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Experimental and numerical analysis of energy dissipation in a sloshing absorber

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ABSTRACT

The paper presents the results of an experimental-numerical study aimed at investigating the sloshing phenomenon in moving tuned sloshing dampers, with a particular attention to the physical mechanisms that determine the onset of hysteretic damping reducing the response of the substructure. Numerical simulations are carried out by a computational fluid dynamic model, while experiments are conducted by considering a rectangular tank having bottom dimensions of 40×20 cm, actuated by an electric torsional servomotor coupled with a ball screw transmission device. The case of harmonic displacements imposed to the tank is investigated, considering different amplitudes, frequencies and depths of the inner liquid. In order to determine the energy dissipation associated with the hysteretic force-displacement cycles, the sloshing force produced by the motion of the liquid is obtained by measuring the shear force between the tank and the moving base through a load cell. The numerical simulations demonstrate a fairly good agreement with the experimental results, both in terms of the kinematic response of the fluid and of the sloshing forces transmitted to the substructure. In particular, it is demonstrated that the computational fluid dynamic model allows an accurate estimation of the dissipated energy in different conditions, significantly outperforming the simplified analytical model often used in the design of tuned sloshing dampers.

1. Introduction

The tuned liquid damper (TLD) or tuned sloshing damper (TSD) is a passive control device (i.e. no need of an external power source), often used to mitigate the response of civil structures under external dynamic excitations, such as wind gusts or earthquakes (Kareem and Sun, 1987; Modi and Welt, 1987; Fujino et al., 1988; Won et al., 1996; Housner et al., 1997; Sadek et al., 1998). TSDs are a particular kind of the so-called Tuned Mass Dampers (TMDs), that have been implemented in several tall buildings since the 1950s to control structural vibration. The strength of the TSDs is their simplicity, as they consist of a tank partially filled with water mounted on the top of a structure, which can also serve as a water storage system (Cotana et al., 2014). When the structure is subjected to massive forces as those caused by wind gusts (Gioffrè et al., 2008; Ubertini and Giuliano, 2010) or earthquakes (Sabetta and Pugliese, 1996), the displacement of the liquid inside the tank (i.e. sloshing) generates a variation of the pressure distribution on the tank walls and, consequently, resultant force and torque on the whole structure. Overall, part of the vibration energy is dissipated

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by the sloshing motion of the fluid inside the tank, which generates an hysteretic inertia force having opposite phase with respect to the structural vibration, and reduces the structural response. The strongly nonlinear damping mechanism of such a device is related to the friction of the fluid in the boundary layers at the interface with the tank and, most of all, to breaking of the waves occurring in the case of large input displacements. As it is well known, such a damping depends upon many factors, among which the depth of the liquid, the oscillation amplitude, the tank geometry and the wall roughness. The sloshing motion has been investigated by several researchers since 1942, when this topic appears for the first time in the scientific literature (Graham and Rodriguez, 1962), due to its great practical interest not only for structural vibration mitigation but also in several other engineering areas, such as aerospace vehicles, transportation engineering and maritime applications (Graham and Rodriguez, 1962; Abramson, 1966; Armenio et al., 1996a, 1996b; Faltinsen and Timokha, 2009; Yingling and Agrawal, 2014).

The need for an accurate prediction of the sloshing forces has then promoted several modeling studies. The analytical approach based on the potential flow theory started with the first seminal work of Abramson (1966), and has been further applied and developed by many other researchers, from the application of the perturbation theory and the introduction of viscous dissipation (Faltinsen, 1974, 1978; Nakayama and Washizu, 1980; Okamoto and Kawahara, 1990; Warnitchai and Pinkaew, 1998), to the additional studies focused on large motion amplitudes as Lepelletier and Raichlen (1988), Okamoto and Kawahara (1990), Sun and Fujino (1994), Chen et al. (1996), Wu et al. (1998) and Faltinsen and Timokha (2001) among others. Theoretical modeling of TSDs with tanks of different shapes has been performed by Deng and Tait (2009) using the linear long wave theory. Olson and Reed (2001) investigated a TSD with non linear numerical modeling.

Equivalent mechanical modeling has been also extensively employed, mainly for design purposes, by considering the overall TSD-structure system and studying its dynamics through lumped parameters (i.e. masses, springs and dashpots) to describe liquid sloshing (Sun et al., 1995; Rana and Soong, 1998; Yu et al., 1999; Kareem et al., 2009).

The difficult theoretical and analytical modeling of the nonlinear effects and the impact pressure of the water onto the tank walls, has motivated the application of computational modeling by means of modern numerical techniques, with the numerical solution of the Navier-Stokes equations with a non linear free surface evolution (Chen and Nokes, 2005; Wang and Khoo, 2005; Wu and Chen, 2009). The use of the volume of fluid (VOF) technique to track the evolution of the free surface has been employed by several authors in the last decade (Celebi and Akyildiz, 2002; Kim and Lee, 2003; Rhee, 2005; Akyıldız and Ünal, 2006; Löhner et al., 2007; Liu and Lin, 2008, 2009; Gómez-Goñi et al., 2013; Jiang et al., 2015). Love and Tait (2013) recently compared shallow water wave theory, small depth and intermediate depth multimodal models for simulating rectangular TSDs. The analysis of sloshing of water in rectangular tanks has been performed by comparing the Reynolds Averaged Navier Stokes Equations (RANSE) and the Shallow Water Equations (SWE) in (Armenio and La Rocca, 1996). The application of Smoothed Particle Hydrodynamics (SPH) for sloshing modeling in TLDs has been studied by Marsh et al. (2011).

Together with the development of theoretical and numerical models, the sloshing phenomenon has been extensively studied also through experimental means (Modi and Welt, 1987; Fujino et al., 1988, 1992; Sun and Fujino, 1994; Koh et al., 1994; Fediw et al., 1995; Sun et al., 1995; Modi et al., 1995; Reed et al., 1998; Chang and Gu, 1999; Yalla et al., 2001; Yalla and Kareem, 2003, Marsh et al., 2011). Modi and his coworkers (Modi and Welt, 1987; Modi et al., 1995) have conducted several experimental studies and characterization on nutation dampers, exploring the effects of different damper characteristics and geometries. Fujino et al. (1988) performed parametric analyses of TLDs of cylindrical geometry with free-oscillation experiments. Other experimental studies on small amplitude oscillations can be found in (Fujino et al., 1992; Sun and Fujino, 1994; Sun et al., 1995). TLDs excited by large amplitude earthquake-like oscillations have been experimentally investigated in (Koh et al., 1994; Reed et al., 1998). Dissipation mechanisms in egg-shaped sloshing devices have been experimentally and numerically studied by Marsh et al. (2011). Chang and Gu (1999) conducted experiments on active TSDs, representing a solution combining passive and active control (Ubertini, 2008). Fediw et al. (1995) studied the performances of a laboratory-scale one dimensional TSD. Molin and Remy (2013) performed an extensive experimental campaign on TSDs with perforated screens. Other researchers (Ibrahim et al., 2001; Ibrahim, 2005; Faltinsen and Timokha, 2009) collected the research work on sloshing dynamics, both numerical and experimental, in civil engineering and naval applications, respectively.

The design of TLDs and TSDs for vibration mitigation in buildings has received an increasing attention in recent years, with many research efforts aimed at enhancing the energy dissipation by conceiving specific shapes of the tanks and/or of obstacles immersed in the fluid, as well as by coupling the sloshing dampers with other dissipation devices. Min and his coworkers (Min et al., 2014) proposed a design procedure for a special damper, called two-way liquid damper, using simplified equations yielding the equivalent sloshing damping. Love and Tait (2015) proposed the use of an equivalent linearized mechanical model coupled with a nonlinear structural model to predict the response of structure-TLD systems in the case of irregular TLD tank geometry. Ross and coworkers (Ross et al., 2015) considered a case study high-rise building and investigated the effectiveness of TLDs in reducing the coupled lateral-torsional motion under wind loading, again using simplified equivalent mechanical models to reproduce the damping mechanisms associated with the sloshing phenomenon. Ruiz et al. (2016) proposed an innovative passive control device consisting of a traditional TLD with the addition of a floating roof with viscous dampers. In demonstrating the effectiveness of the proposed damper, the authors used a simplified Finite Element Method (FEM) formulation based on potential variables.

The presented literature review highlights that a complete understanding of the sloshing phenomenon, which is crucial towards the optimal design of TSDs, is yet to be acquired, at least when strong nonlinearities associated to a large amplitude motion come into play. Indeed, available analytical models, such as those based on equivalent mechanical systems (Yu et al., 1999; Tait et al., 2004) and those based on Navier-Stokes equations (Kaneko and Ishikawa, 1999; Kaneko and Yoshida, 1999), have been typically validated for specific combinations of input parameters. On the other hand, numerical studies based on Computational Fluid Dynamics (CFD) analysis have often investigated hydrodynamic forces and flow characteristics, but rarely examined the energy