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Active sloshing control in a smart flexible cylindrical floating roof tank

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ABSTRACT

An exact three dimensional fully-coupled hydro-elastic analysis for transient liquid sloshing in a partially-filled vertically-standing flexible circular cylindrical shell container fitted with a freely floating smart piezo-sandwich thin elastic circular plate is presented. The problem formulation is based on the linear water wave theory, the classical (Kirchhoff/Sanders) thin plate and shell models, Maxwell's equations of electrodynamics, Stokes' transformation, and eigen-function expansions in cylindrical coordinates. The control action is achieved by combined volume displacement and volume velocity feedbacks (VDF, VVF) implemented in a second order active damping (AD) compensator via two competent evolutionary heuristic optimization techniques that systematically tune the controller gain parameters while constraining the floating panel displacement and control voltage. The uncontrolled and controlled transient responses of the coupled hydro-elastic system under various external disturbances (i.e., a harmonic base excitation, a real seismic event, a severe launch vehicle liftoff event, and a distributed impulsive transverse load on the floating panel) are calculated by means of Durbin's numerical inverse Laplace transform scheme. Moreover, the free vibration characteristics of the coupled fluid/structure interaction (FSI) system are briefly studied. The superior performance of the proposed active floating roof control configuration in effective suppression of the key hydro-elastic parameters (panel displacement, and shell displacements/stresses) is demonstrated. It is also found that, in the current FSI control problem, the Multi-objective Particle Swarm Optimization (MOPSO)-based ADC outperforms the Non-dominated Sorting Genetic Algorithm (NSGA-II)-based method, in terms of convergence rate and computational effort. Limiting cases are examined and the precision of results is verified by comparisons with the existing data as well as with the results produced by a commercial finite element package.

1. Introduction

Liquid sloshing is a classic physical phenomenon that has turned into an interesting field of exploration in regard to performance and structural integrity of partially filled moving or externally excited containers with numerous practical applications within the civil, transportation, mechanical, nuclear, aerospace, and naval industries (Amabili, 2006; Faltinsen

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and Timokha, 2009; Ibrahim, 2005). In particular, the detrimental effects of propellant sloshing upon directional stability, controllability, and maneuverability of launch vehicles, spacecrafts, satellites, missiles, and aircrafts is progressively becoming more critical for successful flight performance (Ananthakumar and Rajesh, 2014; Bauer, 2012; Hall et al., 2015; Rebelo, 2013). Similarly, assessing the safety and integrity of large capacity land and offshore oil storage tanks subjected to sever seismic motion has received substantial attention (Matsui and Nagaya, 2013; Nagaya and Matsui, 2011, 2012; Yoshida et al., 2010). The simplest method for reducing the sloshing wave amplitudes is to passively alter the instability frequency by immerging additional anti-sloshing substructures such as rigid baffles and partitions within the container liquid (Askari et al., 2010; Biswal and Bhattacharyya, 2010; Koh et al., 2013; Xue and Lin, 2011). This reduces the sloshing masses and shifts the natural sloshing frequencies away from the excitation frequency at the cost of increasing the tank weight. A more feasible method is to cover the free liquid surface with a light flexible structural member such as a membrane or a thin elastic plate (i.e., a floating roof). This configuration, which needs no support from the generally flexible side walls of the container, has low maintenance costs, and is operative for arbitrary directions of external excitation (Amabili, 2001; Ohmatsu, 1997; Yoshida et al., 2010).

Strong interactions of liquid sloshing and the single-deck type floating roofs in externally excited large capacity storage tanks (or spacecraft propellant containers) can impose a complicated distribution of potentially catastrophic out-of-plane deformations and damaging stresses which may cause loss of buoyancy and sink of the floating roofs (Cacciatore et al., 2007; Hirokawa et al., 2012; Miura and Kikuchi, 2005). Several authors have investigated the coupled hydro-elasto-dynamic characteristics of partially-filled cylindrical containers with flexible membrane or thin elastic plate covers. Sakai et al. (1984) were the first to treat the floating roof as an elastic solid with mass and presented an exact solution for the coupled liquid-structure interaction of a cylindrical tank with a flexible floating roof within the framework of linear potential theory. Bauer (1995) also used the linear potential theory to calculate the coupled hydro-elastic frequencies of frictionless liquid in a circular cylindrical rigid tank whose free liquid surface is fully covered by a flexible membrane or an elastic circular plate. Bauer and Komatsu (2000) studied liquid sloshing in a circular cylindrical container with a partial surface cover in form of an elastic annular plate. Amabili (2001) investigated the free vibrations of circular plates covering the sloshing liquid free surface of a rigid cylindrical container. Kim and Lee (2005) developed an analytical approach based on Rayleigh–Ritz method to investigate the vibration characteristics of the sloshing and bulging modes for a liquid-filled circular cylindrical storage tank with a clamped-free elastic annular plate cover. Bauer and Chiba (2007) studied the effect of an elastic surface cover (membrane or thin plate) on shifting the liquid sloshing frequencies of a rigid circular cylindrical tank filled with incompressible and viscous liquid. Matsui (2007, 2009) presented analytical solutions based on the linear potential theory and Fourier–Bessel expansion method to predict the sloshing response of cylindrical liquid storage tanks covered by single/double deck floating roofs under seismic excitation. Utsumi et al. (2010) adopted a Galerkin approach to investigate the effect of internal resonance on the coupled nonlinear sloshing response (internal stress magnitudes) of a floating roof in a circular cylindrical oil storage tank while neglecting the effect of large deflections of the deck plate. Golzar et al. (2012) used the extended Hamiltonian variational principle to investigate the large deflection response of floating roof cylindrical liquid storage tanks for different types of ground motions. Yoshida et al. (2012) presented an axisymmetric finite element analysis for the coupled sloshing response analysis of single-deck floating roofs in a rigid-walled cylindrical storage tank under uniform wind flow by using the CFD results as the load condition. Amiri and Sabbagh-Yazdi (2012) utilized the finite element package ANSYS to investigate the influence of dome floating roofs on the natural frequencies and the modes of ground supported partially filled flexible cylindrical liquid storage tanks. Matsui and Nagaya (2013) proposed a hybrid analytical and finite element method to study the nonlinear sloshing in a rigid-walled cylindrical oil storage tank with a single-deck-type elastic floating roof under long-period seismic ground motion. Goudarzi (2014) developed an analytical solution for evaluating the attenuation of dynamic interaction between the liquid and a single-deck type floating roof (i.e., reduction of sloshing wave height and seismic stresses) in a cylindrical liquid storage tank, and made comparisons with a numerical model based on FEM.

There has been a substantial amount of research on active vibration and noise control of flexible structures during the past few decades (Hasheminejad and Keshavarzpour, 2013; Hasheminejad et al., 2014, 2015a, 2015b) owing to the modern developments in active control methodologies accompanied by increasing power of digital computers. On the other hand, applications of the advanced control techniques for active suppression of liquid sloshing is a challenging and scarce problem that has recently been stepped up (Hernández and Santamarina, 2012). In particular, majority of efforts made toward suppression of tank sloshing response has been based on passive or semi-active control methods. For example, Hayama and Iwabuchi (1985) both theoretically and experimentally demonstrated the performance of an inverted U-tube dynamic absorber in successful suppression of liquid sloshing. Hara (1992) proposed a gas-bubble injector, timed by a microcomputer, as a type of active sloshing control device in storage vessels under earthquake excitation. Sharma et al. (1992) experimentally examined various combinations of submerged and floating plates for passive control of fluid sloshing in a cylindrical container at the fundamental mode. They demonstrated that the most effective control action can be obtained with close tolerances between the edge of the floating plate and the tank wall in conjunction with a maximum possible plate thickness to restrain the rocking motion of the fluid surface. Sakai and Inoue (2008) proposed some countermeasures such as an earthquake-resistant structure, an isolation system, and a vibration control method based on a tuned liquid column damper (TLCD), against sloshing in oil tanks with single- and double-deck floating-roofs. Gandhi and Duggal (2009) studied active stabilization of nonlinear lateral and rotary slosh in a cylindrical tank based on two distinct nonlinear sloshing models, namely, a nonlinear multiple pendulae, and a nonlinear rotary slosh model valid near resonance. Control was