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Passive Structural Control using a One-way Rotational Inertia Damper

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Abstract

In recent years, inerters have been increasingly studied for use in passive structural control devices. The inerter, a two-terminal device that has a restoring force proportional to the difference in the acceleration of its terminals, is used to convert translational motion into rotational motion. This transformation can be beneficial because the inerter, in combination with a flywheel, can be used to produce large mass effects, while only possessing a small physical mass. The inerter has been studied for structural control in many different configurations, including alone as a rotational inertia damper, in combination with a tuning spring, and as part of a modified tuned mass damper. While these devices have shown great promise for passive structural control, some authors have noted that the kinetic energy of the flywheel connected to the inerter can at times drive the response of the primary structure it is attached to, reducing the effectiveness of the device. In this study, a new type of one-way rotational inertia damper, featuring a one-way inerter, is studied. This type of inerter is advantageous because it allows energy to transfer only in a one-way fashion from the structure to the rotational inertia damper; thus, the energy that is transferred to the rotational inertia damper can never flow back and drive the response of the structure. In this study, a one-way rotational inertia damper is developed and its performance at mitigating the response of a single-degree-of-freedom structure is evaluated with numerical simulations. The results of this study demonstrate this passive vibration control device can at times be more effective in comparison to traditional rotational inertia dampers.

Keywords: inerter, passive, one-way, structural control, energy dissipation

1 Introduction

Active, passive, semi-active, and hybrid control strategies have been investigated for decades as different types of strategies to control the response of civil structures to dynamic excitations [1]. Passive control strategies are most widely used as they are generally stable, more economical, and reliable as they do not require external sources of power, sensors, actuators, or control computers [2].

Mass dampers, including tuned mass dampers (TMDs), are a popular type of passive control device, proposed for damping the motion of rigid bodies [3]. Traditional TMDs consist of a secondary mass connected to a structure through a spring and damper in parallel. Properly tuned TMDs can be effective in the reduction of the maximum dynamic magnification factor (DMF) and output variance of the primary structure it is attached to. Tuning values of TMDs can be obtained through an optimization problem, where the stiffness and damping coefficients of TMDs are parameters and the minimization of various outputs, including the DMF and the variance of the response, can be considered as objective functions [4-6].

TMDs, as well as other kinds of mass dampers, are usually more effective when larger masses are used in these devices [1,7]; however, the cost of these devices is also greatly influenced by their mass. In an attempt to reduce the physical size of mass dampers, without compromising the device's effectiveness, the concept of providing effective inertia mass by utilizing physically small rotational mass has been proposed [8]. In this context, the tuned viscous mass damper (TVMD), rotational inertia viscous damper (RIVD), rotational inertia double tuned mass damper (RIDTMD), and the tuned mass damper inerter (TMDI) have been proposed, developed, and investigated [8–13].

Rotational inertia mass can be produced by utilizing two terminal mechanical devices called "inerters" [14]. The inerter produces equal and opposite forces proportional to the relative acceleration of its terminals. The proportion constant of the linear relationship between the force and relative acceleration is called "inertance", which is the effective rotational inertia mass. The inerter produces effective rotational inertia mass by transferring relative translational motion to the rotational motion of a flywheel through either the rack and pinon [10,15] or the ball and screw [9] mechanism. Producing a 350 kg effective inertia mass has been reported in a TVMD by utilizing a 2 kg physical mass with ball-screw mechanism [9]. The inerter has been used as a passive control device as a part of a TMD, independently of TMDs, in SDOF structures, and in MDOF structures. The passive control of SDOF structures with rotational inertia mass [8], the effect of the inerter on natural frequencies of the structures [16], and the protection of structures subjected to earthquakes [17] have been studied in this context.

While there are beneficial aspects of utilizing inerters as passive control devices, there are some potential complications and drawbacks. The rotation of the inerter in a structure will stop when the relative velocity of the inerter goes to zero. At this point, the kinetic energy of the inerter will have all transferred back to the structure. This aspect serves as the motivation to seek a new rotational mechanism. Recently, utilizing pairs of flywheels associated with a clutch system, like a bicycle, a new passive system for control of SDOF structures have been proposed [18]. In this, the flywheel is driven by the structure when the displacement and acceleration of the structure have the same sign; however, no consideration is made to the magnitude of the velocity of the flywheel.

As a continuation of the development of rotational inertia dampers for passive control, this paper presents an innovative rotational inertia damper with a modified rotational mechanism. The proposed device consists of a flywheel which can only rotate in one direction and can engage with the structure when the velocity of the structure is equal to or larger than the linear velocity of the flywheel interface. The rotational inertia damper is introduced in the next section, control of a SDOF system utilizing one-way rotational inertia, analysis and discussion are presented after that.

2 Rotational inertia damper:

Rotational inertia dampers consist of an inerter produced with a ball-screw mechanism [8]. However, the rack and pinion mechanism has also been proposed and used in rotational inertia dampers [10], [18]. Figure 1 shows a flywheel associated with a rack and pinion mechanism, which can be used as a rotational inertia damper.

Assuming linear transferring of the translational to rotational motion, the following relationship between angular displacement of the flywheel, θ, and the relative displacement of the device's terminals holds:

$$\theta = \frac{\left(x_2 - x_1\right)}{r_0} \tag{1}$$

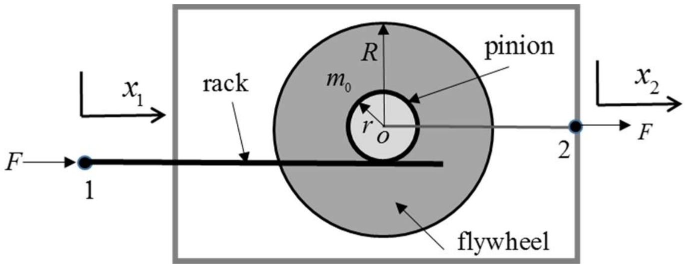

Figure 1: Flywheel with a rack and pinion mechanism

The force F needs to satisfy the equilibrium about point O

$$F = J\ddot{\theta} \tag{2}$$

Where, $J = \frac{1}{2}m_0 R^2$. Substituting Eq. (1) into Eq. (2) gives

$$F = m_r\left(\ddot{x}_2 - \ddot{x}_1\right) \tag{3}$$

In Eq. (3), m_r, the effective rotational inertia mass (inertance), is the following:

$$m_r = m_0\left(\frac{R}{r_0}\right)^2 \tag{4}$$

Where, m_0 is the physical mass of the flywheel, R is the radius of the flywheel, and r_0 is the radius of the pinion. Eq. (4) shows how the geometry of the flywheel and pinion amplify the physical mass m_0. The amplification factor can be increase by using parallel flywheels associated with a gear system [19].

3 Passive control of SDOF structures with rotational inertia dampers:

Figure 2 depicts an undamped single degree of freedom (SDOF) system with mass m_s, stiffness equal to k, and passive control provided with a rotational inertia damper. In this model, the rotational inertia damper is attached to the structure with rigid links as the deformation of the rotational inertia damper and its connections are assumed to be insignificant.

The rotational inertia damper is connected to the SDOF structure at points 1 and 2 (see Figure 2). Because of the rigid links utilized in this model, the relative deformation of these points is equal to x_s, the displacement of the mass relative to the ground. Therefore, the equation of motion of the system can be written as follows:

$$\left(m_s + m_r\right)\ddot{x}_s + kx_s = -m_s\ddot{x}_g \tag{5}$$

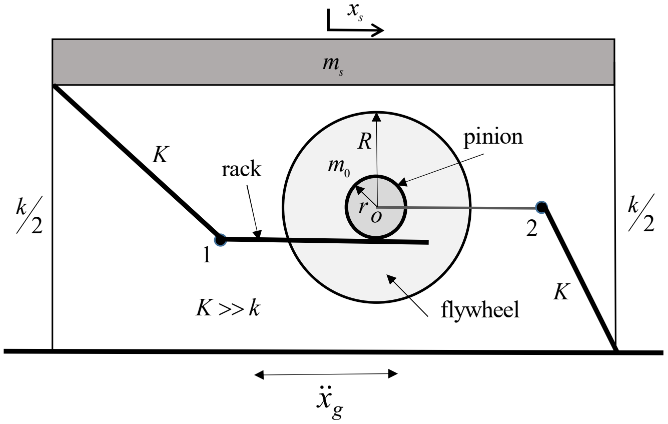

Figure 2: SDOF structure with a rotational inertia damper

Eq. (5) can be rewritten as:

$$\ddot{x}_s + \omega^2 x_s = \frac{-m_s}{m_s + m_r}\ddot{x}_g \tag{6}$$

Where, $\omega = \omega_0\sqrt{\frac{1}{1+a}}$, $a = \frac{m_r}{m_s}$, and $\omega_0 = \sqrt{\frac{k}{m_s}}$. As m_r is always positive, Eq. (6) shows the effective rotational inertia mass decreases the frequency of the system and the effective amplitude of the excitation compared to the uncontrolled system.

As the traditional rotational inertia damper rotates in two directions, it transfers the translational motion to rotation linearly. In other words, when the structure moves to the right, the flywheel rotates clockwise and when the structure moves back to the left, the flywheel rotates in the opposite direction. In this mechanism, kinetic energy is transferred to the inerter when its rotational velocity increases and then is transferred back to the structure when the rotation of the flywheel slows.

In the proposed one-way rotational inertia damper, the flywheel is allowed to rotate in the clockwise direction and be engaged with the structure when the velocity of the structure is equal to or larger than the linear velocity of the flywheel. In other words, when the structure moves to the right $(\dot{x}_s > 0)$ and with an equal to or larger velocity than the surface of the pinion $(\dot{x}_s \geq r_o\dot{\theta})$, the flywheel works as a traditional inertia damper and Eq. (6) is valid. In all other situations, the flywheel rotates freely without interacting with the structure and the structure oscillates as an uncontrolled SDOF system. In this way, energy can only be transferred from the structure to the flywheel and never back to the structure from the flywheel. While, the motion of the flywheel in the traditional and one-way rotational inertia dampers could be damped, no damping of the flywheel is considered in this paper.

4 Time history response

In this section, time history responses of the proposed one-way damper and traditional inertia damper are presented. For both cases, the same primary SDOF structure is considered with unit natural frequency ($\omega_0 = 1$ rad/sec). Additionally, the rotational inertia mass for both dampers are considered the same and equal to 20% of the primary structure's mass ($m_r = 0.2m_s$). In all cases, the excitation ($\ddot{x}_g$) is harmonic and three frequencies are considered to evaluate the performance at different input frequencies. In this stage, the performance evaluation is limited to a comparison of the displacement of the primary structure at three different input frequencies. Figure 3 shows the response of both systems when the input frequency is equal to 0.8. It is observed the proposed damper provides a significant reduction in the maximum displacement of the primary structure in comparison to the traditional inertia damper.

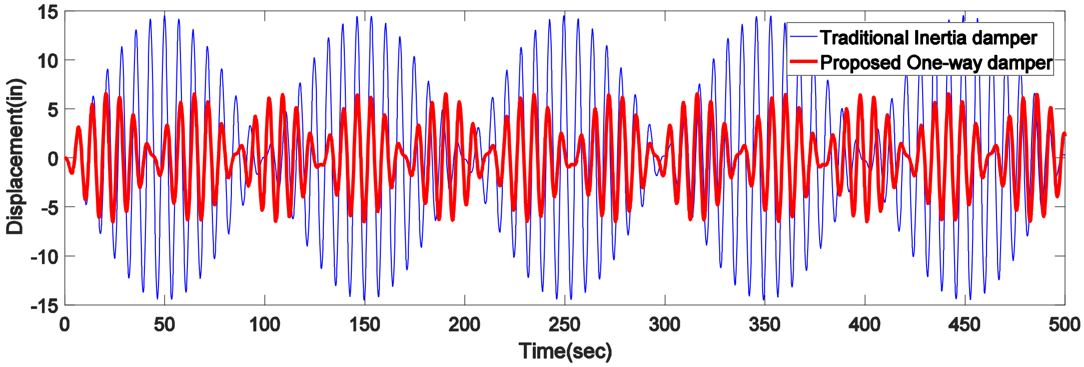

Figure 3: Time history response of the SDOF systems with the traditional and proposed damper (input frequency equal to 0.8 rad/sec)

Figure 4 presents the response of the systems when the input frequency is equal to 1.1 rad/sec. At this frequency, unlike the previous case, it is observed that the traditional rotational inertia damper has a superior performance in terms of the reduction of the displacement of the primary structure. The differences in behaviour seen in Figure 3 and Figure 4 are thought to be primarily due to the shifting of the structure's natural frequency that occurs most predominantly due to the traditional inertia damper.

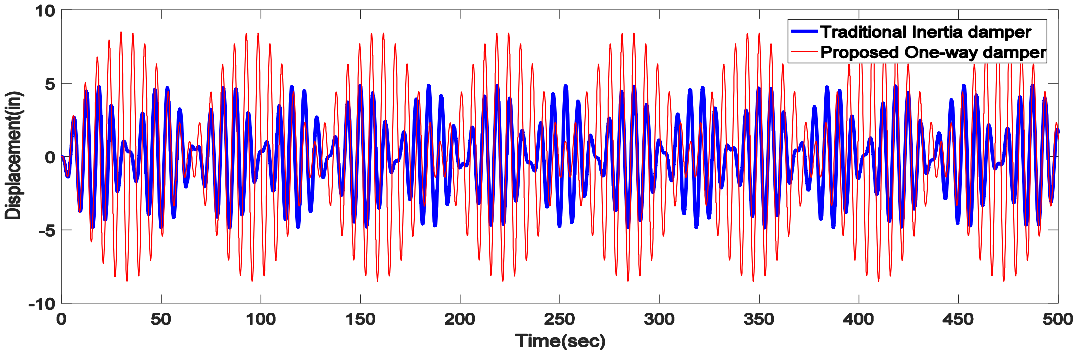

Figure 4: Time history response of the SDOF systems with the traditional and proposed damper (input frequency equal to 1.1 rad/sec)

As the response of the SDOF at the resonance frequency is critically important, the response of an SDOF structure with the traditional inertia damper and the proposed one-way damper at their resonance frequencies are investigated. For the traditional inertia damper, the resonance frequency can be obtained by using $\omega = \omega_0 \sqrt{\frac{1}{1+a}}$ (see Eq. (6)); however, the resonance frequency of the proposed one-way damper is obtained through numerical computation. Figure 5 shows the response of the structure with the proposed one-way damper and the traditional inertia damper in response to their resonant loadings. Because the SDOF system is undamped, the responses of both systems are unbounded. However, the rate of the growth of the response for the SDOF system with the proposed damper is less than the SDOF system equipped with the traditional inertia damper. The primary reason for this reduction is that the energy that is being redirected in a one-way manner to the flywheel in the one-way device can not appear as potential (or kinetic) energy in the primary structure.

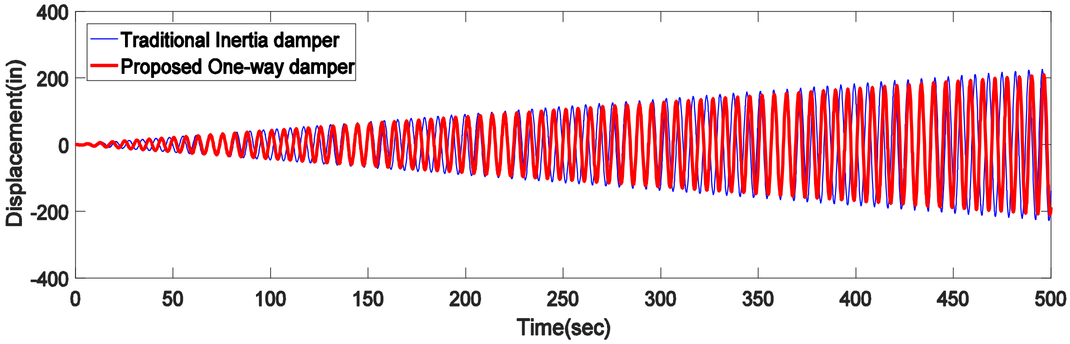

Figure 5: Time history response of the SDOF systems with the traditional and proposed damper (harmonic input at resonance frequencies)

In addition to the harmonic response, the time history response when the structure is subjected to an initial velocity is also investigated. To compare the responses, it is necessary to ensure the input energy for both systems are equal. Considering equal input kinetic energy, the time history response of both systems is presented in Figure 6. It is observed the proposed one-way damper provides a lower response than the traditional inertia damper. With the traditional inertia damper, when the structure is subjected to an initial velocity, the structure vibrates during all times with the additional effective mass from the inertia damper. In contrast, in the proposed one-way damper, the rotational mass is only engaged at the beginning of the response where it takes a portion of energy away from the structure. After this, the conditions to engage the one-way device are never met again and the structure vibrates freely after that. In other words, for the one-way device, the input energy is transferred to the flywheel and causes it to spin continually, while in the traditional case the energy transfers back and forth between the structure and the flywheel.

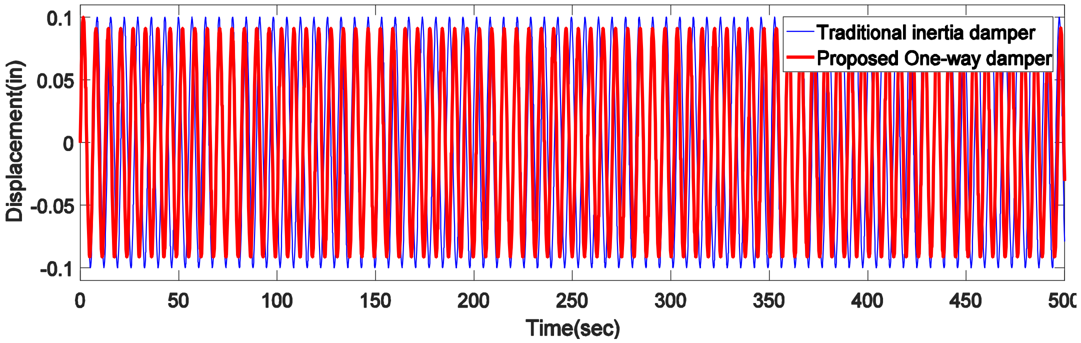

Figure 6: Time history response of the SDOF systems with the traditional and proposed damper subjected to an initial velocity

5 Conclusions

In this paper, an innovative mechanism which functions as a one-way version of a traditional inertia damper is proposed and examined via time domain analysis. With traditional inertia dampers, the flywheel rotates in both clockwise and counter-clockwise directions. Because of this, when the relative velocity of the terminals of the device comes to zero, the rotation of the device stops as well. Due to this relationship, the energy of the flywheel can transfer back to the structure and drive its response. The proposed one-way inertia flywheel can rotate just in the clockwise direction and be engaged with the structure when the structure moves to the right and the velocity of the structure is equal to or larger than the linear velocity of the flywheel interface.

Time domain responses shows the mixed performance of the proposed damper when the primary structure is subjected to non-resonant harmonic loads. It is observed in the resonance case, that the rate of the growth of the response of the structure with the proposed damper is lower than the response of the structure with the traditional inertia damper. In addition, the proposed damper provides a lower response when the structure is subjected to an initial velocity.

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