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Combining TMD and TLCD: analytical and experimental studies

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ABSTRACT

In these years several research efforts have been focused on developing efficient and reliable control devices for mitigating the structural response of tall and lightly damped buildings in case of strong dynamic excitations, such as wind and earthquake ones. In this context, Tuned Mass Dampers (TMDs) represent probably the most common control device due to their high control performances. On the other hand, Tuned Liquid Column Dampers (TLCDs) are increasingly becoming more popular because of some of their attractive features, cost-effectiveness among the others, even though they yield slightly less control performance compared to the classical TMDs. Aiming at combining the beneficial effects of the TMD and the attractive characteristics of the TLCD, in this paper a novel control device is introduced which is realized joining this two systems. The pertinent equations of motion are derived, and the analytical study is developed to analyze the control performance of this device. Finally, theoretical results are validated via vast experimental campaign undertaken in the Laboratory of Experimental Dynamics of the University of Palermo, Italy.

1. Introduction

The current trend toward the use of lightweight, high-strength materials, together with advanced construction techniques, have led to the realization of more flexible and lightly damped structures. On the other hand, modern concepts for lightweight construction require not only new and advanced materials, but also the development of new production processes and novel strategies. For instance, these structures are very sensitive to environmental excitations, such as wind and earthquakes, which cause unwanted vibrations inducing possible structural failure, occupant discomfort, and equipment malfunction. Hence the insistent demand for practical and effective devices able to mitigate these vibrations.

Devices used for mitigating structural vibrations can be divided into two main separate categories based on their working principles.

Passive control devices are systems which do not require any external power source, imparting forces that are developed in response to the motion of the structure (Housner et al., 1997; Soong and Spencer, 2002; Soong and Dargush, 1997; Saaed et al., 2015). Therefore, the total energy in the passively controlled structural system cannot be increased by the devices.

Active control devices are systems requiring external power source to drive actuators applying forces which tend to oppose the unwanted vibrations. The control force is generated depending on the feedback of the structural response. Due to the uncertainty of the power supply during extreme conditions, such systems are vulnerable to power failure, thus making passive systems often favored over active ones.

In recent years passive structural vibration control has been a flourishing research area in civil and mechanical engineering. In fact, passive control systems can be used to prevent structural elements from damage or increase human comfort due to reduced accelerations.

In this regard, several types of devices have been proposed to mitigate the dynamic response of different kind of structural systems. Among them, Tuned Mass Damper (TMD) is undoubtedly the most widely used vibration control device for buildings exposed to earthquake and wind loads (Housner et al., 1997). For this system, control is achieved by transferring the energy produced by the vibrations to the TMD itself which, in its simplest form, consists of a mass-spring-dashpot system connected to the main structure to be controlled (Den Hartog, 1956; Adam et al., 2003; Schmelzer et al., 2010; Tributsch and Adam, 2012).

Although TMDs often lead to the best control performance with respect to other passive control devices, Tuned Liquid Column Dampers (TLCDs) represent now an attractive alternative for some of their particular characteristics as low cost, easy installation, lack of required maintenance, and no need to add mass to the main structure.

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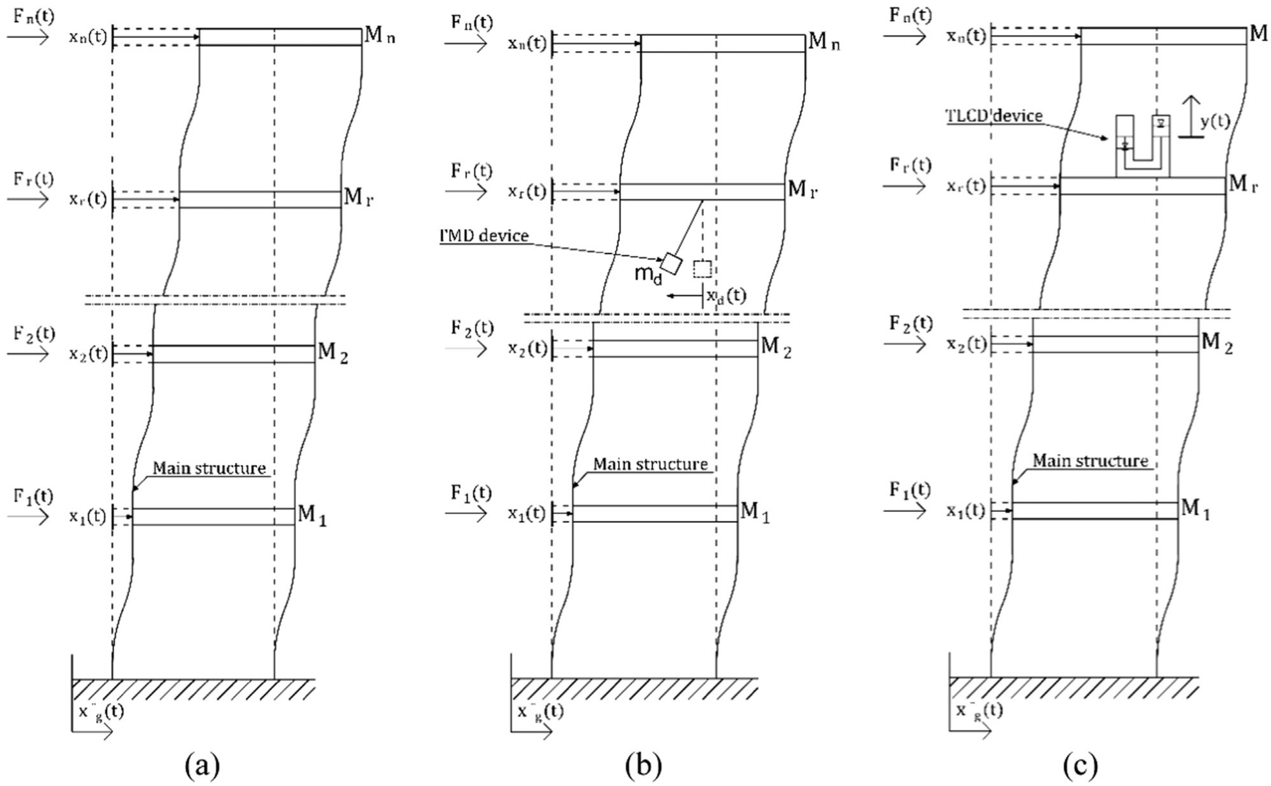

Fig. 1. a) Main system, b) Main system equipped with TMD, c)Main system equipped with TLCD.

The TLCD simply consists of a U-shaped container partially filled with water. It dissipates structural vibrations using a combined action which involves the motion of the liquid mass within the container. Specifically, the restoring force is produced by the force of gravity acting on the liquid while the damping effect is generated by the hydrodynamic head losses which arise during the motion of the liquid inside the TLCD. Moreover, if further dissipation is required, an orifice can be placed inside the horizontal duct of the TLCD device.

Some of the earliest studies on TLCDs for the control of wind-excited structures can be found in (Sakai et al., 1989; Xu et al., 1992; Balendra et al., 1999), while analysis on the performance of TLCDs for applications to seismic-excited structures is reported in (Ziegler, 2007; Sadek et al., 1998). Several research efforts have also been focused on the optimal TLCD parameters estimation. Related studies can be found in (Gao and Kwok, 1997; Yalla and Kareem, 2000; Debbarma et al., 2010; Chang, 1999; Duc La and Adam, 2016), where optimal TLCD parameters are evaluated assuming the main structure to be undamped. Further, to correctly take into account the real damping of the main system, an appropriate optimization procedure has been recently proposed based on an appropriate linearization procedure and confirmed through several experimental tests (Di Matteo et al., 2014a, 2014b, 2015a).

In this regard, experimental studies on these devices can be found in (Balendra et al., 1999; Hitchcock et al., 1997) where the effect of different opening ratio of the inner orifice and TLCD dimensions on the control performance has been studied. Further, in (Chaiviriyawong et al., 2007; Di Matteo et al., 2012) the accuracy of the classical mathematical model of TLCD systems has been analyzed via several experimental tests, showing poor agreement for some particular TLCD configurations. On this ground, a novel mathematical formulation for TLCD systems and TLCD controlled structures has been proposed based on the tools of fractional calculus, and experimental validation has been developed in frequency and time domain (Di Matteo et al., 2015b, 2016).

As previously stated, even though the performance of TLCD is generally lower than the TMD one, TLCD is becoming a consistent alternative to the TMD for its attractive characteristics. In this respect, it is worth noting that the highest costs of TMD are mainly due to the realization of the huge mass and consequent appropriate main structure characteristics, together with higher maintenance expenses.

In this regard, aiming at enhancing the pros of both devices and reducing the cons, in the last years the authors of the present manuscript have investigated on a combination of a TLCD and a lighter TMD. This novel device, labeled as Combined Tuned Damper (CTD), can simply be realized separately installing on the building both the TLCD and a lighter TMD. Interestingly, very recently an analogous study has been developed specifically focusing on optimal design parameters of this combined novel control device (Wang et al., 2016).

On this base, in this paper the proper mathematical model of the combined system is derived, and analytical studies are developed to analyze the control performance of this device. Further, a vast experimental investigation on the control efficacy of the CTD is undertaken, and the reliability of the proposed mathematical formulation is assessed through the experimental data. Notably, results have shown how the CTD can fully combine the economic advantages of TLCDs and the high effectiveness of TMDs.

2. Problem formulation

Let the equation of motion of a planar frame with lumped mass with n degrees of freedom (main structure), subjected to wind actions $\mathbf{F}(t)$ and/or to horizontal earthquake ground acceleration $\ddot{x}_g(t)$, be given in classical matrix form as

$$\begin{aligned} &\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{F}(t) - \mathbf{M}\mathbf{r}\ddot{x}_g(t) \\ &\mathbf{x}(0) = \mathbf{x}_0 \\ &\dot{\mathbf{x}}(0) = \dot{\mathbf{x}}_0 \end{aligned} \quad (1)$$

where $\mathbf{M}$, $\mathbf{C}$ and $\mathbf{K}$ are the $n \times n$ main system mass, damping and stiffness matrix respectively, $\mathbf{x}(t)$ is the vector containing the displacements of the system, $\mathbf{x}_0$, $\dot{\mathbf{x}}_0$ the initial conditions in terms of displace-