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Vibration mitigation in partially liquid-filled vessel using passive energy absorbers

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ABSTRACT

We consider possible solutions for vibration mitigation in reduced-order model (ROM) of partially filled liquid tank under impulsive forcing. Such excitations may lead to strong hydraulic impacts applied to the tank inner walls. Finite stiffness of the tank walls is taken into account. In order to mitigate the dangerous internal stresses in the tank walls, we explore both linear (Tuned Mass Damper) and nonlinear (Nonlinear Energy Sink) passive vibration absorbers; mitigation performance in both cases is examined numerically. The liquid sloshing mass is modeled by equivalent mass-spring-dashpot system, which can both perform small-amplitude linear oscillations and hit the vessel walls. We use parameters of the equivalent mass-spring-dashpot system for a well-explored case of cylindrical tanks. The hydraulic impacts are modeled by high-power potential and dissipation functions. Critical location in the tank structure is determined and expression of the corresponding local mechanical stress is derived. We use finite element approach to assess the natural frequencies for specific system parameters. Numerical evaluation criteria are suggested to determine the energy absorption performance.

1. Introduction

Vessels filled with liquid are used in many fields of engineering, including nuclear [1], vehicle [2,3] and aerospace industries [4], for storage of chemicals, gasoline, water, and different hazardous liquids [5]. External excitations may cause well-known dynamical effect of liquid sloshing. This phenomenon, e.g., can take place in liquid cargo on highways, or in stationary vessels exposed to earthquakes. Dynamic loads related to the liquid sloshing may have direct and rather strong hazardous effect on the vessel stability and robustness. Many methods of seismic analysis of tanks are currently used by researchers and have been adopted by a number of industry standards and guides such as ACI 350.3-06 and ACI 371R-08 covert seismic design, which are based on the simplified methods evolved from earlier analytical work by Housner [6], Veletsos [7–10], Haroun [11–13], and others. Of these, the best known is Housner's pioneering work, published in the early 1960s by the Atomic Energy Commission. Housner's method was adopted by many codes in the world and by a number of industry standards. It serves as a guideline for most seismic designs of the liquid storage tanks. According to Housner's simplified theory, the tank deformation is negligible with respect to the liquid motion. Hence, the analysis takes into account only the motion of the liquid with respect to the tank, and assumes that the tank displacement is proportional

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to the ground excitation. Housner observed that in certain parts of the tank structure, the sloshing of the water was the dominant factor, whereas for other parts, the sloshing had relatively small effect.

So far, detailed analytical explorations are limited to the small-amplitude sloshing in rectangular and cylindrical vessels. While being most interesting and potentially hazardous, high-amplitude liquid sloshing in cylindrical tanks still lacks complete analytic description. The reason is that the liquid in the tank is continuous system with infinite number of degrees of freedom, and the boundary conditions on the free surface are nonlinear and time-dependent. Nevertheless, loads created by high-amplitude liquid sloshing are so crucial for designing the containing vessel, its supports and payload limitations [14], that a number of approximate phenomenological models were developed in order to get at least qualitative insight into this phenomenon.

In well-known phenomenological models, the sloshing dynamics in the partially filled liquid tank is modeled by a set of mass-spring-dashpot systems or by a set of pendula; each sloshing mode is related to different particle in the set. The former model is less complex, since it involves only one-dimensional dynamics and interactions, however it fails to represent vertical liquid motion (e.g. water jets [15]) and vertical excitation, that are better represented by the pendulum model (parametric excitation of liquid-filled vessel modeled by high-exponent potential pendulum by El-Sayad [16], Pilipchuk and Ibrahim [17]). Moreover, mass-spring-dashpot system is more common in engineering design regulations, as shown by Malhotra et al. [18]. Values of parameters for both models mentioned above are presented by Dodge [19] and Abramson [20].

This study involves seismic-induced horizontal excitation. Therefore, we take into account only horizontal internal forces. Consequently, the sloshing dynamics in a partially filled liquid tank with total mass M is modeled by the mass-spring-dashpot system with mass m, stiffness k, linear viscosity of c and a transversal coordinate y with respect to the vessel centerline. In this simplified model, three dynamic regimes are usually distinguished:

(a) The liquid free surface performs small oscillations around its trivial stable equilibrium and remains planar. This regime can be successfully described by small – amplitude oscillations of the linear mass-spring-dashpot system.
(b) Relatively large oscillations in which the liquid free surface does not remain planar. This motion is described by a differential equation with weak nonlinearity, and can be treated by perturbation methods [17,21,22]. In this regime, the equivalent mass-spring-dashpot system is considered to perform moderate oscillations, so that a cubic stiffness spring addition is reasonable, and the nonlinearity can be treated as weak.
(c) The free liquid surface is involved into a strongly nonlinear motion, related to liquid sloshing impacts with the tank walls. This regime can be described with the help of a mass-spring-dashpot system, where the mass can impact the tank walls.

High-amplitude sloshing can cause hydraulic jumps. In this case (Fig. 1(c)) major hydraulic impacts can act on the vessel structure walls [23]. Despite obvious practical interest, methods for evaluation of the impact in this case are not well developed, and rely primarily on data of direct experiments [20]. Hydraulic jumps and wave collisions with vessel shell are

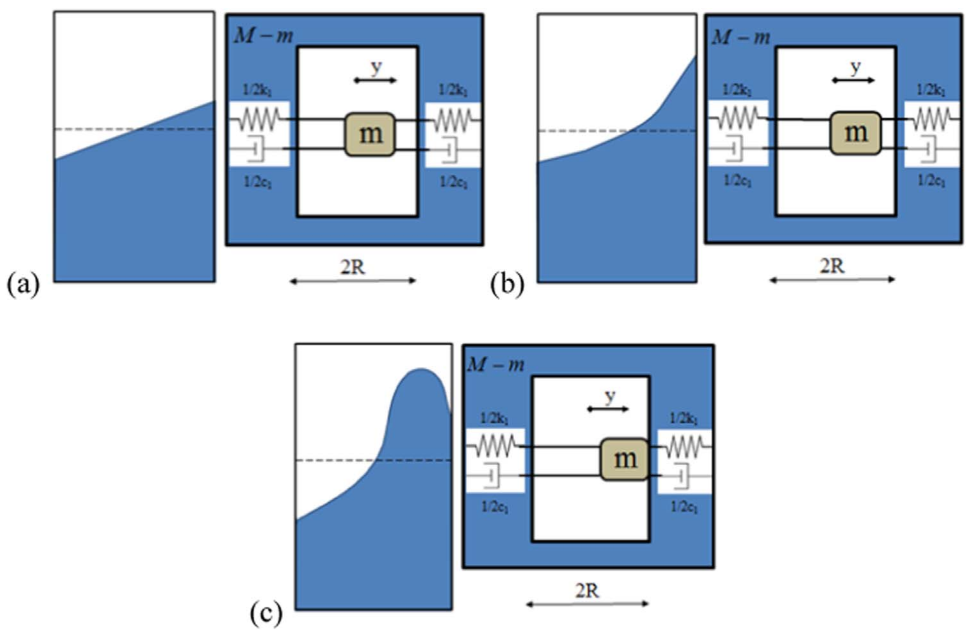

Fig. 1. - Sketches for various possible motion regimes of the liquid free surface, and their equivalent mechanical models; (a) small amplitude sloshing, (b) moderate amplitude sloshing, (c) vibro-impact sloshing.