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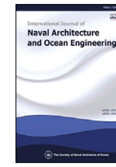

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The pressure distribution on the rectangular and trapezoidal storage tanks' perimeters due to liquid sloshing phenomenon

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Abstract

Sloshing phenomenon is a complicated free surface flow problem that increases the dynamic pressure on the sidewalls and the bottom of the storage tanks. When the storage tanks are partially filled, it is essential to be able to evaluate the fluid dynamic loads on the tank's perimeter. In this paper, a numerical code was developed to determine the pressure distribution on the rectangular and trapezoidal storage tanks' perimeters due to liquid sloshing phenomenon. Assuming the fluid to be inviscid, the Laplace equation and the nonlinear free surface boundary conditions were solved using coupled boundary element – finite element method. The code performance for sloshing modeling was validated using Nakayama and Washizu's results. Finally, this code was used for partially filled rectangular and trapezoidal storage tanks and free surface displacement, pressure distribution and horizontal and vertical forces exerted on the tanks' perimeters due to liquid sloshing phenomenon were estimated and discussed.

Keywords: Pressure distribution; Liquid sloshing phenomenon; Sway motion; Trapezoidal storage tank; Free surface displacement; Horizontal and vertical forces; Coupled boundary element-finite element method

1. Introduction

The sloshing phenomenon in a moving container is associated with various engineering problems, such as tankers on highways, liquid oscillations in large storage tanks caused by earthquakes, sloshing of liquid cargo in ocean-going vessels and the motion of liquid fuel in aircraft and spacecraft. This phenomenon is of interest in a variety of engineering fields as it may cause large structural loads. Many researchers studied this phenomenon in the last few decades. Some researchers considered the fluid to be inviscid (Choun and Yun, 1996; Frandsen, 2004; Wu, 2007; Chen et al., 2012; Zhang, 2015a; Zhang et al., 2015; Lee et al., 2007a) while others considered it as viscous (Lee et al., 2007b; Wu et al., 2012; Gomez-Goni et al., 2013; De Chowdhury and Sannasiraj, 2014; Jing Li and Zhen Chen, 2014; Zhao and Chen, 2015). Different geometric shapes were proposed for storage tanks to model the sloshing phenomenon by researchers. Choun and Yun (1996), Chen and Chiang (2000), Celebi and Akyildiz (2002), Frandsen (2004), Akyildiz and Unal (2006, 2005), Chen and Nokes (2005), Wu (2007), Lee et al. (2007a, 2007b), Liu and Lin (2008), Panigrahy et al. (2009), Belakroum et al. (2010), Ming and Duan (2010), Huang et al. (2010), Pirker et al. (2012) and Lu et al. (2015) studied the sloshing phenomenon in rectangular tank. Hasheminejad and Aghabeigi (2012) used an elliptical tank shape. Papaspyrou et al. (2004), Karamanos et al. (2005), Wiesche (2008) and Shekari et al. (2009) studied sloshing in cylindrical tanks. Gavrilyuk et al. (2005) studied linear and nonlinear sloshing in a circular conical tank. Mciver (1989), Papaspyrou et al. (2003), Patkas and Karamanos (2007), Yue (2008) and Curadelli et al. (2010) modeled sloshing in spherical tanks. Some researchers such as Liu and Lin (2009), Panigrahy et al.

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(2009) and Jung et al. (2012) used horizontal and vertical baffles inside the tank to prevent sloshing with different geometric shapes. Ketabdari et al. (2015), Ketabdari and Saghi (2013a, 2013b, 2013c), Saghi and Ketabdari (2012) and Zhang (2015b) studied the behavior of the trapezoidal storage tank with linear and nonlinear sidewalls due to liquid sloshing phenomenon. Zou et al. (2015) studied the effects of boundary layer grid, liquid viscosity and compressible air on sloshing pressure, wave height and rising time of impact pressure. Lee et al. (2013) evaluated the sloshing resistance performance of a huge-size LNG carrier's insulation system by the fluid−structure interaction (FSI) analysis. Jung et al. (2015) studied the effect of natural frequency modes on sloshing phenomenon in a rectangular tank. Kim (2013) calculated the rapid response of LNG cargo containment system under sloshing load using wavelet transformation method.

The principal objective of this study is to develop a numerical model assuming incompressible and inviscid fluid in the rectangular and trapezoidal storage tanks to find the free surface displacement, pressure distribution, horizontal and vertical forces exerted on the tank's perimeter that is caused due to liquid sloshing phenomenon. The coupled boundary element − finite element methods were used to solve the Laplace equation and the nonlinear free surface boundary conditions to model the sloshing phenomenon.

2. Problem definition

In this research, rectangular and trapezoidal storage tanks were considered for the fluid storage and the pressure distribution in different points on the tank's perimeter panels (see Figs. 1 and 2) due to liquid sloshing phenomenon were estimated using coupled boundary element − finite element methods.where W is the width of the tank, H is the water depth, x and y are the coordinate axes, O is origin, $\eta(x,t)$ is the free surface displacement. A, B, C and D are the points on the tank perimeter that are estimated pressure due to liquid sloshing phenomenon on them and S_1 and S_2 are the boundaries applied in Eqs. (5)−(7).

3. Governing equations and boundary conditions

The dynamic behavior of an inviscid and incompressible fluid and flow-irrotational is governed by the Euler equations. Instead of modeling the problem for a moving storage tank with acceleration vector of (a_x,a_y), it was assumed that an opposite acceleration has been exerted to the fluid of the fixed storage tank. Therefore, the governing equations are derived as:

$$\frac{\partial u}{\partial t}+\nabla.(uV)=\frac{-1}{\rho}\frac{\partial P}{\partial x}-a_x \quad (1)$$

$$\frac{\partial v}{\partial t}+\nabla.(vV)=\frac{-1}{\rho}\frac{\partial P}{\partial y}+g-a_y \quad (2)$$

In these equations u and v are velocity components in the x and y directions respectively, V is the velocity vector as $V = (u,v)$, P is the hydrodynamic pressure, ρ is the fluid density and g is the gravity acceleration. The 2D incompressible continuity equation is:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \quad (3)$$

Using velocity potential in Eq. (3), the Laplace equation is obtained as follows:

$$\frac{\partial^2\varphi}{\partial x^2}+\frac{\partial^2\varphi}{\partial y^2}=0 \quad (4)$$

For the sloshing modeling, impermeable condition for the side and the bottom boundaries and the free surface boundary conditions are considered as follows:

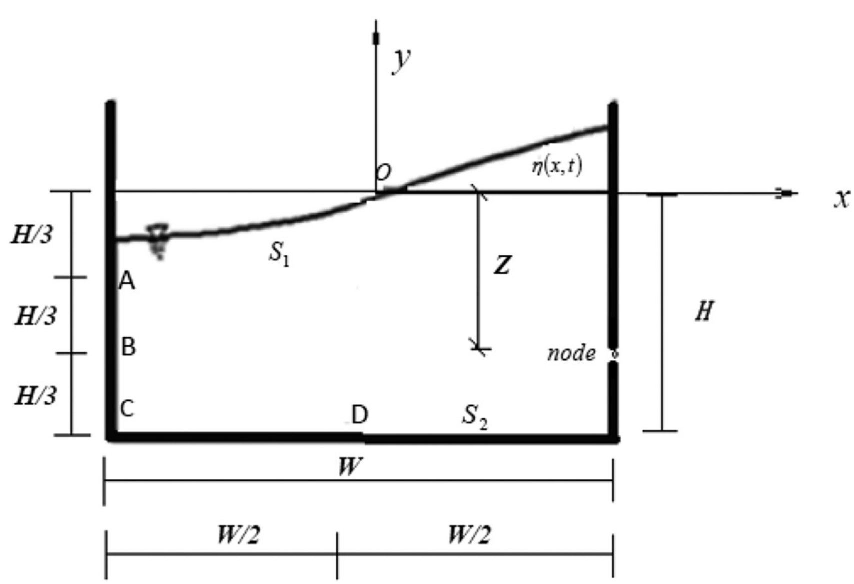

Fig. 1. Sloshing phenomenon in the rectangular storage tank.