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Characterization and design of tuned liquid dampers with floating roof considering arbitrary tank cross-sections

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ABSTRACT

A recently proposed new type of liquid mass damper, called Tuned Liquid Damper with Floating Roof (TLD-FR), is the focus of this paper. The TLD-FR consists of a traditional TLD (tank filled with liquid) with the addition of a floating roof. The sloshing of the liquid within the tank counteracts the motion of the primary structure it is placed on, offering the desired energy dissipation in the vibration of the latter, while the roof prevents wave breaking phenomena and introduces an essentially linear response. This creates a dynamic behavior that resembles other types of linear Tuned Mass dampers (TMDs). This investigation extends previous work of the authors to consider TLDs-FR with arbitrary tank cross-sections, whereas it additionally offers new insights on a variety of topics. In particular, the relationship between the tank geometry and the resultant vibratory characteristics is examined in detail, including the impact of the roof on these characteristics. An efficient mapping between these two is also developed, utilizing Kriging metamodeling concepts, to support the TLD-FR design. It is demonstrated that the overall behavior can be modeled through introduction of only four variables: the liquid mass, the frequency and damping ratio of the fundamental sloshing mode of the TLD-FR, and the efficiency index, which is related to the portion of the total mass that participates in this mode. Comparisons between TLDs-FR and other types of mass dampers are established through the use of the latter index. A design example is presented considering the dynamic response of a structure under stationary excitation. It is illustrated in this example that for complex tank cross-sectional geometries there exists a manifold of tank configurations leading to the same primary vibratory characteristics and therefore same efficiency of the TLD-FR. Considerations about excessive displacements of the roof can be then incorporated to indicate preference towards some of these candidate configurations.

1. Introduction

Mass dampers, with main representative the Tuned Mass Damper (TMD), are widely acknowledged as a highly effective device for suppressing structural vibrations [1–7]. They consist of a secondary mass attached to the primary structure

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(whose vibration is to be controlled) through a spring and a dashpot. Through proper selection (tuning) of the spring/dashpot parameters the vibration of the secondary mass counteracts the motion of the primary structure in some chosen mode (typically fundamental mode), facilitating the desired energy dissipation for this motion. The main requirement in this tuning is that the frequency of oscillation of the mass damper is close to the fundamental frequency of the primary structure. Additionally, it involves a proper selection of the dashpot characteristics, providing damping directly for the vibration of the secondary mass, with dashpot values lower than the optimal one significantly reducing the implementation effectiveness [5]. Many variations of such mass dampers have been proposed in the literature, mainly distinguished by the approach for creating the secondary mass of the damper and facilitating the equivalent spring/dashpot connection [5,8–11]. Liquid dampers, creating this mass through water within some type of tube or tank, are one of the most popular variants due to their lower cost, easy tuning, and potential alternative use of the added mass [8,9,11].

Within the class of liquid mass dampers one can further distinguish between Liquid Column Dampers (LCDs), such as the Tuned Liquid Column Damper (TLCD) and the Liquid Column Vibration Absorber (LCVA), and Tuned Liquid Dampers (TLDs). LCDs consist of a U-shaped tube filled with water [10–12]. In this case the water movement within the horizontal part of the tube is responsible for counteracting the motion of the structure, resulting in an effectiveness of the TLCD/LCVA that is directly related to the liquid mass within that part, and not to the overall liquid mass [5]. The frequency of oscillation of the liquid is related to the length of the liquid column, which is the only parameter that can be adjusted for tuning, whereas the equivalent dashpot effect can be created through the placement of an element (typically an orifice plate [11] or even through the recently proposed inclusion of a spherical ball [13]) that facilitates energy dissipation (damping). LCD behavior can be predicted through a single degree of freedom model which facilitates a simple design process, like for many other types of mass dampers, though they are typically restricted to one-directional applications, and this behavior is still nonlinear because the aforementioned damping is amplitude-dependent [14]. Nevertheless, they have been proven efficient in reducing both wind-induced [10,15] and earthquake-induced [14,16,17] vibrations. TLDs on the other hand, consist of a tank filled with liquid, the sloshing of which facilitates the desired energy dissipation while providing seamlessly capabilities for bi-directional applications [8,9,18]. The frequency of oscillation is related to the dimensions of the tank and the depth of the liquid, whereas establishing the desired optimal level of damping requires addition of submerged obstacles [19,20] whose behavior is in general difficult to reliably predict. Additionally, their dynamic behavior is typically nonlinear due to wave breaking phenomena [18,21]. Like LCDs their implementation has been examined for different type of excitations [7,22,23].

Motivated by these challenges for liquid dampers a variation of the traditional TLD was recently presented [24] by introducing a floating roof as shown in Fig. 1. The new device is called TLD with floating roof, TLD-FR. The roof, being stiffer than water, prevents wave breaking, hence facilitating a linear response even at large amplitudes while it also accommodates the addition of supplemental devices (such as viscous dampers) with which the level of damping in the liquid vibration can be substantially augmented to reach the desired optimal value. The new device maintains desired attributes of both LCDs and TLDs [25]: its dynamics can be ultimately characterized by considering a single degree of freedom, linear model; modification of the natural frequency is highly versatile; independent operation in both directions can be supported; damping in the liquid vibration can be easily enhanced. The studies for TLDs-FR [24,25] have been restricted, though, to rectangular tank geometries and placed focus on the experimental validation of the proposed numerical models for characterizing their dynamic behavior. Here, this analysis is extended to tanks with arbitrary cross-sections and emphasis is placed on the theoretical assessment/design framework, aiming to offer new insights on a variety of topics; examine what is the relationship between the tank geometry and the resultant vibratory characteristics, develop an efficient mapping between these two, examine how the inclusion of the floating roof impacts the vibratory characteristics. After the theoretical discussions all these concepts are illustrated within a design example that examines the dynamic response of a structure under stationary seismic excitation. It is demonstrated in this example that for complex tank geometries there exist a manifold of configurations leading to the same primary vibratory characteristics, and therefore efficiency for the

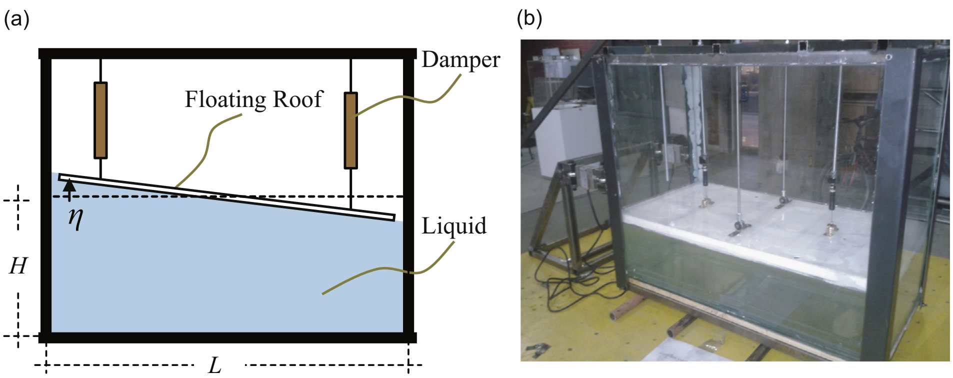

Fig. 1. Tuned Liquid Damper with Floating Roof (TLD-FR) concept. (a) Schematic with different components and (b) Photo from experimental configuration at Pontificia Universidad Catolica de Chile.