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Investigations of the application of gyro-mass dampers with various types of supplemental dampers for vibration control of building structures

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ABSTRACT

A gyro-mass damper (GMD) is an inertia-based passive control device. It has a gear assembly that amplifies the rotational inertias developed in the gears and generates a resultant resisting force that is proportional to the relative acceleration at the end terminals of the GMD. The amplification provided by the gear assembly can be adjusted by changing the gear masses or the gear ratios of the compound gears. Although similar inertia-based devices have been successfully used for vibration mitigation of motor vehicles and optical tables, there are only a few studies that investigated their application in building structures. This number is even lower for the particular type of inertial damper that has been considered in this study, i.e., GMD. Unlike other types of inertial dampers, the supplemental energy dissipation component of GMDs is not built-in to the device and can be independently attached as an external component. This allows the design engineers to use this cost-effective device and select any available energy dissipation device to use in parallel. In this study, using a small-scale GMD, by considering the rotational inertias of the intermediate gears, characteristic equation which describes the relationship between the applied relative acceleration and the resulting resisting force is derived and experimentally verified. For the introduction of GMDs into building structures, three different configurations are evaluated: (i) standalone GMD, (ii) GMD-brace system, and (iii) GMD–Viscous damper–Brace (GVB) system. The structure-GMD interaction, considering these three configurations, is investigated in frequency domain and in time domain through energy balance equations and time history analyses. It is shown that by selecting the system parameters properly, GVB systems with nonlinear viscous dampers can effectively improve the seismic behaviour of the structure. This is discussed in more detail when the effects of the damper nonlinearities, as well as the various GMD equivalent mass, brace stiffness, damping values and selected ground motions are investigated. The key findings related to the design, implementation and performance considerations of these systems are provided.

1. Introduction

The current direction of structural engineering research aims to achieve sustainable and resilient design alternatives that must go beyond life safety. These alternatives include earthquake protective systems with passive, active and hybrid (semi-active) control techniques. Passive control techniques are perhaps the most widely employed as they require no external energy supply and are easier to set-up and maintain. This paper studies a recently-developed mechanical device [1], namely a gyromass damper (GMD), which is an inertia-based passive control device that uses gear assemblies. There is a long history of development, design, modeling, analysis and application of various mechanical devices that use gear assemblies. However, their first practical application as a passive control system was reported in early 2000s by Smith [2], where the term "inerter" was used for them. They have since been used to suppress vibrations of optical tables [3] and cables [4], used in Formula 1 racing car suspension systems, under the name of "J dampers" [5], and subsequently in motorcycles, trains and regular cars [6–8]. In most of these studies, the dynamics of inerters was usually studied by using the electrical circuit analogy. Although there has been considerable research focused on the use of inerters in mechanical systems, their application in civil engineering and especially structural dynamics is limited.

In comparison to other types of inertia-based devices, GMD has a simpler design and can be relatively inexpensive. By increasing

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the inertial terms of the system, GMDs increase the period of vibration of the structure and which is similar to the effect of base isolation systems. However, unlike base isolation systems in which the excessive deformation of the isolation layer is problematic for the structural response, the gears in a GMD are fixed and they spin freely around their axes. It is also common in the literature to draw a comparison between various types of inertial dampers and TMDs and several previous studies have shown the similarities between these two control systems [9]. TMDs installed on the roof of the structures provide an alternative passive control strategy [10]. However, it should be noted that there are several major differences between these two control strategies. Similar to GMDs, TMDs modify the response of the system by changing the inertial force component of the equation of motion. However, TMDs require a relatively large mass and thus a large space for their installation. The equivalent mass of GMDs can be modified by changing the gear ratios and employing multiple compound gears. Thus they can provide similar level of force while occupying a much smaller space. Moreover, by design, TMDs are in resonance with the main structure, and they undergo large displacements which need to be accommodated. As mentioned before, the free spinning of the gears of the GMDs does not impose any such problems.

In general, three types of inertial dampers have been proposed and tested experimentally, i.e. hydraulic, ball-screw and rack-and-pinion type of devices [11]. In 2011, Wang et al. [12] proposed a device in which forces were translated by hydraulic means. In the second type, a ball-screw mechanism is used. This configuration is very similar to the original inerter proposed by Smith [2] and thus in comparison to the other two types, has been studied more extensively. In these devices, the rotary ball-screw converts the axial movement into rotary movement thereby the axial velocity is amplified and applied to a viscous material [13,14]. Ikago et al. [15] called this type of inertia-based dampers as Tuned Viscous Mass Dampers (TVMDs). They derived a closed-form optimum design equation for the TVMD vibration control system to minimize the peak amplitude of the resonance curve in undamped structures and verified their numerical simulation by conducting shake table tests. More information about the development and verification of TVMDs can be found in other publications of these authors [16] including the real-life application of these devices in a steel building in Japan [17].

In the third type, using a rack and assembly of gears, the relative translation of the terminals is transformed into rotation of the gears [1]. In this group of inertial dampers, the equivalent mass of the device can be easily adjusted and unlike TVMDs, there is no viscous damper component inside these dampers. The lack of the necessity of employing a viscous medium inside the damper leads to reduced maintenance requirements. In addition, the simple assembly of this type of inertial dampers makes them an effective alternative solution for the vibration control of building structures in various parts of the world [18,19].

Unlike the other two types, the performance of the rack-and-pinion inertial dampers has still not been well studied and thus the current study investigated this type of inertial dampers in more detail. The device considered in the current study is similar to the damper in the study of Saitoh [1] and hence the same terminology, i.e. "gyro-mass damper", is used herein. Saitoh used a GMD to mitigate the lateral displacements of base isolators. In a similar application, Wang et al. [20] studied the effects of the application of these dampers to limit the horizontal and vertical displacements of the building base. However, it should be emphasized that both of these two studies are purely numerical and GMDs are only employed at the base level of the structure.

This study is arranged as follows: with the objective of illustrating the desirable dynamic properties of stand-alone GMDs, Section 2 summarizes the governing equations of motion for a stand-alone GMD and then to verify the derived equations, a prototype of this device is tested experimentally. In order to better investigate the performance of GMDs, energy terms are provided as quantitative measures. The main advantage of the energy formulation is the replacement of vector quantities, such as displacements, velocities and accelerations by the corresponding scalar quantities. Despite their benefits, due to geometric limitations and alignment issues, it would be very difficult, if not impossible, to design a GMD that spans along the entire height of a story diagonally to work based on relative floor accelerations. In Section 3, the benefits and shortcomings of different configurations for the introduction of GMDs into real structures are studied. The limitations of a configuration in which the GMD is attached to the structure through V braces, and the dynamic properties of the resulting system, considering also the flexibility introduced by the brace, are studied. As it is discussed in Section 3, an energy dissipation component (which does not have to be necessarily a linear viscous damper) can be added externally to the GMD-brace system. The effects of different parameters on the behaviour of this practical configuration with a GMD–Viscous damper–Brace (GVB) are investigated. The behaviour of a Single-Degree-of-Freedom (SDOF) system with the GVB control system is evaluated under different seismic loading scenarios and for various equivalent mass and stiffness values, and damping mechanisms. A numerical example is included in Section 4 that demonstrates the properties of the proposed configuration. Finally, the key findings of the paper are provided in Section 5.

2. Dynamic behaviour of GMDs

2.1. Stand-alone GMDs

In many ways, gears in rotating systems act similarly to levers in translating systems. The GMD prototype used in this study is shown in Fig. 1. Fig. 1(a) shows a GMD element subjected to a time varying relative axial force f. It consists of two simple (gears 1 and 6) and two compound (gears 2, 3, 4 and 5) gears. Free Body Diagrams (FBDs) of the gears are also shown in Fig. 2. The forces acting on each of these gears are determined by considering the equilibrium between the gears in contact. It should be pointed out that, unlike the study of Saitoh [1], the rotational inertias of the intermediate gears are also considered in the following derivation. By neglecting the mass of the rack and using the FBDs in Fig. 2, the equations of motion for each of the gears can be written as Eqs. (1)–(4).

$$J_1\ddot{\theta}_1 - f_1 r_1 + f_{1-2} r_1 = 0 \tag{1}$$

$$-J_2\ddot{\theta}_2 - J_3\ddot{\theta}_3 + f_{1-2} r_2 - f_{3-4} r_3 = 0 \tag{2}$$

$$J_4\ddot{\theta}_4 + J_5\ddot{\theta}_5 + f_{5-6} r_5 - f_{3-4} r_4 = 0 \tag{3}$$

$$-J_6\ddot{\theta}_6 + f_{5-6} r_6 = 0 \tag{4}$$

where r_i and J_i denote the radius and mass moment of inertia of the ith gear, respectively. In the above equations of motion, an ideal efficiency is assumed and the damping effects of gear friction or backlash are neglected. It can be shown that, the geometric relationship between the arc lengths of the gears results in the following relations between the angular rotations of each of the gears and the first gear:

$$\ddot{\theta}_2 = \ddot{\theta}_3 = \frac{r_1}{r_2}\ddot{\theta}_1 \tag{5}$$