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Soil-dependent optimum design of a new passive vibration control system combining seismic base isolation with tuned inerter damper

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ABSTRACT

The papers addresses a novel passive vibration control system combining seismic base isolation with a tuned inerter damper (TID) system. The latter, by analogy with the tuned mass damper (TMD), is a dynamic vibration absorber in which the physical mass of the TMD is partly or entirely replaced by an apparent mass, also called inertance, created by a particular arrangement of mechanical gearings—the *inerter*. By attaching a TID to the isolation floor, not only the displacement demand of base-isolated structures can be significantly reduced, but also the superstructure response (e.g. interstory drift, base shear) is effectively controlled. Optimum parameters of this system are found based on a simplified three degree-of-freedom model that reflects the dynamic properties of both the isolation system and the TID while accounting for the flexibility of the base-isolated superstructure. Within a probabilistic framework, the influence of soil conditions is investigated by modeling the seismic ground motion as a filtered Gaussian random process. Different filter parameters are considered that may be associated with firm, medium or soft soil conditions depending on the frequency content of the power spectral density function. A wide parametric study is performed in order to detect the optimal TID parameters depending on the soil conditions for a variety of isolation ratios, mass ratios and damping ratios of both the superstructure and the isolation system. Finally, a multi-story building equipped with the proposed passive vibration control system is examined. Effectiveness of the proposed system is assessed via the evaluation of the structural response in the time domain. Detuning effects are investigated via a sensitivity analysis. Comparison with alternative passive vibration control systems proposed in the literature and based on different arrangements of TMD and inerter-based device is discussed.

1. Introduction

Over the last few decades, passive vibration control systems of civil engineering structures, including seismic base isolation [1–3], energy dissipation systems [4,7,5,6] and tuned-mass-dampers (TMDs) [8–10], have been increasingly adopted in earthquake-prone regions to mitigate or reduce potential damage due to the shaking ground. The common backbone of these strategies is to absorb most the earthquake-induced kinetic energy through specific devices that usually combine flexibility with some inherent (viscous, hysteretic or frictional) damping mechanism. With regard to base isolation, some supports featured by low lateral stiffness (typically, laminated rubber bearings or sliding elements) are interposed between the superstructure and the foundation so as to decouple the building structure from the ground motion. The lengthening of the first-mode period combined with the damping features provided by the base-isolation system (BIS), significantly reduces the earthquake-induced forces in the superstructure, which essentially behaves as a rigid body. On the other hand, by providing flexibility at the base of the structure, most of the earthquake-induced displacement demand is absorbed by the BIS, which undergoes large displacements (whose magnitude depends on the design value of the BIS effective period). This has important implications in the construction costs: large-size isolators should be adopted that can accommodate the required displacements, in addition to considering costly flexible connections for utilities (e.g., waterworks, gas fittings and electrical conduits). Furthermore, an adequate separation distance between adjacent buildings is necessary in order to prevent mutual collisions or structural pounding [11]. Increasing the BIS damping ζ_b or, alternatively, providing supplementary dampers, do reduce the excessively large displacements in the BIS, but at the expense of increasing interstory drifts and floor accelerations [12], thus proving to be detrimental for the superstructure response.

As a result, alternative, so-called “*hybrid*” control strategies combining the conventional base isolation scheme with other active or

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passive control systems have emerged in the literature [13]. The most popular strategy is to connect the BIS to a TMD [14–17], i.e., a secondary mass equipped with a dashpot and a spring generally attached immediately above or below the isolation floor of the building. Indeed, while the TMD systems in fixed-base buildings are usually placed in an upper floor or at the roof in order to experience larger accelerations and energy absorption [18], in base isolated structures the maximum relative displacements occur at the level of the isolators, which justifies the implementation of the TMD at the isolation floor. Although this strategy does reduce the displacement demand of the BIS, two limitations can easily be recognized: 1) very large mass of the TMD is necessary to attain an effective vibration reduction, which hampers the feasibility and cost-effectiveness of this control strategy in practice; 2) usually, large space in the building should be devoted to the secondary mass in order to accommodate the large TMD displacements (related to the TMD stroke [32]), with the latter in some cases being even larger than the maximum admissible displacement of the BIS.

As a more effective alternative, the authors have recently proposed a new passive vibration control technique combining the conventional base isolation system with the *tuned-inerter-damper* (TID) [33]. The latter system, by analogy with the TMD, consists of spring and damper elements installed in series with the *inerter* [19], already successfully employed in the automotive sector under the name of J-damper for Formula 1 racing car suspensions [20]. The inerter is a two-terminal device consisting of a combined arrangement of rack, pinions and gears that produce a rotating flywheel. The internal force is proportional to the relative acceleration of its two terminals, thus acting as an additional, apparent mass for the system it is connected to. The key feature of the TID is the so-called *mass amplification effect*, as the apparent mass (also called "*inertance*") can be orders of magnitude (e.g. 200 times) higher than its physical mass by simply increasing the gearing ratios [20]. As a result, the TID can be viewed as a lower-mass and more effective alternative to the TMD, wherein the device inertance can partly or entirely play the role of the mass of the conventional TMD.

In the very last few years, inerter-based devices (sometimes called inertial mass dampers) have been proposed in the field of vibration isolation of mechanical elements and structural systems, see e.g. [21,22,27,24,25,28,23,26,29–31]. These studies have pointed out some unique characteristics of these devices in terms of vibration isolation and cost-effectiveness. In this paper we explore the advantages of introducing the TID in base isolated structures according to a vibration control layout wherein the BIS is used to decouple the building from the ground motion, while the TID keeps the displacements of the BIS limited to within a reasonably acceptable threshold [33]. The use of inerter-based devices to mitigate excessive displacement demand in base isolated structures is not a novelty of the present paper. In particular, Saito et al. [34] were the first to consider the use of rotary inertia for the displacement reduction of base isolated building structures, however the optimal design of this system was not discussed and the dynamic layout was different from the one proposed in this paper. More recently, Saitoh [35] proposed various combined spring-damper-inerter configurations for mitigating displacements of base isolation systems, but in these models the inerter (or gyro-mass damper [36], or inertial damper [29], which are other nomenclatures adopted in the literature) was not placed according to the TID-arrangement as proposed in the present paper. A well-documented overview of structural control systems combining base isolation with various arrangements of TMD with and without inerter was presented in [31]. The placement of a TMD at basement was proposed for avoiding the problems associated with the excessive vertical loads induced by a large mass-ratio TMD, while the issue of large TMD stroke was overcome by introducing the inerter in parallel to the spring-damper elements in between the BIS and the TMD. The optimal design of the system was carried out considering (deterministic) long-period and pulse-type ground motions, and the dynamic response of high-rise buildings was assessed through the use of a single-degree-of-freedom (SDOF) equivalent model for the superstructure.

The TID dynamic configuration proposed in this paper stems from that of the TMD system, in which an additional inerter, installed in series with spring and damper elements, is interposed between the mass and the ground. Unlike the latter research work [31], optimal design of this system is carried out based on a probabilistic framework, by performing the dynamic stochastic analysis in the frequency domain. The optimization problem is here solved numerically by a nonlinear programming subroutine. The optimal design is related to the soil characteristics in order to assess how the TID tuning changes if different soil types are considered. To this aim, the earthquake ground motion is modelled as a white-noise process and as a filtered Gaussian random process whose filter parameters may be associated with firm, medium or soft soil conditions depending on the frequency content of the power spectral density (PSD) function. A wide parametric study is performed in order to identify the optimal TID parameters depending on the soil conditions for a variety of isolation ratios, mass ratios and damping ratios of both the superstructure and the isolation system. Subsequently, the effectiveness of the proposed vibration control technique is assessed via time-domain analyses. Although modeling the superstructure as a SDOF equivalent system [31] is a reasonable and appropriate simplification for base isolated buildings, which is adopted for detecting the optimal TID parameters, the time-domain investigation is here subsequently extended to multi-degree-of-freedom (MDOF) systems for modeling the superstructure. This has allowed us to evaluate some response indicators of the superstructure such as the base shear, the floor accelerations or the interstory drifts that are useful for design purposes and that cannot be properly assessed unless the superstructure dynamic properties are explicitly taken into account. Besides the above response indicators and the BIS displacement demand, also the TID displacement and stroke as well as the transmitted forces of spring, damper and inerter supporting the TMD are computed, in order to evaluate the performance of the novel control strategy with respect to the overall structural system. An important point that we investigate is the quantification of the stroke of the additional mass in the TMD and TID configurations, which is of valuable importance for design purposes. It is observed that for a particular choice of the inertance, the TID stroke is kept quite limited; therefore, the BIS displacement demand can be reduced without causing unacceptably large displacements in the TID, which instead may occur if a simple TMD is connected to the isolation floor. Detuning effects are investigated via a sensitivity analysis and the role of soil conditions is analyzed. A comparison with alternative structural control systems proposed in the literature and based on different arrangement of TMD and inerter-based device is also discussed.

1.1. Notation

In the matrix-vector notation, boldface lowercase and capital variables denote vectors and matrices, respectively. A super-imposed dot denotes the derivative with respect to time, i.e., $\dot{u} = \mathrm{d}u/\mathrm{d}t$ and $\ddot{u} = \mathrm{d}^2u/\mathrm{d}t^2$. The symbol $:=$ means equality by definition, the superscript T applied to vectors and matrices is the transpose operator, $\mathrm{diag}\{(\cdot)\}$ is the square diagonal matrix of elements $(\cdot)$. Other symbols will be defined in the text at their first appearance.

2. Seismic base isolation combined with tuned inerter damper (TID)

Throughout the paper, linear dynamical systems are considered modeling the damping mechanisms occurring in the BIS, TID and superstructure by an equivalent linear viscous damping idealization. Three different passive vibration control systems are compared in the sketch of Fig. 1. For the sake of simplicity, a structural SDOF system is considered (representative of the first mode of vibration of a multi-story building) whose main dynamic properties are the mass m_s, equivalent