Journal of Fluids and Structures 27 (2011) 1165–1181

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

A study of sloshing absorber geometry for structural control with SPH

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ARTICLE INFO

Article history:
Received 16 August 2010
Accepted 28 February 2011
Available online 30 April 2011

Keywords:
Liquid sloshing
Absorber shape
Structural control
Smoothed Particle Hydrodynamics
Fluid–structure interaction

ABSTRACT

A liquid sloshing absorber consists of a container, partially filled with liquid. The absorber is attached to the structure to be controlled, and relies on the structure's motion to excite the liquid. Consequently, a sloshing wave is produced at the liquid free-surface within the absorber, possessing energy dissipative qualities. The primary objective of this work is to numerically demonstrate the effect of a sloshing absorber's shape on its control performance. Smoothed Particle Hydrodynamics (SPH) is used to model fluid–structure interaction of the structure/sloshing absorber system in two dimensions. The structure to be controlled is a lightly damped single degree-of-freedom structure. The structure is subjected to a transient excitation and then allowed to respond dynamically, coming to rest either due to its own damping alone or with the added control of the sloshing absorber. It is identified that the control performance of the conventionally used rectangular container geometry can be improved by having inward-angled walls. This new arrangement is robust, and of significant advantage in situations when the external disturbance is of uncertain magnitude.

1. Introduction

Sloshing is the oscillation of a liquid within a partially full container. In the study of sloshing, efforts are usually made in the direction of suppression, due to the damaging effects it can impose (Koh et al., 2007; Shekari et al., 2008; Faltinsen, 1993; Panigraphy et al., 2009). On the other hand, sloshing has an inherent ability to dissipate large amounts of energy. For this reason, it is possible to employ liquid sloshing as an effective energy sink in structural control applications, providing protection for structures exposed to excessive levels of vibration (Sun et al., 1989; Modi et al., 1996; Sun and Fujino, 1994; Modi and Munshi, 1998; Marsh et al., 2010a).

Generally, a sloshing absorber is tuned so that the frequency of sloshing coincides with the natural frequency of the structure (Kareem, 1990; Banerji et al., 2000). When designed properly, the sloshing fluid oscillates out of phase from the structure, creating a counteracting pressure force on the side of the container. Shearing of the fluid is the primary form of mechanical damping, providing that the liquid level is low (Kareem, 1990).

Liquid sloshing in rectangular tanks has long been an area of study (Sun et al., 1989; Ikeda and Nakagawa, 1997; Rafiee et al., 2010), with significant effort being focused on increasing the energy dissipation performance of this widely used conventional design. Variations on the conventional design have included the introduction of wedge shaped objects on the container bottom (Modi and Akinturk, 2002), baffles on the container walls (Anderson et al., 2000), wall flexibility

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0889-9746/$ - see front matter
doi:10.1016/j.jfluidstructs.2011.02.010

(Gradinscak et al., 2002), floating solid particles at the free-surface (Sun and Fujino, 1994) and submerged nets within the fluid volume (Kaneko and Ishikawa, 1998). Studies involving varying liquid depth have been undertaken, focusing on increasing the amount of energy dissipation produced (Anderson et al., 2000; Guzel et al., 2005; Reed et al. 1998; Marsh et al., 2010b). These studies have demonstrated that shallow depths are more effective at dissipating energy than deep liquid levels, on a per unit mass basis.

Alternative container shapes to that of a rectangle have been studied in order to assess their control performance (Tamura et al., 1996; Casciati et al., 2003). Tait and Deng (2008) conducted a comparative study between different absorber shapes using Linear Long Wave Theory. This study outlined the structural control characteristics of the shapes investigated; however, such a numerical model is limited to the analysis of small structural displacements only, due to the approximations made. Therefore, the effect that an absorber's shape has on its control performance is still largely unknown, particularly when the system is energetic enough to produce breaking waves within the absorber.

The primary objective of this work is to investigate the effects that an absorber's shape has on its control performance, particularly during circumstances of large structural displacements. In such conditions, violent fluid behaviour is observed at the free-surface. Such behaviour is known to be responsible for dissipating large amounts of structural energy (Marsh et al., 2009), and is therefore a desirable phenomenon. Potential enhancements are explored, with shapes different than a rectangle, through numerical investigation. The relationship between container shape and fluid behaviour is assessed.

Due to complex free-surface behaviour, Smoothed Particle Hydrodynamics (SPH) is used as a numerical modelling tool in this study. SPH is a Lagrangian method for solving the equations of fluid flow. It is suitable for modelling liquid sloshing due to its grid free nature, and inherent ability to capture free-surface behaviour accurately (Monaghan, 1992). SPH has been successfully applied to a wide range of industrial fluid flow applications involving complex geometries in many instances (Cleary et al., 2007a, 2007b, 2002, 2006; Marsh et al., 2009).

In order to validate the predictions of fluid–structure interaction with the SPH model, simple experimental observations (Marsh, 2009) are also presented here. SPH is found to provide an accurate prediction of structure's oscillations, employing a wide range of liquid depths. A brief description of the experiments, along with comparisons of two representative cases is given in the Appendix.

2. Numerical model

Smoothed Particle Hydrodynamics (SPH) is used in this study to model fluid–structure interaction. CSIRO's (Commonwealth Scientific and Industrial Research Organisation) Mathematical and Information Sciences Division has developed the code used here. SPH is a Lagrangian method of solving the equations of fluid flow, suitable for modelling liquid sloshing due to its grid-free nature, and inherent ability to model complex free-surface behaviour. This particular SPH code has been successfully applied to a wide range of industrial fluid flow applications (Cleary et al., 2006). A description of the method and the governing equations used in the code is presented here for the sake of completeness. A more detailed description of the method can be found in Monaghan (1992).

In SPH, the fluid being modelled is discretized into fluid elements or particles, the properties of which are attributed to their centres. The method works by tracking particles and approximating them as moving interpolation points. These fluid particles (or moving interpolation points) have a spatial distance over which field variables such as density, velocity and energy are smoothed. This is achieved via an interpolation kernel function.

The fundamental concept of the integral representation of a function used in the SPH method comes from the identity shown in Eq. (1)

$$f(\mathbf{x}) = \int_V f(\mathbf{x}')\delta(\mathbf{x}-\mathbf{x}')\,d\mathbf{x}', \tag{1}$$

where $f(\mathbf{x})$ is a function of the three-dimensional position vector $\mathbf{x}$. V is the volume of the integral that contains $\mathbf{x}$ and $\delta(\mathbf{x}-\mathbf{x}')$ is the Dirac delta function defined by

$$\delta(\mathbf{x}-\mathbf{x}') = \begin{cases} 1 & \mathbf{x}=\mathbf{x}', \\ 0 & \mathbf{x}\neq\mathbf{x}'. \end{cases} \tag{2}$$

Identity (1) implies that a function can be represented in integral form. This integral representation is exact since the delta function is used, providing that $f(\mathbf{x})$ is defined and continuous in V (Liu and Liu, 2003). In SPH the Dirac delta function is replaced by the smoothing function $W(\mathbf{x}-\mathbf{x}',h)$ so that the integral representation of $f(\mathbf{x})$ is specified as

$$\langle f(\mathbf{x})\rangle = \int_V f(\mathbf{x}')W(\mathbf{x}-\mathbf{x}',h)\,d\mathbf{x}', \tag{3}$$

where W is the interpolation kernel and h is the smoothing length that defines the region in which the smoothing function operates. A cubic smoothing kernel has been used here for $W(\mathbf{x}-\mathbf{x}',h)$, approximating the shape of a Gaussian profile but having compact support, so that $W(\mathbf{x}-\mathbf{x}',h)=0$ for $\mathbf{x}-\mathbf{x}' > h$.