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Applications of RANS Turbulence Modeling Based on Two-Equation Closure Models in Sloshing Simulations

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Reynolds-averaged Navier–Stokes (RANS) turbulence modeling based on two-equation closure models can create excessive turbulence levels, leading to the unphysical motion of the interface in sloshing simulations. Five two-equation closure models are studied in this paper. Two strategies of modification are introduced to avoid the unphysical motion of the interface. One is to modify the transport equations of closure models, and the other is to utilize the eddy-viscosity eliminator. The results are compared with the experiments, and a corresponding relationship is found. The appropriate methods are recommended for RANS simulations of sloshing flow.

INTRODUCTION

Two vessels have been developed for long-term sea operation: the floating liquefied natural gas (FLNG) vessel, which can collect natural gas from the sea, and the floating storage and regasification unit (FSRU), which is a vital component for transferring the LNG. There is no restriction on the filling level of the internal tanks of these vessels exposed to external excitations caused by sea waves, and the resonant sloshing happens inevitably in partially filled tanks.

Currently, computational fluid dynamics (CFD) is becoming an excellent tool to investigate the sloshing flow with rapid developments in computing technology. Sloshing is an interfacial flow with strong turbulence effects. Maillard and Brosset (2009) and Karimi et al. (2016) found that the gas phase plays a crucial role in sloshing flow, and CFD can consider both gas and liquid phases. Moreover, Reynolds-averaged Navier–Stokes (RANS) simulation is more widely used than large eddy simulation (LES) and direct numerical simulation (DNS) because LES and DNS have much larger computation efforts than RANS simulations.

Wave–structure (wall) interaction and wave breaking can lead to turbulence (Devolder et al., 2017; Larsen and Fuhrman, 2018). Thus, the turbulence effects need to be considered in sloshing simulations. RANS simulations need turbulence closure models. It is found that two-equation closure models can easily create unphysical motion of the interface in sloshing simulations. The influence of closure models on RANS simulations of sloshing flow is significant but is not fully discussed. Few studies focus on the influence of the turbulence modeling methods in sloshing simulations. Kishev et al. (2006) and Gómez-Goñi et al. (2013) used the laminar model to simulate sloshing flow. Lee et al. (2011) and Liu and Lin (2008) studied sloshing flow by using LES. Similar unphysical phenomena are also reported in other areas. Mayer and Madsen (2000) diagnosed the unphysical phenomenon in simulations of surface waves based on RANS turbulence modeling. Moreover, the critical decrease of wave elevation over the length in the numerical wave flume was reported by Devolder et al. (2017), which attributed the wave elevation decrease to excessive turbulence levels around the interface and proposed the buoyancy-modified k–ω shear stress transport (SST) closure model to avoid the unphysical decrease of wave elevations. Larsen and Fuhrman (2018) proved that classical two-equation RANS closure models are unstable for wave simulations regardless of the number of phases being considered. They also proposed a new and stable k–ω model. Zwart et al. (2004), Frikha et al. (2008), Niedźwiedzka et al. (2016), and Long et al. (2017) found that cavitation dynamics cannot be accurately predicted because of overestimated eddy viscosity in the cavitation region. They also proposed several different approaches to overcome these problems.

In this paper, in order to seek the appropriate methods of RANS turbulence modeling for sloshing flow, different two-equation RANS closure models are studied, such as the standard k–ϵ model (abbreviated as k–ϵ model), re-normalization group (RNG) k–ϵ model, realizable k–ϵ model, standard k–ω model (abbreviated as k–ω model), and k–ω SST model. Two strategies of modification are introduced to avoid the unphysical motion of the interface. One is to modify the transport equations of closure models. The other is to adopt the eddy-viscosity eliminator (EVE) while transport equations are not modified. The results achieved by using different methods are compared with the experiments and the results achieved by using the adaptive asymptotic model (AAM). The potential reasons for different results are analyzed. The appropriate methods of RANS turbulence modeling are recommended for sloshing simulations.

THE NUMERICAL MODEL

The present work is implemented in the open-source package OpenFOAM. The finite volume method is adopted to discretize governing equations (Devolder et al., 2017). The two-phase flow is treated as a single continuum (single-fluid model). The dynamic mesh technology is used to handle the movement of the tank (Demirdžić and Perić, 1988; Jasak and Tukovic, 2006). The volume-of-fluid (VOF) method is used to capture the interface because mass conservation is essential in an enclosed tank (Li et al., 2019). There is a transition layer from the gas phase to the liquid phase around the interface in numerical computations, and the layer is a density-stratification layer.

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KEY WORDS: Sloshing flow, RANS closure model, excessive turbulence level, buoyancy effect, eddy viscosity.