treated linearly, nonlinear effects can be introduced only in the numerical solution of the sloshing problem. Approaches along this line can be found, for instance, in Kim et al. (2007) and Zhao et al. (2014), where nonlinear time domain potential flow approaches are used under the assumption of a free surface retaining a single-valued behaviour. However, this assumption does not allow taking into account strong nonlinear phenomena such as free surface fragmentation or wave breaking, which characterise violent sloshing. The possibility of handling complex, non-single valued, free surface dynamics was instead introduced by Bunnik and Veldman (2010), where a VOF solver for the internal sloshing flow was coupled in time domain with a linear ship motions model handling the linear potential external fluid–structure interaction and the linearised rigid body dynamics.

However, there are many situations where linear approaches to ship motions are insufficient. This is, for instance the case when the interest is on the assessment of ship behaviour in severe environmental conditions, or when the interest is on typically nonlinear dynamic stability phenomena in waves (e.g. parametric roll, pure loss of stability, surf riding and broaching, large rolling amplitudes in beam waves – see IMO (2009)), or when the interest is on the simulation of the behaviour of a vessel, having free surface tanks onboard, and which is free running in waves. In all such, and other, cases, nonlinear models need to be used for simulating the dynamics of the vessel. Approaches making use of nonlinear

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ship motions models together with simplified models for the behaviour of the fluid in the tank can be found in Francescutto and Contento (1999) for the beam sea case, and in Neves et al. (2009) for the case of longitudinal sea and, in particular, parametric roll. 6-DOF ship motions models coupled with 1-DOF U-tube tank models have been reported by Youssef et al. (2003) and Holden and Fossen (2012).

More sophisticated models are required when nonlinear effects are to be introduced in both ship motions and in the solution of the fluid flow in the tank. Nonlinear effects in the fluid flow can become particularly relevant in case of tanks featuring large free surfaces. Along the line of increasing the accuracy of the CFD solver for the internal flow, Hashimoto et al. (2012) coupled a nonlinear 1-DOF roll motion model for the simulation of parametrically excited roll motion, with a fully nonlinear solution of the fluid flow in the tank using the Moving Particle Semi-implicit (MPS) method, which is able to take into account strongly nonlinear free surface flows. In Mitra et al. (2012) a nonlinear potential flow model was solved by FEM for the internal tank, assuming the free surface to be single valued (therefore, also in this case, free surface fragmentation, breaking and strong nonlinearities cannot be accounted for), and the coupling was done with a partially nonlinear 6-DOF ship motions model.

In this study an approach is used where a 6-DOF ship motions simulation code is coupled with a CFD solver addressing the behaviour of the fluid in the tank. The nonlinear ship motions code is of the blended (hybrid) type, intended for the simulation of free running vessels in waves. The nonlinear CFD solver is a 3D Weakly-Compressible Smoothed-Particle Hydrodynamic (WCSPH) solver, allowing the use of graphical processing units (GPUs). In the following, the simulation tool is firstly described. Then, numerical results are presented for the nonlinear roll motion of a vessel with and without a free surface tank in regular beam waves with different steepnesses.

2. Simulation tool

The tool developed in the present study is intended to be able to simulate the general case of nonlinear motions for a free running ship sailing in regular or irregular waves, with a liquid tank onboard. Since nonlinear motions and nonlinear fluid flow inside the tank are of interest, and since the tool is expected to be able to deal with the general case of a ship free running in waves, linear frequency domain approaches (Kim and Shin, 2008; Malenica et al., 2003) do not represent a relevant option for the scope of the study. Although research is ongoing (Carrica et al., 2012; Sadat-Hosseini et al., 2010) regarding the use of direct computational fluid dynamics approaches for nonlinear ship motions of, possibly free running, ships in waves, the required computational time and resources are still prohibitive for practical applications.

Considering the situation, herein an intermediate approach has been followed, where the nonlinear rigid body dynamics and the ship-waves interaction is dealt with by means of a blended (hybrid) nonlinear 6-DOF approach, while the internal fluid–structure interaction, i.e. the fluid dynamics within the tank, is handled through a CFD approach based on a fully nonlinear SPH solver. The two tools are then coupled, in order to incorporate the tank effects in the solution of ship motions.

In particular, the ship dynamics is handled by the 6-DOF blended simulation code SHIXDOF ("nonlinear SHIp motion simulation program with siX Degrees Of Freedom"), under development at the University of Trieste. The code has been described and applied previously by Bulian et al. (2012) and Bulian and Francescutto (2013) and herein some main details are reported.

The simulation approach used in SHIXDOF is a typical hybrid approach along the line of de Kat and Paulling (1989). To date, approaches of such type have been considered suitable for practical assessment of nonlinear ship motions in waves, and their suitability for such purpose has been stated also in the framework of IMO “Second Generation Intact stability Criteria” (Bulian and Francescutto, 2013; IMO, 2010, 2013). As described in some more details by Bulian et al. (2012) and Bulian and Francescutto (2013), SHIXDOF solves nonlinear rigid body motions equations with respect to the ship-fixed reference system:

$$\begin{cases} m\cdot\left[\underline{u}_O{}'+\underline{\omega}\wedge\underline{u}_O+\underline{\omega}'\wedge\underline{x}_G+\underline{\omega}\wedge\left(\underline{\omega}\wedge\underline{x}_G\right)\right]=\underline{F}_{ext}(t) \\ \underline{\underline{I}}_O\cdot\underline{\omega}'+\underline{\omega}\wedge\left(\underline{\underline{I}}_O\cdot\underline{\omega}\right)+m\cdot\underline{x}_G\wedge\underline{u}_O{}'+m\cdot\underline{x}_G\wedge\left(\underline{\omega}\wedge\underline{u}_O\right)=\underline{M}_{ext,O}(t) \end{cases} \tag{1}$$

The vessel is then moved and oriented with respect to an earth-fixed reference system. The external force $\underline{F}_{ext}(t)$ and moment $\underline{M}_{ext,O}(t)$ comprise the following main effects: Froude–Krylov pressure, including hydrostatic term, calculated up to the instantaneous wetted surface of the hull (to catch geometrical nonlinearities); linear hydrodynamic radiation terms through convolution of kernel functions and infinite frequency added mass terms obtained from linear potential flow pre-calculations; instantaneous diffraction forces from linear frequency domain pre-calculations; manoeuvring forces, comprising a cross-flow model. Furthermore, it is possible to consider: constant and gusty wind effects; additional empirical damping terms (typically for, but not limited to, roll); linear/nonlinear, mooring-like springs; propulsors; lifting surfaces (rudders, fins).

In addition to the abovementioned effects, in the simulation tool developed herein, $\underline{F}_{ext}(t)$ and $\underline{M}_{ext,O}(t)$ also contain the instantaneous action, on the vessel, of the fluid in the tank. Such actions are calculated by the coupled CFD solver, which is based on the numerical solution of the 3D fluid field through a meshless Smoothed-Particle Hydrodynamics (SPH) approach.

The SPH approach has become very popular in CFD field thanks to the adaptability to complex geometries, and the capability of dealing with heavily fragmented fluids, while keeping a reasonable computational cost. The particular solver used herein is AQUAgpusph (Cercos-Pita, 2015; Cercos-Pita et al., 2013), developed at Technical University of Madrid. To address the actually incompressible flow, AQUAgpusph uses the commonly employed weakly-compressible SPH approach (WCSPH) (Colagrossi et al., 2009; Monaghan, 2005; Souto-Iglesias et al., 2006), which is based on the solution of the Navier–Stokes equations, where an artificial weak compressibility is considered through a pressure–density state equation which provides small density variations:

$$\begin{cases} \frac{d\rho_a}{dt}=-\rho_a\,\nabla\cdot\underline{u}_a \\ \frac{d\underline{u}_a}{dt}=-\frac{\nabla p_a}{\rho_a}+\frac{\mu}{\rho_a}\Delta\underline{u}_a+\underline{g} \\ p_a=p_a(\rho_a) \end{cases} \tag{2}$$

AQUAgpusph solves the discretised version of (2) using the Lagrangian kernel-based SPH formalism. Other formulations can be found in order to perform truly incompressible SPH simulations (e.g. Cummins and Rudman, 1999; Souto-Iglesias et al., 2014), but the WCSPH formulation has the main benefit that a purely explicit scheme can be used to perform the integration, and hence, no linear system of equations needs to be solved in order to compute the pressure field at each time step. In order to speed up the computation, AQUAgpusph can exploit, through OpenCL, the parallel computing capabilities of graphical processing units (GPUs), if such hardware, as in the present application, is available (Cercos-Pita, 2015; Cercos-Pita et al., 2013).