Journal of Sound and Vibration 428 (2018) 179–194

Contents lists available at ScienceDirect

Journal of Sound and Vibration

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

Analytical and experimental investigations of Modified Tuned Liquid Dampers (MTLDs)

Yongjian Chang, Ali Noormohamed *, Oya Mercan

Department of Civil Engineering, University of Toronto, 35 St George Street, Toronto, ON, M5S 1A4, Canada

ARTICLE INFO

Article history:
Received 14 September 2017
Revised 24 April 2018
Accepted 29 April 2018
Available online XXX
Handling Editor: L. Huang

Keywords:
Earthquake response
Energy dissipation
Modified Tuned Liquid Damper
Passive control
Real time hybrid simulation
Vibration control

ABSTRACT

Modified Tuned Liquid Dampers (MTLDs) are a variation of a traditional Tuned Liquid Damper (TLD) which utilize a rotational spring system at the base, and therefore experience combined horizontal and rotational motions as the structure sways. To date, there have been very few studies conducted on MTLDs with experimental validation. In this research study, an MTLD-structure system is investigated using Lu's analytical model. Using Real-Time Hybrid Simulation (RTHS), a state-of-the-art testing method, the capabilities of the analytical model are experimentally verified. Important MTLD parameters such as the dimensionless rotational stiffness parameter, frequency ratio, and damping ratio are studied in detail. RTHS is used to study the effectiveness of the MTLD in mitigating structural response under sinusoidal inputs, as well as a range of ground motion records. It is shown both analytically and experimentally that when properly designed, the MTLD can exhibit more efficiency than a traditional TLD in mitigating vibrations.

1. Introduction

Tuned Liquid Dampers (TLDs) are supplemental passive devices that are used especially in some flexible, high-rise structures to control vibrations. They are typically rectangular tanks partially filled with water, and are installed on the roof of the structures with a fixed connection. A sloshing TLD dissipates energy through wave breaking, boundary layer friction and free-surface contamination [1]. By tuning the sloshing frequency to the natural frequency of structure, a significant amount of sloshing and wave breaking can be achieved. Thereby, a considerable amount of vibration can be dissipated at the resonant frequency [2]. Malekghasemi suggested that the TLD can remain effective as long as the ratio of the natural frequency of structure to the sloshing frequency of TLD is in the range of 1–1.2 [3]. In addition, the mass ratio (the ratio of TLD mass to the structural mass) is also an important parameter of the TLD. Banerji et al. indicated that the structural vibration control is more effective if the mass ratio is in the range of 1%–4% [4].

Early applications of TLDs were in space satellites [5] and offshore platforms [6] [7]. The first proposed application of TLDs to ground structures was in 1980 [8], and in the late 1980s TLDs were introduced to tall towers in Japan, such as the Haneda Airport Tower, the Narita Airport Tower [9] and Shin Yokohama Prince (SYP) Hotel in Yokohama [10].

The first nonlinear model of a rectangular TLD was developed by Shimizu and Hayama [11], where the model combines shallow water wave theory with potential flow theory. Later, Sun et al. [12] improved the model for harmonic motion and accounted for the wave breaking with the introduction of two empirical parameters. Response to random input was studied in Koh et al.'s extended work [13]. Sun et al. developed a numerical model for rectangular TLDs under purely pitching motion based

* Corresponding author.
E-mail address: ali.noormohamed@alum.utoronto.ca (A. Noormohamed).

https://doi.org/10.1016/j.jsv.2018.04.039
0022-460X/

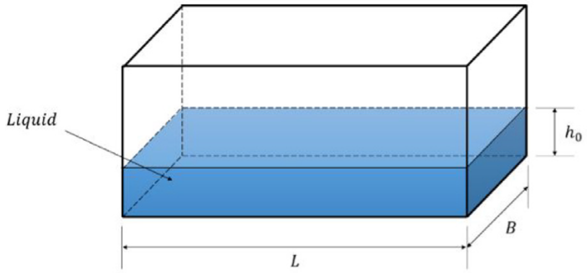

Fig. 1. The dimensions of a regular TLD.

on non-linear shallow water wave theory where linear damping was considered [14]. Lu created a new numerical model by using classical shallow water theory with an improved boundary shear model to simulate the sloshing of a liquid in a rectangular TLD that experiences combined horizontal and rotational motion [15]. More recently, modifications have been made to TLDs to increase energy dissipation characteristics, including adding adjustable damping screens to make a semi-active TLD system [16].

The Modified Tuned Liquid Damper (MTLD) is a relatively new type of TLD, first proposed by Samanta and Banerji [17]. Instead of connecting the tank rigidly to the top of the structure, as is done for typical TLD applications, an MTLD is connected by using an appropriately designed set of springs and pivot. Once the structure starts to move due to dynamic loading, the MTLD will move horizontally along with structure. At the same time, due to the calibrated spring and pivot connection, the tank will also be allowed to have small angle rotations. As such, it is anticipated that in an MTLD, more of the water will be quickly set into the sloshing motion, increasing the effectiveness of TLD in controlling structural vibrations. The angle of rotational motion depends on the rotational spring stiffness K_θ. If the rotational spring is extremely rigid, the MTLD will be identical to a traditional TLD.

Only a limited number of numerical studies have been published on the behaviour of MTLDs and the theoretical design of an optimal rotational spring without any experimental verification. Samanta and Banerji numerically investigated the dynamic behaviour of a structure equipped with a Modified Tuned Liquid Damper (MTLD) under harmonic motions using Lu' s model [17]. They showed that there is an optimum value for the rotational spring stiffness that maximizes the effectiveness of the MTLD. Therefore, if properly designed, an MTLD can outperform a traditional TLD in terms of mitigating structural vibrations.

In this study, the optimal rotational spring proposed by Samanta and Banerji (which is not physically implementable) is transferred to a traditional spring system. Instead of using one rotational spring, the base rotation of the MTLD is achieved using two sets of linear springs separated by a distance L_s. This research effort investigated how to convert the rotational spring to a traditional spring system, studied key parameters of the traditional spring system including the spring separation L_s, and performed experimental validation of the MTLD concept applied to a single-degree-of-freedom (SDOF) structure subjected to sinusoidal and ground motion records.

2. Numerical model

2.1. Governing equations of MTLD

A rigid rectangular tank shown in Fig. 1 is considered in this study. The length and width of tank are represented by L and B, respectively, and h_0 represents the initial value of the liquid depth inside the tank.

The tank shown in Fig. 2 experiences both horizontal and rotational motions, which are specified by x_b and θ_b, respectively. It should be noted that the horizontal motion x_b is the absolute displacement at the top of structure, and the rotational motion θ_b is specified in clockwise direction [17].

For the tank in Fig. 2, with the assumption that the liquid does not reach the top of the tank, and by using shallow water wave theory, the governing equations of the liquid's sloshing motion can be determined, and are listed below [15]:

$$\frac{\partial h}{\partial t} + h\frac{\partial v}{\partial x} + v\frac{\partial h}{\partial x} = 0 \tag{1}$$

and

$$\frac{\partial v}{\partial t} + g\frac{\partial h}{\partial x} - v\frac{\partial v}{\partial x} - g(\theta_b - S) + \frac{\partial^2 x_b}{\partial t^2} = 0 \tag{2}$$

where v is the velocity of the water relative to the base of the tank, g is the acceleration due to gravity, and h is the sloshing liquid depth at each location of the tank x and time t. A detailed discussion of the differential equations can be found in the