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Numerical simulation of coupling effect between ship motion and liquid sloshing under wave action

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ABSTRACT

The coupling effect between ship motion response and internal sloshing flow is analyzed in this paper. The viscous two-phase flow model in OpenFOAM based on the Volume Of Fluid (VOF) interface capturing technique is adopted for solving the internal sloshing flow, while an impulse response function (IRF) method is employed for external ship response. A three-dimensional simplified LNG-FPSO ship with two partially-filled prismatic tanks is considered. Numerical simulations show that the coupling effect is significant at low-filling conditions in Beam Sea and the typical anti-rolling characteristics can be observed in such cases. The ship motion response shows strong sensitivity to incident wave steepness, especially around the natural frequencies for ship motion and sloshing motion respectively. Besides, no impact behavior in sloshing pressure and moment signals is observed when the incident wave is close to natural frequency of ship motion. Instead, impact phenomena can be observed only when the incident wave is close to sloshing natural frequency. However, the steady-state ship motion response is still found to be almost linear and sinusoidal at that wave frequency. The higher-order harmonics of the sloshing moment are filtered out by the system. The sloshing impact loading has no significant coupling effect on global ship response.

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1. Introduction

A ship carrying liquid cargo in partially filled tanks may experiences violent liquid sloshing under wave actions and this sloshing flow affects the ship motion response in return. In such a situation, the coupling effect significantly influences the hydrodynamic behavior of the ship; especially when the natural frequency of sloshing flow is close to that of ship motion response. This topic therefore, is of special interest for LNG tankers and FPSO vessels, particularly during loading and offloading operations and many numerical simulations on coupling analysis have been carried out, such as Rognebakke and Faltinsen (2003), Newman (2005) and Gou et al. (2011). In these studies, the linear potential theory is adopted, both on external wave action and internal sloshing flow. Based on the physical experimental results by Rognebakke and Faltinsen (2003), the steady-state ship motion is found to be almost linear and sinusoidal with the frequency of incident wave, even if violent sloshing happens. These findings from experimental data indicate that the assumption of linear ship motion in coupling analysis seems adequate. However, the same assumption may not be reasonable for internal liquid sloshing flow.

Therefore, a time domain solution is necessary due to the importance of nonlinearities for internal sloshing flow. There is a popular viscous numerical wave flume model available at present for the simulation of ship motion response in waves. However, that model is computationally very expensive and become even more time consuming while coupled with internal sloshing flow. Since the linear assumption has been proved to be applicable in simulating ship response under external wave action, an impulse-response function (IRF) method can be applied for the time-domain analysis of ship motion response. By converting the frequency domain solutions to time domain, the IRF method can provide much faster simulations than the direct solvers. This method was suggested by Cummins (1962) firstly and a detailed description was given in Ogilvie (1964). Lee and Newman (2005) suggested an analytic form of IRF for compensating cut-off frequency error.

Using the IRF method in external ship motion, the free surface nonlinear effect of the internal sloshing flow can be considered in the coupling analysis. Lee et al. (2007) considered the effect of LNG-tank sloshing on the global motions of LNG carriers and investigated the pattern of coupling effect between vessel motion and liquid sloshing. Kim et al. (2007) studied the nonlinear coupling effect of internal sloshing flow by considering a rectangular barge with partially-filled tanks and a ship with rectangular passive-type ART, respectively. It

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was found that the nonlinearity of sloshing flow is very important in coupling motion response, and the ship motion shows a strong sensitivity to incident wave steepness. A coupling analysis between ship motion response and inside liquid sloshing was carried out by Nam et al. (2009), in which a LNG-FPSO with two partially-filled tanks and a modified S175 hull with an anti-rolling tank were considered. In their work, the numerical study was extended to observe the sloshing pressure field inside the tanks. Numerical results indicate that the coupling effect on impact pressure depends on ship geometry, tank shape, incident wave frequency and wave amplitude. Bunnik and Veldman (2010) adopted the CFD model for internal sloshing flow to consider the nonlinear effect. Li et al. (2012) examined the tank sloshing and ship motion coupling effect based on a LNG carrier with two liquid tanks. Except IRF method, Kim (2002) used a time-domain panel method for ship motion to simulate the coupling effect problem.

The main purpose of the current work is to investigate the sloshing coupling effect, including the ship motion response and sloshing impact loading. In Section 2, the viscous two-phase flow model with VOF interface capturing technique based OpenFOAM is established for solving the internal liquid sloshing problem. Using IRF method for external wave action, the coupling effect between the ship motion response and internal sloshing flow can be analyzed. After the validation in Section 3, a three dimensional simplified LNG-FPSO ship with two partially-filled prismatic tanks is considered in Section 4. Numerical simulations are carried out to examine the global ship response, including the influence of incident wave direction, frequency, amplitude and liquid filling condition. The sloshing-induced nonlinear coupled hydrodynamic behavior is also investigated. Special attention is given towards ship motion natural frequency and sloshing motion natural frequency. The occurrence of sloshing flow impact loading moment is observed and its effect on global ship response is also investigated. Finally, the impulsive phenomena and impact magnitudes on local sloshing pressure are discussed.

2. Mathematical formulation

A ship equipped with partially-filled prismatic tanks is shown in Fig. 1. Two coordinate systems, ship-fixed coordinates (X, Y, Z) and tank-fixed coordinates (x, y, z) systems are defined. The tank-fixed coordinates system is defined at the center of the tank, rotating with respect to the point G, while the ship-fixed coordinates system is defined at the origin G of motion. In present coupling model, the internal sloshing flow model is established under ship-fixed coordinates system, while the external fluid flow model, including coupling strategy, is performed under space-fixed coordinates systems. Both of these flow models are described below:

2.1. Internal sloshing flow model

The inside sloshing flow can be represented as incompressible, viscous and Newtonian fluids and the governing equations in Arbitrary Lagrangian Eulerian (ALE) reference system can be express as:

$$\frac{\partial \rho u_i}{\partial x_i}=0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial \rho (u_j-u_j^m)u_i}{\partial x_j}=\rho g-\frac{\partial p}{\partial x_i}+\mu\frac{\partial}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{2}$$

where u_i is the velocity component in the i-th direction and p, ρ, μ denote the pressure, fluid density and dynamic viscosity, respectively. u_i^m is the velocity of mesh motion.

In order to simulate the complex free surface motion, such as wave breaking, particle splash, jet flow, and impact occurrence, the indicator function of fluid volume φ is adopted

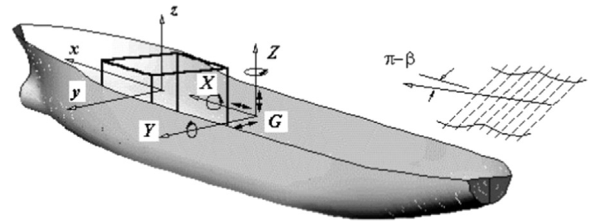

Fig. 1. Coordinate system.

$$\varphi=\begin{cases}\varphi=0, & \text{in air}\\ 0<\varphi<1, & \text{in free surface}\\ \varphi=1, & \text{in water}\end{cases} \tag{3}$$

which obeys the transport equation as:

$$\frac{\partial \varphi}{\partial t}+\frac{\partial (u_i-u_i^m)\varphi}{\partial x_i}=0 \tag{4}$$

The choice of Eq. (4) as an indicator function is a popular way; however, it is prone to problems associated with the convection of a step function. Herein, an extra, artificial compression term is introduced as follows:

$$\frac{\partial \varphi}{\partial t}+\frac{\partial (u_i-u_i^m)\varphi}{\partial x_i}+\frac{\partial (\varphi(1-\varphi)u_i^r)}{\partial x_i}=0 \tag{5}$$

where u_i^r is a velocity filed suitable to compress the interface. The artificial term is only active in the interface region because of the multiplication term $\varphi(1-\varphi)$. And hence it does not affect the solution significantly outside this region. In this work, the contour $\varphi=0.5$ is defined to represent the free surface. In the computations, the averaging density and viscosity are used

$$\rho=\varphi\rho_w+(1-\varphi)\rho_a,\ \mu=\varphi\mu_w+(1-\varphi)\mu_a \tag{6}$$

where the subscripts w and a represent the water and air phases, respectively, and $\rho_w=1.0\times10^3$ kg/m^3, $\mu_w=1.0\times10^{-3}$ kg/m s, $\rho_a=1.0$ kg/m^3 and $\mu_a=1.48\times10^{-5}$ kg/m s.

The governing equations are discretized by the Finite Volume Method (Jasak, 1996; Jasak and Tukovic, 2006) on a collocated grid and the pressure-velocity coupling is solved using the PISO (Pressure Implicit with Splitting of Operators) algorithm (Issa, 1986). In this work, the Euler method is used to discretize the time-dependent term. The convection term and diffusion term are discretized by the Gauss limited linear method and the Gauss linear corrected method, respectively. The Incomplete Cholesky preconditioned Conjugate Gradient (ICCG) solver is used for solving the symmetric matrices; see Jacobsn (1980) for more details. The solver adopted for the asymmetric matrices is the Bi-CGSTAB developed in Van Der VORST (1992). A thorough description about the numerical implementation and the discretization scheme can be found in Rusche (2002) and Ferziger and Peric (2002).

The time step is automatically determined according to the CFL condition, that is,

$$\Delta t<Cr\cdot\ \min\left\{\sqrt{S_e}/|u_e|\right\} \tag{7}$$

where Cr can be interpreted as the Courant number, S_e and u_e are the cell area and velocity, respectively. Generally, $Cr=1/3$ can guarantee the numerical stability and produce good accuracy. However, in order to simulate the transient impulsive pressure well and avoid the possible error produced by the large time step, the $Cr=0.1$ and $\Delta t_{\max}=0.001$ s are imposed in the present calculations.

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