Ocean Engineering 146 (2017) 434–456

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Sloshing of liquid in partially liquid filled toroidal tank with various baffles under lateral excitation

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ARTICLE INFO

Keywords:
Toroidal tank
Scaled boundary finite element method
Sloshing
Baffles
Sub-domains
Sloshing frequencies
Sloshing force

ABSTRACT

A technique to study effect of various baffles on liquid oscillations in partially filled rigid toroidal tanks is first developed by extending the semi-analytical scaled boundary finite element method (SBFEM), which utilizes the advantages of both the boundary element (BEM) and finite element methods (FEM). As found in the BEM, only the boundary is discretized to reduce the space by one, and no fundamental solution is needed unlike the BEM. The calculated liquid domain is divided into several simple sub-domains so that the liquid velocity potential in each liquid sub-domain becomes the class C^1 with continuity boundary conditions. Based on the linear potential theory and weighted residual method, the semi-analytical solutions of the liquid velocity potential corresponding to each sub-domain are obtained by means of SBFEM, where the geometry of each sub-domain is transformed into scaled boundary coordinates, including the radial and circumferential coordinates by using a scaling centre, and the finite-element approximation of the circumferential coordinate yields the analytical equation in the radial coordinate. By discretizing the flow boundaries, the integral equation governed on the boundary is formulated into a general matrix eigenvalue problem. Based on the eigenvalue problem and multimodal method, an efficient methodology is adopted to computer the sloshing masses and sloshing force. Accuracy, simple and fast numerical computations are observed by the convergence study, and excellent agreements have been achieved in the comparison of results obtained by the proposed approach with other methods. Meanwhile, several baffle configurations are considered including the horizontal bottom-mounted and surface-piercing ring baffles as well as their combination form, bottom-mounted and surface-piercing ring baffles as well as their combination, and free surface-touching baffles. The effects of baffled arrangement, the ratio b/a of elliptical cross section, liquid fill level, and baffles' length upon the sloshing frequencies, the associated sloshing mode shapes and sloshing forces are investigated in detail and some conclusions are outlined. The results show that the present method allows for the simulation of complex 3D sloshing phenomena using a relative small number of degrees of freedom while the mesh consists of two-dimensional elements only.

1. Introduction

Sloshing is a widespread physical problem and has the oscillation behavior of fluid in a partially filled tank, which is subjected to the external excitation. The understanding of the complex hydrodynamic characteristic of sloshing has far-reaching significance in the fields of engineering and technologies disciplines and has great interest concerning economy, environment and safety, which can often be found in moving vehicles such as liquid bulk cargo carriers (e.g., oil tankers, ships, trucks, railroad cars), aircrafts, spacecrafts, and rockets as well as in storage containers, dams, nuclear vessels, and reactors undergoing seismically excitation (Ibrahim, 2005). Ibrahim (2005), and Faltinsen and Timokha (2009) have carried out extensive reviews on the applications and physics of sloshing problems. If the sloshing frequencies are sufficiently near to the structures' natural frequencies, the waves of resonant sloshing may induce amount hydrodynamic loads on the system of tank walls and associated support structures, which can reduce the fatigue life of the system and even cause failure.

In order to avoid failure of structure system due to the undesirable dynamic behaviors, the hydrodynamic loads of sloshing should also be

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https://doi.org/10.1016/j.oceaneng.2017.09.032
Received 10 June 2017; Received in revised form 12 August 2017; Accepted 24 September 2017

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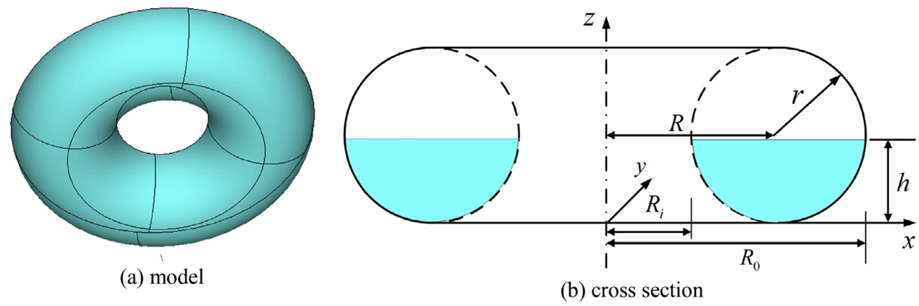

Fig. 1. Schematic of a toroidal tank. (a) model, and (b) cross section.

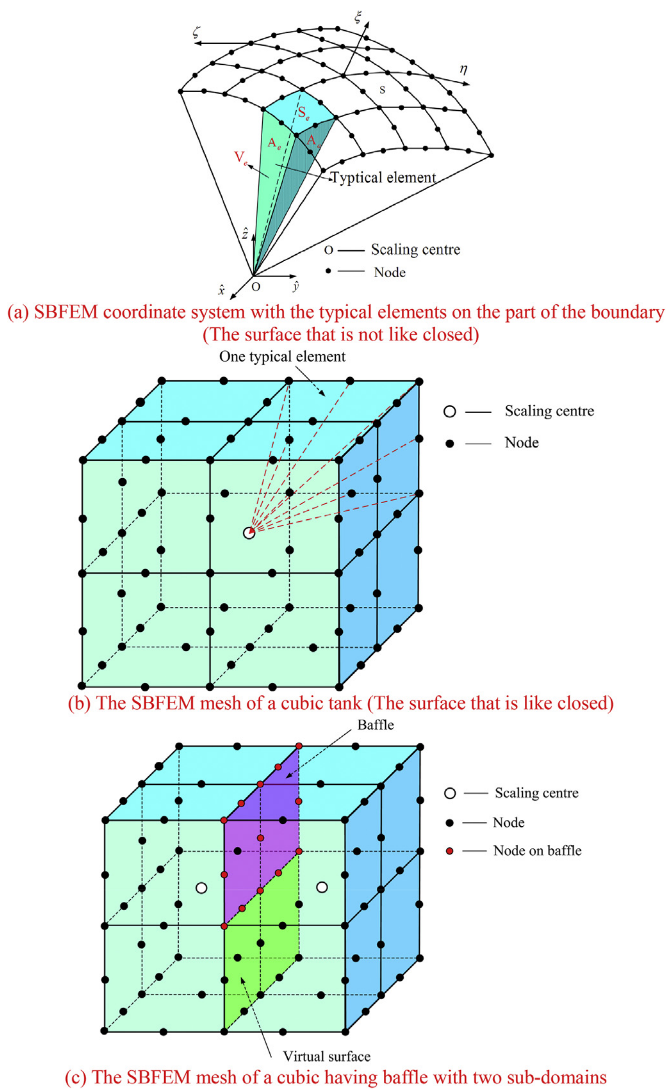

Fig. 2. The SBFEM coordinate system and the SBFEM mesh of a cubic tank. (a) SBFEM coordinate system with the typical elements on the part of the boundary (The surface that is not like closed), (b) The SBFEM mesh of a cubic tank (The surface that is like closed), and (c) The SBFEM mesh of a cubic tank having baffle with two sub-domains.

restrained. Baffles installed in the tanks have been effectively chosen as an internal components to suppress liquid sloshing, and consequently reduce the sloshing forces in most of the practical engineering problems. The issue of using baffles to suppress sloshing behavior can go back to late 50s when Abramson (1969) analyzed the influence of baffles on the sloshing in continuers of space vehicles filled with fuel. Since then, a mount of valuable studies have been conducted to study the effects of various types of baffles on the sloshing behavior of containers by using experimental, theoretical, and numerical approaches. For examples, Dodge (1971), Strandberg (1978), Younes et al. (2007), Panigrahy et al. (2009), Goudarzi et al. (2010), Hosseini and Farshadmanesh (2011), Hosseinzadeh et al. (2014), Akyldz et al. (2013), Turner et al. (2013), Wei et al. (2015) and Xue et al. (2013, 2017) investigated the parametric effects of different baffles including vertical, horizontal, annular, slat-screens, ring-type, flexible and perforated configuration concerning about the baffle shapes, dimensions, arrangements and numbers on the sloshing characteristics in the 2D, 3D and cylindrical containers. Evans and McIver (1987), Watson and Evans (1991), Gavrilyuk et al. (2006, 2007), Chantasiriwan (2009), Hasheminejad and Aghabeigi (2009), Wang et al. (2012a, 2012b), Goudarzi and Danesh (2016) and Cho and Kim (2016), Cho et al. (2017) represented the analytical or semi-analytical approaches to obtain the natural frequencies, mode shapes and the sloshing response of liquid sloshing in the partially fluid-filled the 2D, 3D and cylindrical container with horizontal, vertical, annular and porous baffles and internal bodies for different submergence depths, lengths, location and configuration, respectively. Hasheminejad and Mohammadi (2011), Hasheminejad, et al. (2014), Hasheminejad and Aghabeigi (2011, 2012), and Hasheminejad and Soleimani (2017) introduced the analytical solutions to study the free or transient liquid sloshing characteristics in the two-dimensional (2D) horizontal circular or elliptical cylindrical filled half-full or an arbitrary depth tanks with various baffles such as bottom-mounted and surface-piercing vertical baffles as well as the horizontal side baffles with arbitrary extension placed at the free liquid surface. In addition to these two methods, many useful numerical schemes have been developed for the sloshing problems with different baffles due to the great benefits of computers. Armenio and Rocca (1996) presented the numerical test to analyze the effect of a vertical internal baffle in a rectangular container on the liquid sloshing, and it has been observed that the presence of this baffle brought out a strong reduction of the sloshing response in the whole range of roll frequencies. Wang et al. (2010) adopted the cell-centered pressure-based algorithm along with the level set technique to evaluate the potential of baffles including the orientation, and the number of the fluid sloshing motion in a two-dimensional (2D) rectangular tank. Zheng et al. (2013) used FLUENT software to simulate liquid sloshing in tanks installing various kinds of baffles including the circular baffle, the conventional baffle, and the staggered baffle undergoing the constant braking excitation. Zhou et al. (2014) used multi-modal method of Lukovsky-Miles variational to model the nonlinear liquid sloshing in a cylindrical tank with annular baffles. Cho et al. (2002, 2005), Khalifa et al. (2007), Belakroum et al. (2010), Biswal and Bhattacharyya (2010), and Nayak and Biswal (2016) conducted the finite element method (FEM) to study the effects of parametric baffle including number, location and inner-hole diameter as well as liquid fill height on the natural frequencies and corresponding modes as well as resonance sloshing response in the containers. Meanwhile, Cho and Lee (2004) and Biswal et al. (2006) introduced a nonlinear finite element method (FEM) for simulating the large amplitude slosh in the two-dimensional baffled container undergoing the horizontal based on the fully nonlinear potential flow theory.

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