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Nonlinear analysis of sloshing and floating body coupled motion in the time-domain

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ABSTRACT

The aim of this paper is to develop a coupled nonlinear time-domain simulation scheme for nonlinear interactions among sloshing flows and floating body motion for both regular and irregular wave excitation. The contributions of a variety of nonlinear factors, outside waves and inside sloshing induced forces, as well as their influences on body coupled sway and roll motion were investigated. The induced forces are due to the changes in the transient wet surface of the floating body and full nonlinear sloshing. The effects of tank fill ratio and excitation wave height on the nonlinear coupled motion, as well as the relationship between sloshing and floating body nonlinear coupled motion under large wave amplitudes and severe sea conditions were also investigated and the results are presented. Finally, the numerical solutions are compared with existing experimental result. The fully nonlinear sloshing and floating body coupled motion are simulated based on the potential flow theory, with the transient position hydrodynamic assumption. The boundary value problem is solved by the B-spline higher-order panel method. The ISITIMFB (iterative semi-implicit time integration method for floating bodies) is applied to solve for the body's velocity and displacements. The sloshing energy dissipation is modeled by changing the boundary condition on the tank's solid boundaries. An extended principle to determine the energy dissipation coefficient for both regular and irregular cases is extracted. Then, the sloshing and floating body nonlinear coupled motion under large wave amplitudes and severe sea conditions are investigated, and the numerical solutions are compared with existing experimental results. The effects of tank fill ratio and excitation wave height on the nonlinear coupled motion is also investigated.

1. Introduction

Loading and offloading operations of vessels such as FPSOs and LNG carriers near shore or in the open sea can cause liquid sloshing in the carrier's insulated tanks, which are very large and partially filled with fluid. Violent sloshing waves can generate large loads which can damage the structure or influence stability (vessel sway and roll motion). In this coupled system, both the global motions of the floating body and the tank sloshing flows will influence each other.

The literature review revealed several interesting studies on this topic. Generally, the studies can be categorized into two approaches: (1) the linear frequency-domain approach based on potential theory (Molin et al., 2002; Malenica et al., 2003) and (2) the time-domain approach. According to previous studies, the assumption of linear sloshing and ship motion appears adequate in small amplitude coupled motion analysis. However, even if the incident wave is small and in the linear region, violent nonlinear sloshing can occur due to resonance. Sloshing-induced impact pressure can lead to a significant change in the transient wet surface and balance position of the hull in a certain frequency range. The hydrodynamic load characteristics on the hull are nonlinear, which inherently cannot be accounted for in linear theory.

Some conclusions that can be drawn from previous studies include the following: sloshing may be violent which can be modeled by Navier-Stokes equation and nonlinear potential theory model; the motion of floating structures can be linear or nonlinear, but at the outside of the wave it is linear; hydrodynamic forces can be calculated in the frequency-domain or by strip theory; Froude–Krylov forces can be nonlinear. The current study focuses on the influencing characteristics of

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sloshing and coupled effects on ship motions. To model these, the behaviors of both the external and the internal flow are needed. For the external flow, models based on linear potential theory are used and are accurate enough in most cases except for viscous effects such as roll damping (Faltinsen and Timokha, 2009). For the internal flow, models based on linear potential theory and Computational Fluid Dynamics (CFD) are used. Sloshing is a nonlinear phenomenon, especially in resonance conditions. Although in some cases it is possible to accurately predict the coupled sloshing and ship motions by using linear theory (Rognebakke and Faltinsen, 2003), CFD methods account for nonlinearity in sloshing that cannot be ignored in some cases. Kim (2002, 2003) presented a series of numerical results of the anti-rolling tank and ship coupled motion by using a finite-difference method and the commercial sea-keeping program LAMP. Kim et al. (2007), Nam et al. (2009) and Lee et al. (2007) studied the coupled effects between the ship motion and the sloshing flows by using the impulse response function (IRF) formulation for linear ship motion and a CFD simulation for nonlinear sloshing flows. Li et al. (2012) investigated the coupled motion of sloshing and ship motion using the STF & IRF method for ship motion, and the CFD model OpenFOAM for the nonlinear sloshing flows. The coupled model is established for the motion response of the ship in waves coupled with induced internal sloshing and their effects on sloshing-induced impact loads, which was analyzed by Jiang (2014) and Xue et al. (2017). The linear ship motion is solved with an impulse IRF method combined with OpenFOAM to address the viscous sloshing flow. However, generally speaking, CFD methods calculation time is prohibitively long and a more computationally efficient solution for the problem is needed.

A study of global ship motion coupled with tank sloshing using potential flow theory for flow inside and outside the vessel was conducted by Hong et al. (2012) and Ning et al. (2012). The research shows that the wave elevation and pressure can be obtained exactly if a highly nonlinear phenomenon does not occur. A 2-D coupled numerical code was developed considering nonlinear sloshing and linear ship motions based on a boundary element method, and later the results were verified by a series of corresponding model tests by Zhao et al. (2014). Zhang (2016) extended the modal decomposition method for floating vessel simulations and developed an explicit seakeeping-sloshing decoupling approach. In this method, the exact acceleration of a vessel at any instant is calculated explicitly in one step without iterations. Three-dimensional cases of a floating vessel with four nonlinear sloshing tanks were also simulated. This method was further used by Wang et al. (2017) in their 2D simulations. Su and Liu (2017) also investigated the coupling effects of barge motion and sloshing, using a nonlinear Boussinesq-type approach in terms of velocity potential for the sloshing simulation. In the preliminary investigation on the coupling mechanism between ship motions and nonlinear sloshing, roll motion is most affected compared to other degrees of freedom.

Faltinsen and Timokha (2001, 2005) found that the damping due to viscous energy dissipation in the form of sloshing wave spilling and breaking in a certain frequency range plays an important role in determining the coupled motion and it must be carefully considered. In the past, such problems have been analyzed by using the Navier-Stokes equations (Su et al., 1982 and Hamlin et al., 1986). The calculation time of this method is prohibitively long, so a more computationally efficient solution based on potential theory is considered. With potential theory, viscous effects are neglected and so development is needed to resolve an appropriate dissipation effect. Kim and Shin (2008) proposed to add a damping term to the free surface condition. Unfortunately, this approach introduces two damping coefficients, which are not easy to define for modeling the coupled motions of ships with sloshing in internal tanks. Malenica et al. (2003) proposed a model that modifies the tank wall condition instead of the free surface condition, but it is only suitable for frequency-domain analysis. This method was improved by Huang et al. (2011), who reported a new energy dissipation condition which is applicable to time-domain simulation.

The nonlinear body boundary conditions of a floating body and tank-sloshing are complex. The accurate calculation of the velocity potential for the time derivative is critical to obtain the correct pressure and force on the body surface at each time step. To decouple this mutual dependence, some methods have been suggested in the literature, such as the indirect method (Wu and Eatock, 1994), the mode-decomposition method (Koo and Kim, 2004) and the iterative method (Yan and Ma, 2007). Each method has its own advantages and disadvantages. In this paper, the iterative method is applied due to the importance of nonlinearities for sloshing and to obtain the probability density functions of response variables caused by sloshing.

There are still many uncertainties in the methods described in the literature. The method based on the linear assumption fails to incorporate the strong nonlinearities of internal sloshing and the transient position hydrodynamic nonlinearities of external ship motion, while the CFD method can be prohibitively time consuming. Thus, establishing a fast, efficient time-domain prediction technique, which is capable of considering the strong nonlinear sloshing flows and nonlinear ship motion to simulate the real motion of vessels like an LNG carrier or FPSO in regular and irregular waves is necessary. For vessel design, a good understanding of the ship's performance and reliability is required. However, to date, there has been a lack of systematic investigation of the nonlinear effects analysis of sloshing and ship coupled motion, especially applied to sloshing energy dissipation.

In the present study, a nonlinear numerical model is developed to examine the violent sloshing coupled with the floating body motion. The fully nonlinear model, the linear free surface condition and the transient nonlinear body condition satisfy the Green function, adopted to solve for the inner tank flow and the ship's outer domain. In the numerical implementation, the ISITIMFB (iterative semi-implicit time integration method for floating bodies) is applied to solve for the body's velocity and displacements with high efficiency with acceptable accuracy. The sloshing coupled with nonlinear floating body motion is simulated for large amplitudes of regular and irregular waves and the numerical solutions are compared with the existing experimental results. The change in wave and sloshing-induced forces caused by the change in hull wet surface and the full nonlinear free surface of the internal fluid on sway and roll are analyzed in detail, with consideration given to a variety of non-linear contributions and mechanisms.

2. Numerical modeling method

2.1. Coordinate system

Three Cartesian co-ordinate systems are defined: in one, OYZ is fixed in space and in the others, oyz and $o_T y_T z_T$, are fixed on the floating body and on the tank, respectively. When the tank and floating body are at rest, the OYZ and oyz systems coincide and their origins are at the center of the undisturbed free surface along the vertical line through the center of gravity of the floating body G_0. The transient wetted surface of the body under the free surface S_F is defined as S_H. The positive direction of the normal vector $\vec{n}$ points to the outside of the fluid domain S_Ω. The free surface of the tank liquid is defined as S_{TF} and tank wall wetted surface as S_{TH}. The directions of the axes are shown in Fig. 1. The relationships between the coordinate frames are:

$$\begin{cases} \nabla_{YZ} = \nabla_{y_T z_T} \\ \left(\frac{\partial}{\partial t}\right)_{YZ} = \left(\frac{\partial}{\partial t} - \vec{U}\nabla\right)_{y_T z_T} [T] = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \\ \begin{pmatrix} Y \\ Z \end{pmatrix} = \begin{pmatrix} y_o \\ z_o \end{pmatrix} + [T]\begin{pmatrix} y_T \\ z_T \end{pmatrix} \end{cases} \tag{1}$$

where $[T]$ is the transformation matrix and α is the angle between frames OYZ and oyz.

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