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# Numerical Simulation of Liquid Sloshing Using a Fully Nonlinear Potential Flow Model in the Noninertial Coordinate System

Zaibin Lin*, Ling Qian* and Wei Bai
Centre for Mathematical Modelling and Flow Analysis, Department of Computing and Mathematics
Manchester Metropolitan University, Manchester, United Kingdom

**Liquid sloshing has been one of the primary concerns in ocean and offshore engineering because of its significant effects on ship stability and structural integrity. To investigate sloshing flow problems, the present study develops a 3-D finite volume method (FVM)-based fully nonlinear potential flow (FNPF) model in the noninertial coordinate system. In this model, the Laplace equation is spatially discretised and solved using a second-order accurate FVM from the open source computational fluid dynamics software OpenFOAM. For the fully nonlinear free surface problems, both kinematic and dynamic boundary conditions at the free surface are implemented in the mixed Eulerian–Lagrangian (MEL) form to update the free surface elevation and velocity potential, respectively. The FNPF sloshing model is validated against a number of available experimental measurements and numerical results for test cases under different external excitations. Finally, the conclusions in terms of model accuracy and applicability are summarised based on the validation and application results. It is found that the proposed FVM-based sloshing FNPF model is able to simulate the fully nonlinear liquid sloshing process in the noninertial coordinate system.**

## INTRODUCTION

Liquid sloshing has been a long-standing engineering issue for aerospace, civil, and marine engineering, and it plays an important role in ensuring structural stability and safety. Violent structural motions induced by external conditions (such as launch and recovery of spacecrafts; ship motion, especially liquefied natural gas (LNG) tankers under waves and wind; and skyscrapers under the combined effects of earthquakes, winds, and other environmental sources) may lead to significant sloshing flows and impulsive loading on structure walls. These loads, in turn, may affect the stability and safety of structures and eventually cause structural damage to container walls, such as tank rupture. On the other hand, liquid sloshing in tanks has long been utilised as a vibration and motion control device, and examples include the tuned liquid damper in civil engineering applications and antiroll tanks for mitigating the roll motion of ships. Therefore, a robust, accurate, and effective numerical model that can capture fully nonlinear free surface behaviour is desired to estimate the fluid sloshing process inside a container.

Aiming at accurately capturing the complex fully nonlinear liquid sloshing process in a container, numerous numerical models based on fully nonlinear potential flow (FNPF) theory have been proposed and implemented using different numerical methods, such as the finite difference method (FDM) (Frandsen, 2004), finite element method (FEM) (Wu et al., 1998; Kim et al., 2003; Wang and Khoo, 2005), finite volume method (FVM) (Lin et al., 2019; Lin, Qian, Bai, Ma, et al., 2021), boundary element method (BEM) (Faltinsen, 1978; Nakayama and Washizu, 1981; Zhang, 2015), and the harmonic polynomial cell (HPC) (Shao, 2010; Liang et al., 2020). In these models, the free surface is updated based on the kinematic and dynamic boundary conditions; additionally, because of the potential flow assumption and its inherent limitations, they are not capable of capturing the violent postwave breaking process such as free surface turbulence and air entrainment. However, compared to the two-phase viscous Navier–Stokes (NS) models based on volume of fluid (VoF) (Çelebi and Akyıldız, 2002; Lee et al., 2007; Liu and Lin, 2008) or level set method (LSM) (Gu et al., 2005; Chen and Price, 2009; Wang et al., 2011; Bai et al., 2015), the FNPF-based liquid sloshing model is far more computationally efficient (Ransley et al., 2019) under nonbreaking sloshing scenarios.

Among these aforementioned FNPF-based sloshing models, Wu et al. (1998) adopted the FEM-based sloshing model to investigate the sloshing waves in a 3-D tank and found that the occurrence of high pressure under certain circumstances may lead to significant damage to engineering structures. Subsequently, Wang and Khoo (2005) applied the FEM-based sloshing model to investigate the nonlinear sloshing problem due to random excitations and concluded that energy concentration may occur at the natural frequency of the container. Zhang et al. (2015) developed a BEM-based FNPF sloshing model to examine the second-order sloshing resonance in a 3-D container, which was further developed to simulate the sloshing process in an inverted trapezoid tank (Zhang, 2015). By extending the HPC-based FNPF model (Shao, 2010), Liang et al. (2020) incorporated an overset mesh technique to study liquid sloshing process under focused-wave-type excitations.

In this study, we propose an FVM-based liquid sloshing model in open access computational fluid dynamics (CFD) software OpenFOAM by extending our in-house FNPF model for water wave problems (Lin et al., 2019; Lin, Qian, Bai, Ma, et al., 2021). To better simulate the sloshing flow excited by potentially six degree-of-freedom external motions, such as the tuned liquid multicolumn damper in Fath et al. (2020), the numerical model is constructed in the noninertial coordinate system, which has the advantage of simplicity in dealing with body motions as well as implementing solid wall boundary conditions. In the following

*ISOPE Member.

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KEY WORDS: OpenFOAM, finite volume method, liquid sloshing, fully nonlinear potential flow, noninertial coordinate system.