Enhanced base isolation system utilizing one-directional rotational inertia supplement devices

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Abstract

Rotational inertia devices have been developed and utilized as effective passive control devices including in base isolation systems. One-directional rotational inertia dampers have recently been proposed and show superior performance compared to traditional inerters under specific circumstances. The main difference between traditional inertia dampers and one-directional rotational inertia dampers is the mechanism of transferring energy. While traditional dampers store energy and transfer it back to the structure, one-directional rotational inertia devices do not transfer energy back to the structure. In an attempt to reduce the amount of energy transferred back to the structure, this study investigates the enhancement of base isolation systems by utilizing one-directional rotational inertia devices. The potential benefit of one-directional rotational inertia devices on base isolation during earthquakes is also examined. Results show superior performance of one-directional rotational inertia dampers on the improvement of base isolation systems when compared to traditional inerters in terms of frequency response and response to the considered seismic ground motions.

Keywords: Passive Control, Base Isolation. Rotational Inertia Damper

1. Introduction

Various passive control methods have been proposed and developed in recent decades to protect structures subjected to dynamic loads such as wind and earthquakes [1]–[3]. Recently, inerter-based systems have received significant attention as potential passive control devices. An inerter is a two node mechanical device that provides two equal and opposite forces that are proportional to the relative acceleration between the nodes [4]. In other words, an inerter is a rotational inertia mass which can produce large effective mass by transferring translational motion into rotational motion.

One such device that has been proposed and used for the passive control of single degree of freedom (SDOF) structures is the rotational inertia viscous damper (RIVD), which consists of an inerter rotating in a viscous fluid [5]. The tuned viscous mass damper (TVMD) adds a tuning spring in series with the RIVD and shows the potential for effectively reducing the dynamic response of SDOF structures [6]. The tuned inerter damper (TID) is another inerter-based passive control device that consists of a dashpot and spring that are connected to an inerter in series [7], [8]. In addition, inerters have been used to improve the tuned mass damper (TMD) [9], [10], three element vibration absorber [11], and nonlinear energy sink [12].

In addition to improving passive vibration absorbers, inerters have also been used for other passive control approaches. Recently, an enhanced tuned mass damper inerter was developed and shown to effectively improve traditional tuned mass damper base isolation [13]. In the same way, TIDs and other types of inerter layout configurations have recently been proposed for base isolation improvement [14]–[16]. It should be noted that base isolation systems are one of the most effective methods for reducing damage to structures subject to ground accelerations [17]. The literature on base isolation systems is broad and includes systems featuring rolling/balls, rubber bearings, active control, tuned mass dampers, and tuned liquid mass dampers [18– 23].

Novel rotational inertia dampers have been proposed recently, but have not been investigated for use in base isolation systems. A clutch inerter damper (CID) consists of an inerter mass damper (IMD) and a simple clutch, which disengages the rotational mass when the acceleration and the velocity are in opposite directions. This leads to the further reduction of the structure's response when compared to the traditional inerter [24], [25]. Another innovative rotational inertia damper is the one-directional rotational inertia viscous damper (ODRIVD) which consists of a rotational mass that can only be engaged in one direction [26]. The ODRIVD will only engage the inerter if the linear velocity of the structure is equal to or larger than the linear velocity of the contact point on the mechanism. This feature allows the device to only transfer energy to the rotational mass and not back to the structure, providing potentially more reduction in response as compared to the RIVD.

This paper investigates utilizing the ODRIVD for the base isolation of structures. The goal is to formulate a base isolation system using a ODRIVD, analyze its effectiveness at reducing the response of a structure, and compare the results to those utilizing a RIVD or traditional inerter. Section 2 briefly introduces the ODRIVD and the model of the isolated system, Section 3 discusses the results of the study, and Section 4 presents the conclusions produced from this effort.

2. Inerter and One-directional Rotational Inertia Damper

Considering a flywheel combined with a ball-screw with lead length ρ, the relationship between the relative longitudinal motion, u, and the rotational angle of the flywheel, θ, can be expressed as:

$$\theta = \frac{2\pi}{\rho} u \tag{1}$$

Denoting the flywheel's moment of inertia as J, the inertance b of the device can be calculated as follows:

$$b = J \frac{4\pi^2}{\rho^2} \tag{2}$$

For an inerter with a rotational mass (inertance) equal to b and the displacement of the end nodes equal to u_1 and u_2, the force, F, developed at each node can be expressed as:

$$F = b(\ddot{u}_2 - \ddot{u}_1) \tag{3}$$

The general idea of the ODRIVD is similar to a spinning push top toy. In a spinning push top toy, pushing down on the handle of the top causes it to spin. This spinning continues until it is damped or is interrupted. A diagram of a SDOF structure with base isolation controlled with two ODRIVD (2ODRIVD) and subjected to base excitation is presented in Fig 1. In this figure, D_1 and D_2 are the device's damping coefficients and ρ_1 and ρ_2 are the leads of the ball screws connected to the mass of the base isolation system. J_1 and J_2 are the moment of inertia of the device's flywheels, which can be calculated as follows:

$$J_1 = \frac{1}{2} m_{01} R_1^{\,2} \tag{4}$$

$$J_2 = \frac{1}{2} m_{02} R_2^{\,2} \tag{5}$$

In Eq. (4) and Eq. (5), m_{01} and m_{02} are physical masses of the flywheels and R_1 and R_2 are the radii of the flywheels.

The 2ODRIVD performs in three different states [26].

- State One (S_1): The one-way rotational device is in S_1 if the attached structure is moving left and the relative velocity of the structure is equal to or larger than the linear velocity of the flywheel at the contact point. In this state, the first ODRIVD is engaged and the flywheel of the second ODRIVD spins freely.
- State Two (S_2): The device is in S_2 if the structure is moving right and the relative velocity of the structure is equal to or larger than the linear velocity of the second flywheel at the contact point. In this state, the second ODRIVD is engaged and the flywheel of the first ODRIVD spins freely.
- State Three (S_3): The device is in S_3 if none of the above conditions for S_1 or S_2 are satisfied. The attached system oscillates without being engaged with either rotational inertia mass. In this state, the flywheels of both devices spin freely.

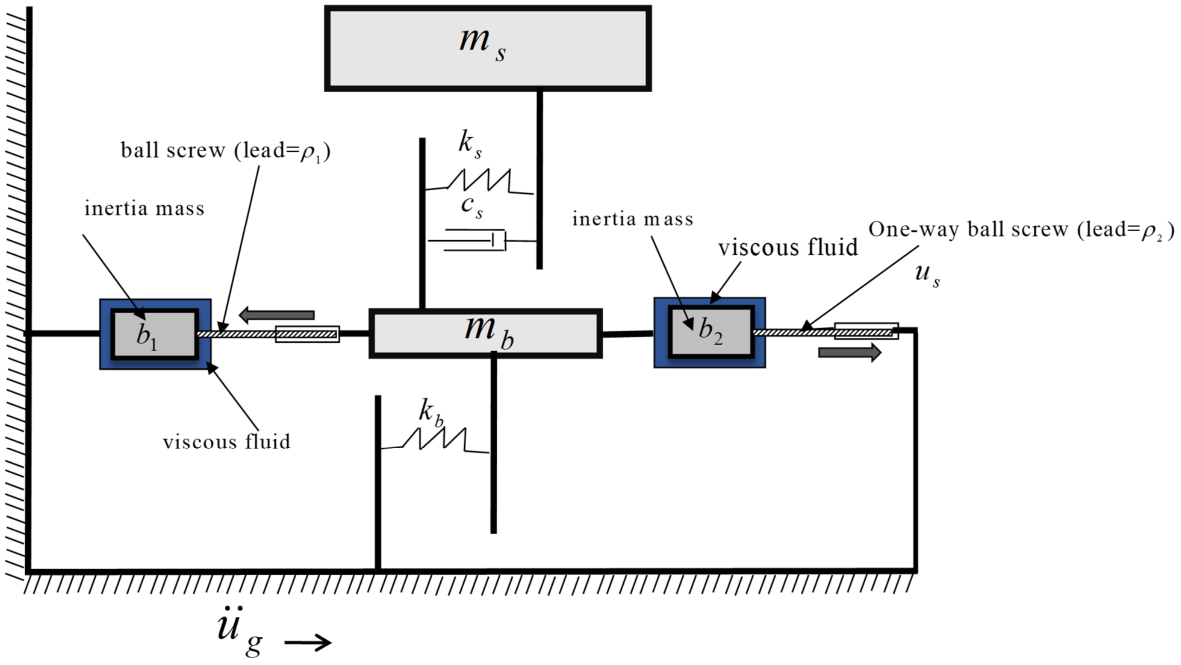

Fig 1 – Base isolation system with 2ORIVD

The equation of motion of the isolated system can be expressed as follows:

State S_1: The base isolation mass is engaged with the 2ODRIVD's first ODRIVD.

$$\begin{bmatrix} m_b + b_1 & 0 \\ 0 & m_s \end{bmatrix} \begin{bmatrix} \ddot{u}_b \\ \ddot{u}_s \end{bmatrix} + \begin{bmatrix} c_{b1} + c_s & -c_s \\ -c_s & c_s \end{bmatrix} \begin{bmatrix} \dot{u}_b \\ \dot{u}_s \end{bmatrix} + \begin{bmatrix} k_b + k_s & -k_s \\ -k_s & k_s \end{bmatrix} \begin{bmatrix} u_b \\ u_s \end{bmatrix} = \begin{bmatrix} m_b \\ m_s \end{bmatrix} \ddot{u}_g \tag{6}$$

As the second ODRIVD is not engaged, its flywheel spins with the following equation of motion:

$$J_2 \ddot{\theta} + D_2 \dot{\theta} = 0 \tag{7}$$

State S_2: The base isolation mass is engaged with the 2ODRIVD's second ODRIVD.

$$\begin{bmatrix} m_b + b_2 & 0 \\ 0 & m_s \end{bmatrix} \begin{bmatrix} \ddot{u}_b \\ \ddot{u}_s \end{bmatrix} + \begin{bmatrix} c_{b2} + c_s & -c_s \\ -c_s & c_s \end{bmatrix} \begin{bmatrix} \dot{u}_b \\ \dot{u}_s \end{bmatrix} + \begin{bmatrix} k_b + k_s & -k_s \\ -k_s & k_s \end{bmatrix} \begin{bmatrix} u_b \\ u_s \end{bmatrix} = \begin{bmatrix} m_b \\ m_s \end{bmatrix} \ddot{u}_g \tag{8}$$

As the first ODRIVD is not engaged, its flywheel spins with the following equation of motion:

$$J_1 \ddot{\theta} + D_1 \dot{\theta} = 0 \tag{9}$$

State S_3: The SDOF system is not engaged with either of the 2ODRIVD's ODRIVDs. The primary structure is then undamped with the following equation of motion:

$$\begin{bmatrix} m_b & 0 \\ 0 & m_s \end{bmatrix} \begin{bmatrix} \ddot{u}_b \\ \ddot{u}_s \end{bmatrix} + \begin{bmatrix} c_s & -c_s \\ -c_s & c_s \end{bmatrix} \begin{bmatrix} \dot{u}_b \\ \dot{u}_s \end{bmatrix} + \begin{bmatrix} k_b + k_s & -k_s \\ -k_s & k_s \end{bmatrix} \begin{bmatrix} u_b \\ u_s \end{bmatrix} = \begin{bmatrix} m_b \\ m_s \end{bmatrix} \ddot{u}_g \tag{10}$$

As both ODRIVDs are not engaged, their flywheels spin with the following equations of motion:

$$J_1 \ddot{\theta} + D_1 \dot{\theta} = 0 \tag{11}$$

$$J_2 \ddot{\theta} + D_2 \dot{\theta} = 0 \tag{12}$$

In the next section, the performance of the isolated system with the 2ODRIVD will be compared to an isolated system with an RIVD. The equations of motion for this system are:

$$\begin{bmatrix} m_b + b_1 + b_2 & 0 \\ 0 & m_s \end{bmatrix} \begin{bmatrix} \ddot{u}_b \\ \ddot{u}_s \end{bmatrix} + \begin{bmatrix} c_{b1} + c_{b2} + c_s & -c_s \\ -c_s & c_s \end{bmatrix} \begin{bmatrix} \dot{u}_b \\ \dot{u}_s \end{bmatrix} + \begin{bmatrix} k_b + k_s & -k_s \\ -k_s & k_s \end{bmatrix} \begin{bmatrix} u_b \\ u_s \end{bmatrix} = \begin{bmatrix} m_b \\ m_s \end{bmatrix} \ddot{u}_g \tag{13}$$

3. Analysis and Results

In this section, the performance of the RIVD and 2ODRIVD on improving the response of a base isolated SDOF structure is investigated. The parameters of the isolated system introduced in Section 2 that are considered for this analysis are as follows:

$$m_s = 50000 \text{ kg}, \; m_b = 10000 \text{ kg}, \; b_1 = b_2 = 12500 \text{ kg},$$

$$k_s = 21935454 \; {}^{\text{N}}\!/\!{}_{\text{m}}, \; k_b = 175459 \; {}^{\text{N}}\!/\!{}_{\text{m}}, \; c_{b1} = c_{b2} = 10000 \; {}^{\text{N-s}}\!/\!{}_{\text{m}}, \; \xi_s = 0.03$$

For this analysis, a harmonic load is considered as the input. The maximum and root-mean-square (RMS) of the relative displacement of the primary structure ($\max(u_s - u_b)$, $rms(u_s - u_b)$) are considered as the evaluation criteria. The frequency response of the system is calculated by considering multiple analyses of the systems when the frequency of the input is varied over the range of 0-80 rad/sec ($\ddot{u}_g = A\sin(\omega t)\left(0 \le \omega \le 80\frac{rad}{\sec}\right)$).

Fig 2 graphs the RMS of the displacement of the structure relative to the base structure as a function of input frequency for both a system using a RIVD and one using a 2ODRIVD. The results show that the RMS response of the structure in its first mode, which is related to the isolation layer, increases by utilizing the 2ODRIVD. However, the 2ODRIVD greatly reduces the RMS response of the relative displacement of the structure in its second mode, which is related to the primary structure.

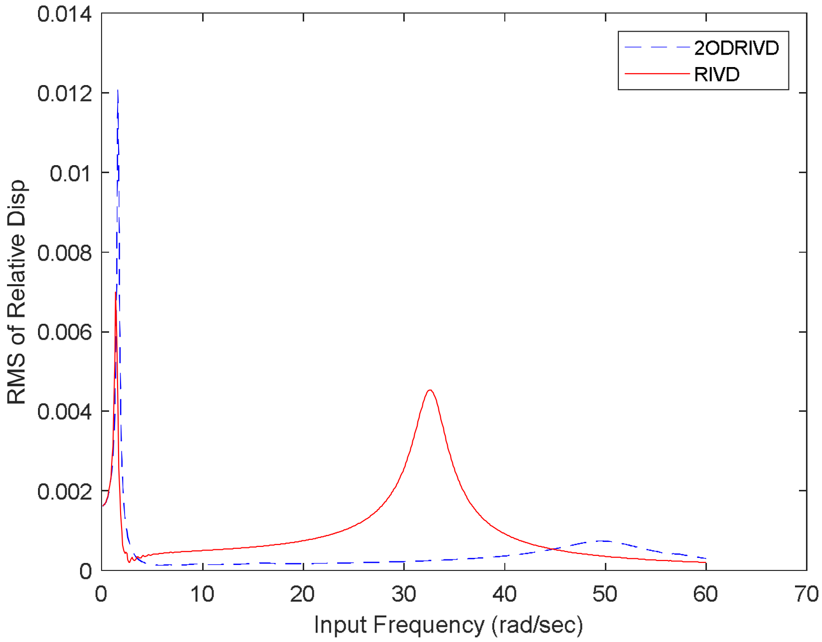

Fig 2 – RMS of the displacement of the primary structure relative to the base isolation layer utilizing the RIVD and 2ODRIVD

Fig 3 graphs the maximum of the displacement of the structure relative to the base structure as a function of input frequency for both a system using an RIVD and one using a 2ODRIVD. The results are similar to those of the RMS graph. The response of the structure in the first mode is increased somewhat by utilizing the 2ODRIVD. However, the maximum displacement of the structure in its second mode is again significantly reduced by using the 2ODRIVD.

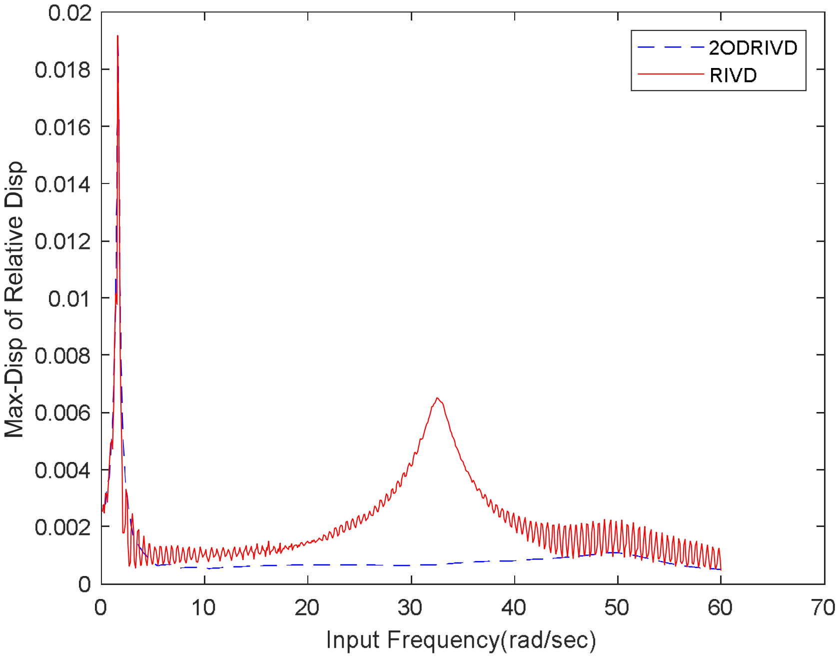

Fig 3 – Maximum displacement of the primary structure relative to the base isolation layer utilizing the RIVD and 2ODRIVD

In order to show the effectiveness of the one-way damper when the structure is subjected to seismic loading, the performance of both devices is examined by considering two benchmark seismic excitations as the input loads. The first earthquake is the Kobe (Japan) 1995 earthquake (recorded at the Takarazuka station) and the second one is the 1940, Imperial Valley ground motion (recorded at the El Centro station). Fig 4 shows the relative displacement of the structure to the base structure for an isolation system using a RIVD and one using a 2ODRIVD that has been subjected to the Kobe earthquake. These results show the 2ODRIVD performs superior to the RIVD in reduction of the maximum displacement of the structure relative to the base isolation layer.

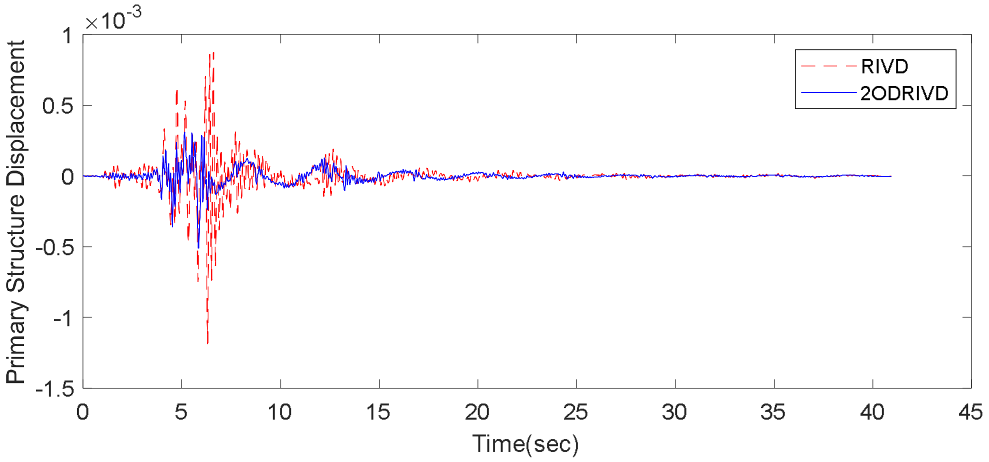

Fig 4 – Relative displacement of the primary structure to t*he base isolation layer utilizing the RIVD and 2ODRIVD subjected to the Kobe earthquake

Fig 5 shows the relative displacement of the structure to the base structure for an isolation system using a RIVD and one using a 2ODRIVD that has been subjected to the El Centro ground motion. These results show the 2ODRIVD again has superior performance, compared to the RIVD, in reduction of the maximum displacement of the structure relative to the base isolation layer.

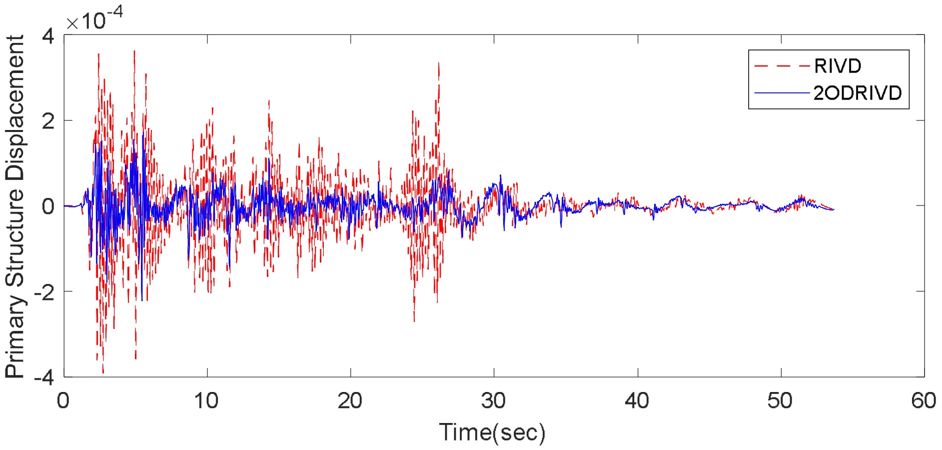

Fig 5 – Relative displacement of the primary structure to the base isolation layer utilizing the RIVD and 2ODRIVD subjected to the El Centro ground motion

4. Conclusion

This paper proposed using two one-directional rotational inertia viscous dampers to enhance the base isolation of a structure subjected to ground excitation. The addition of the 2ODRIVD improves the base isolation system by transferring energy to the damper in one direction without allowing the transfer of any energy back to the primary structure. Considering the ground excitation as a harmonic load across a range of frequencies, the performance of the proposed enhancement was studied and it was found the 2ODRIVD provides an effective reduction in the response of the structure at higher frequencies. In addition, the time history response of the structure subjected to two benchmark earthquakes also shows superior performance of the 2ODRIVD in comparison to the RIVD. However, more investigation is needed to provide a comprehensive performance evaluation of the 2ODRIVD for base isolation systems.

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