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Base-isolated structure equipped with tuned liquid column damper: An experimental study

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ABSTRACT

In this study, a novel passive vibration control strategy is investigated experimentally, where a Tuned Liquid Column Damper protects a base-isolated structure. The Tuned Liquid Column Damper is attached to the base, in contrast to typical attachment points of passive energy dissipation devices in high-rise buildings at elevated levels. Experiments on a base-excited small-scale three-story shear frame are conducted in order to study effects of both control devices – base-isolation and Tuned Liquid Column Damper – on the structural model. The dynamic properties of the stand-alone shear frame and the base-isolation subsystem are derived using standard dynamic test methods based on displacement and acceleration response measurements. In the base-isolation subsystem both viscous damping and friction effects are identified. The water level of the Tuned Liquid Column Damper is tracked by means of computational image processing of video recordings, facilitating the identification of the fundamental liquid motion mode as well as the nonlinear damping properties. An experimental parametric study is conducted for three Tuned Liquid Column Damper devices with different frequency tuning ratios. The assessment of the hybrid control strategy is based on the determined transfer functions of the studied setups. Experimental outcomes confirm recent theoretical findings that a passive hybrid control strategy combining a base-isolation and a Tuned Liquid Column Damper reduces the displacement demand of the base-isolation subsystem as well as the total story acceleration demand if both control devices are properly tuned.

1. Introduction

Control system approaches for vibration mitigation in civil structures can be classified into passive control, semi-active control, active control, and hybrid control strategies [1]. Semi-active and active control devices (and also the hybrid ones when active/semi-active schemes are involved) rely on a control algorithm, where either a variable damper property or a variable control force is adjusted, based on the identification of the structural vibration behavior. In contrast, passive control strategies are characterized by a fixed set of control parameters. Since passive systems cannot self-adjust to varying structural and/or excitation parameters, it is crucial that for these systems optimal control parameters are employed to achieve reliable vibration mitigation. Although from this point of view active or semi-active control systems seem to have superior

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performance properties, passive control devices are still the primary choice in engineering applications. They are more robust since they do not rely on additional external energy supply. During typical dynamic loading scenarios such as earthquake excitation a reliable external energy supply cannot be ensured. Additionally, passive devices are usually cheaper in installation and maintenance. Because for civil structures critical vibration states are often related to a specific vibrational mode that in many structures only varies slightly over time, a fixed optimal control strategy related to this mode is sufficient to reduce the dynamic response significantly.

Two passive control systems frequently used to mitigate earthquake induced structural vibrations are seismic base-isolation devices and tuned vibration absorbers. The concept of a base-isolation corresponds to the application of a low-pass filter to the earthquake ground motion. This is accomplished by means of laterally extremely flexible and vertically almost rigid devices, such as reinforced rubber bearings or frictional sliding elements, arranged between foundation and base of the load-bearing structure. In this manner, the natural frequency of the base-isolation subsystem ω_b serves as fundamental frequency of the controlled structure, whereas the fundamental frequency of the stand-alone structure is shifted to a higher value, depending on the mass ratio [2]. Furthermore, the first mode shape approaches a rigid body mode where most of the deformation is concentrated in the base-isolation. Thus, the main parameter influencing the efficacy of a base-isolation is frequency ω_b.

The tuned liquid column damper (TLCD) is an innovative absorber, where a oscillating liquid column inside a U-shaped container dissipates structural vibrations. The efficacy of a TLCD depends on its natural frequency and equivalent damping ratio optimally tuned to the parameters of the main structure. For a wide variety of different excitation signals and optimization criteria, optimal tuning parameters were derived [3]. In [4], the performance of a TLCD mounted on a spatial one-story frame was investigated experimentally, varying the excitation direction. Generally it is observed that the reduction of the dynamic amplification of the main structure increases with increasing ratio of effective TLCD mass to effective structural mass. In practical application, this mass ratio is limited to about 5%. As such, the efficacy of the TLCD is based on the same mechanical principle as the classical tuned mass damper (TMD), however the TLCD has some advantages compared to the TMD [5]. For instance, it is a low cost device easy to implement, fine tuning of the TLCD frequency can be conducted by simply adding or removing some liquid, and maintenance of this device is straightforward because no elaborate mechanical components are involved. The fundamental frequency of a TLCD with constant cross-section depends on the length of the liquid column only. Thus, a TLCD can be used to mitigate vibrations of structures with a fundamental frequency less than approximately 2 Hz because the column length cannot be reduced below a certain value.

As a drawback, a base-isolation subsystem may be subjected to excessive large dynamic displacement demands, and consequently, it must resist those large deformations, which can be a limiting design factor. To overcome this limitation, a passive hybrid control strategy has been proposed, composed of a base-isolation subsystem and a tuned vibration absorber, see e.g. [7,8]. The principal idea is to reduce the displacement demand of the base-isolation subsystem by application of an absorber tuned to the natural frequency of the base-isolation subsystem. The absorber is directly attached to the base, and as such the dead weight does not stress the main structure as encountered in a solely tuned vibration absorber-controlled structure. In the large majority of the studies (for instance [8,7,9–11]), a TMD was used as vibration absorber. In the context of taking into account the beneficial properties of the TLCD, in [6] the effect of a TLCD on a base-isolated five-story frame structure was studied numerically, and in [12] a novel base-isolation control system with increased effective damping supplied by a TLCGD was proposed. Recently, the authors of the present contribution investigated in detail the control performance of a TLCD on the seismic response of a base-isolated multi-degree-of-freedom (MDOF) frame structure [13]. They proposed a straightforward procedure for direct evaluation of the equivalent linear TLCD parameters. Based on this procedure, and assuming that the base-isolated load-bearing structures behaves rigid, a direct optimization procedure of the TLCD design parameters was performed, aiming at maximum control of the seismic response of base-isolated frame structures.

Although a large number of papers exist on theoretical considerations based on numerical simulations, application and experimental verification of the performance of a TLCD respectively seismic base-isolation in combination with other control devices is scarce. For instance, in [14] the outcomes of experimental tests on a small-scale shear frame equipped with a TLCD, however, without base-isolation subsystem, are presented. In [15,19] the investigation of a TLCD attached to a single-story frame model verified experimentally that a numerical procedure proposed in [16–18] is capable of predicting the response of both the main structure as well as of the TLCD. A new type of tuned liquid damper was validated experimentally in [20]. Experiments on base-isolated structures were conducted in [21], with particular emphasis on revealing the performance of viscous and elastic-plastic damper devices. In [22] the effects of the frequency tuning ratio on the dynamic response of a base-isolated structure controlled by a TMD system were studied experimentally, using a pendulum with adjustable length as TMD.

To the best knowledge of the authors, no experimental verification of the effect of a TLCD device on a base-isolated structure is available. Therefore, in this contribution for the first time this passive hybrid control strategy is investigated experimentally on a small-scale three-story model frame, with the main goal of examining both dissipation mechanisms, base-isolation and TLCD device. The present experimental study complements the numerical considerations of [13], thus, putting theory and application in one framework. The paper is organized as follows. At first, the experimental setup is described, and the corresponding analytical model for comparative numerical studies is established. Then, the identification of the structural parameters of each subsystem – stand-alone shear frame, base-isolation subsystem, and TLCD device – is described and nonlinear effects are assessed. Experiments on the base-isolated small-scale model are conducted, considering three