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Effects of tank sloshing on submerged oil leakage from damaged tankers

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ABSTRACT

In order to gain advanced understanding of the mechanism of the submerged oil leakage from damaged tankers subjected to wave-excited motions, a three-dimensional (3D) full scale numerical model is developed in this paper. The model is based on the three-phase Navier-Stokes equation and the continuity equation, which are solved by using the finite volume method (FVM). The volume of fluid (VOF) method is implemented to identify the interfaces between different phases and the k-ε turbulence model is employed to approximate the turbulence effects. The prototype of the oil tanker is taken as the side tank of VLCC, which is subjected to a periodically forced motions yielding a liquid sloshing inside the tank. After being validated by comparing its prediction with experimental data, the present model is utilized to a systematic investigation with wide range of applications including different motion amplitudes and periods. The dynamic characteristics of both the macroscopic parameters, e.g. the volume of the oil/water, and the microscopic parameters, e.g. the velocity distributions, are analyzed. The results fill the gap in the existing numerical and experimental work, in which the tank is assumed to be stationary, and produce a more reliable prediction on the dynamic process of the oil leakage and the stability of the damaged oil tankers subjected to wave actions.

1. Introduction

The submerged crude oil leakage from damaged tanker in is considered as a major potential hazard to the ocean environment. A great effort has been devoted to both experimental and numerical investigations.

In terms of experimental studies, Yamaguchi and Yamaguchi (1992) has applied 1/50 side tank of the VLCC to explore the behavior of crude oil leakage in grounding condition (bottom rupture) and confirmed the importance of geometry and dynamic similarity; Debra et al. (2001) investigated the effect of oil density on the characteristics of oil leakage. Tavakoli et al. (2008, 2009, 2010, 2011, 2012) have carried out a systematical experiment with wide range of considerations including the draft factor, characteristics of oil leakage and capability of ballast tank for single hull tankers (SHT); Lu et al. (2014, 2015 and 2016) have carried out similar experiments but using double hull tankers (DHT), in which different positions of the rupture holes, initial water layers in the ballast tank (to reflect the time difference between the damage on the external hull and that on the internal hull) These experimental studies have explored the dynamic characterizes of the oil leakage for ideal conditions, i.e. fixed oil tankers originally placed in still water.

On the other hand, the analytical and empirical models for predicting the oil leakage were mainly established based on the theory of orifice flow subjected to hydrostatic conditions in the earlier stage (e.g. Dodge and Bowles, 1982; Fthenakis and Rohatgi, 1999; Fay, 2003). Such researches brought benefits on estimating the ultimate volume of spilled oil in an ideal condition. In order to reveal the hydrodynamic feature of the oil leakage process, which has been confirmed in the above-mentioned experimental studies, the computational fluid dynamics (CFD) has also been attempted (e.g. Chang III and Lin, 1994; Cheng et al., 2010; Tavakoli et al., 2011, 2012; Yang et al., 2014, 2016, 2017). Similar to the experimental studies, the majority of the numerical work did not take into account of the effects of the tank motion on the oil leakage.

In fact, during the oil leakage process, the tanker is often subjected to the action of water wave, current and wind, yielding translational and/or rotational motion, which influences the oil leakage process. On the other hand, the oil leakage poses loading on the oil tanker and may significantly affect the motion of the damaged tankers. Consequently, the motion of the tanker, the oil leakage and the ocean environment need to be modelled simultaneously as an integrated system in both the numerical and experimental studies. However, in most of the existing researches, the tankers are assumed to be stationary and, therefore, the effects of the tanker motion on the oil leakage, as well as the external

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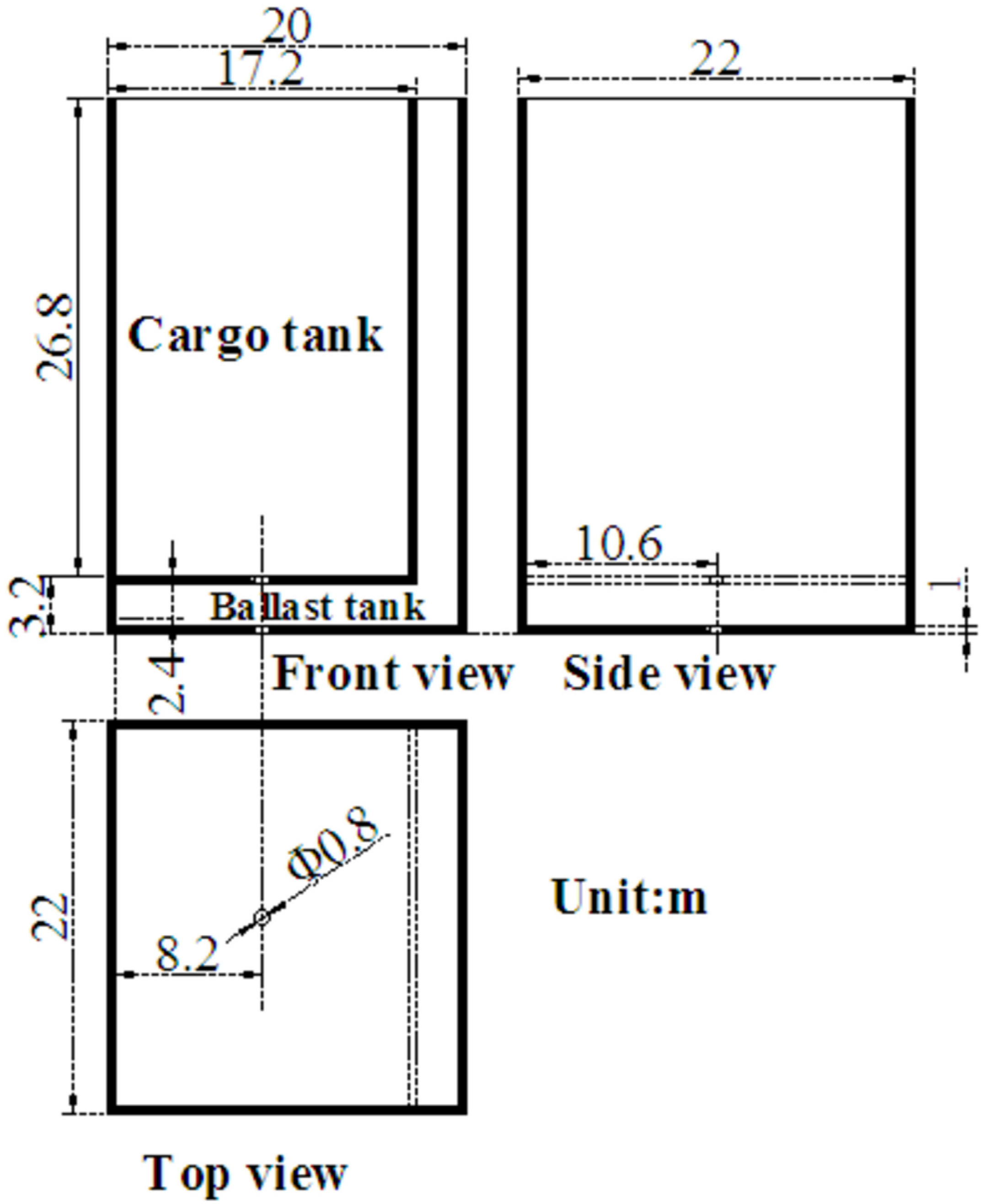

Fig. 1. Sketch of the L-shape tank.

environmental fluid conditions, are ignored. Theoretically, the CFD models established for modelling oil leakages from fixed oil tankers can be extended to simulate the scenario where the oil tankers are subjected to a motion, its complexity emerges when comprehensively considering the integrated system combining the external environment (tide, current and wave), the ship response (damaged ship motion and sloshing) and the oil leakage (Zhang and Suzuki, 2006). To the best of our knowledge, only Yang et al. (2016) have preliminarily attempted to numerical simulate the oil leakage from a two-dimensional (2D) SHT subjected to pre-specified periodic motions without considering the action of wave and current. They have demonstrated that the tank motion does not only cause a periodic oscillation of the oil/water flow through the broken hole, but also results in a second long-duration stage of spilling after a quasi-hydrostatic-equilibrium condition occurs, leading to more significant amount of spilled oil. Nevertheless, their work was restricted by 2D assumption and is difficult to be applied to the reality.

In this paper, a three-dimensional numerical model is established and couples the oil leakage and the motion of the DHT to investigate the effect of tanker motion on both the oil leakage and the liquid sloshing inside the tank. Only the grounding scenario, in which the oil spills from the bottom of the tank, is considered. Dynamic characteristic of the oil leakage, the free surface deformation and the flow field inside the tank are obtained to analyze the mechanism of oil leakage from a grounded tank in motion. Similar to Yang et al. (2016), only pre-specified periodic tank motion with different amplitudes and periods of motion, are taken into account. Although it is understood that the oil leakage and external fluid motion in turn influence the motion of the tank, one may agree that the present research leads to a better understanding on the hydrodynamics associated with the oil leakage.