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Study of a roller seismic isolation bearing coupled with an eddy current damping system.

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Abstract. In seismic protection of structures, seismic isolation systems have been implemented successfully. By this year, Japan is probable to exceed 4500 buildings built with this technology. Seismic isolators, in addition to decoupling the seismic excitation of the structure, provide energy dissipation capacity through different mechanisms such as friction and yield of materials. A disadvantage of these dissipation methods is the contact between the damping system components with seismic isolation system. This work studies an efficient energy dissipation alternative, with the application of eddy currents in a roller seismic isolation system; it should be noted that this alternative does not require direct contact with the isolation system components. The characterization of the dissipation system was carried out with the use of magnets and non-ferromagnetic material, coupled to a seismic isolator with rolling supports. Seeking to reduce the horizontal displacement of the seismic isolation without affecting its dynamic behavior, several aspects were considered in this study, such as: rolling friction coefficient, eddy current damping forces and the gap between the conductor and the magnetic system. According to the study's results, the proposed damping system is viable for use in seismic isolation.

Palabras clave: Roller seismic isolation, eddy currents, energy dissipation, eddy current damping, rolling supports.

1 Introduction

Seismic isolation is a structural design alternative that reduces earthquake damage. Numerous studies, patents and research have led to its application in different kinds of structures around the world. Seismic isolation decouples a structure from ground motion, protecting it from the damaging effects of earthquakes. [1]

According to structural design codes, a seismic isolation system must have the following properties: (1) lateral flexibility that separates the structural system and its components from the seismic excitation, increasing the period of the structure (2) provide energy dissipation capacity and (3) self-centering capacity after the earthquake has occurred.

Seismic isolation system technology can also be used in the rehabilitation of patrimonial structures, preserving their esthetics and improving their structural performance in earthquake conditions [2]. In the seismic protection of structures, different countries have implemented this technology. Japan, for example, has at least 5000 buildings with seismic isolators system. [3]

As mentioned, seismic isolation systems incorporate energy dissipation mechanisms, such as high damping rubbers, lead cores and sliding systems [4]. This research work studies the effectiveness of a novel eddy current damping system, different from the conventional damping mechanisms used in seismic isolation technology.

Among the seismic isolation systems, rubber isolation has been the most widely applied systems, however, these are characterized by a natural frequency and therefore susceptible to resonance effects. An isolation alternative is the use of roller supports as proposed by Tsung-Wu et al. [5] and Lee et al. [6]. The latter, designed a system of roller seismic isolation bearing that move on inclined surfaces, thus achieving self-centering capability, without evidence of a characteristic frequency, also, the system was provided with a damping by the friction of sliding plates.

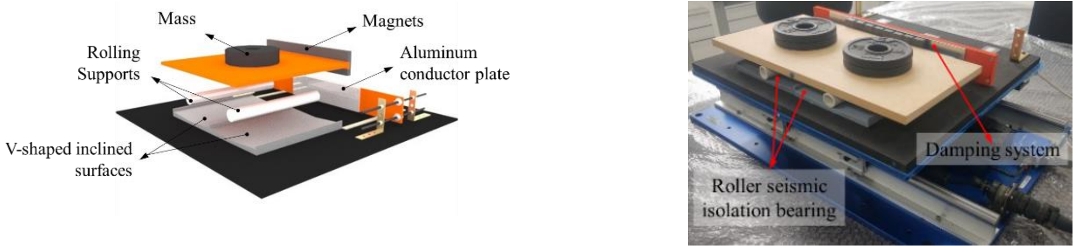
Although the effectiveness of the roller seismic isolation bearing was proven [7], the use of sliding plates in permanent contact could bring disadvantages of material wear and operating difficulties over time. A proposal to avoid the contact between the plates was presented by Sánchez et al. [8], proposed the use of magnetic fields, however, its application led to an increase in the accelerations of the isolation.

An energy dissipation system that avoids direct contact with the isolation is the use of eddy currents that are generated by the relative motion between a conductive material and a magnetic system. With proper implementation, it exhibits adaptability as it depends on the proximity of the magnets to the conductor and the strength of the magnetic field. This dissipation mechanism has been used in braking systems, vibration reduction and damping systems [9],[10],[11], [12]. It is important to note that these eddy currents do not alter the stiffness of the isolation system and the damping is proportional to the velocity [13], so their dynamic modeling is simplified.

To reach the main objective of this study, experimental and numerical dynamic analysis methodologies were applied with the use of an earthquake shake table [14] and the development of programming codes. Free vibration and harmonic seismic excitation tests allowed to verify the performance of the proposed dissipation system for the displacement control of a rolling bearing isolator.

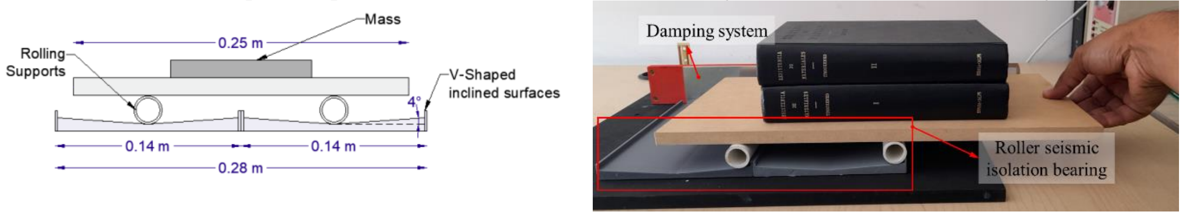
2 Physical model of the isolation system coupled to the damping system

This study proposes a new damping system that can be coupled to a seismic isolator with roller bearings supports. It differs from the sliding plate system proposed by Lee et al. [6] and consists of the use of eddy currents as an energy dissipation mechanism. Since it does not require direct contact with the damping system, this dissipation alternative exhibits high durability and reliability. To characterize the dissipation system and validate its dynamic behavior, an isolation with rolling supports coupled to a magnet system and an aluminum plate was built as shown in Fig. 1.



(a) Principal components

(b) Physical model of the isolation system



(c) Principal dimensions

(d) Physical model of the damping system

Figure 1. Roller seismic isolation bearings with damping system.

The isolation system is composed of V-shaped inclined surfaces, PVC rolling supports, and wooden plates arranged at the top and bottom for attachment to shaking tables and installation of structural models. The roller surfaces were designed with an inclination angle of 4° taking into account the recommendations presented by Lee et al. [6] and Sanchez et al. [8], their confection was made using a 3D printer with the following dimensions

$14cm \times 20cm$. This design allowed maintaining the self-centering capacity of the isolation system.

To build the energy dissipation system, eight ceramic magnets were installed on the top plate of the isolation system. In addition, a $300mm \times 50mm \times 3mm$ aluminum conductor plate was arranged, with the facility to define $2mm$ and $6mm$ of separation between the aluminum plate and the magnetic system. Fig. 1(a). presents the layout of the eddy current dissipation system studied in this work.

3 Experimental tests

To characterize the dynamic behavior of the isolation system coupled to the energy dissipation system, different experimental tests were carried out, which were classified into free vibration tests and seismic excitation tests. In all tests, the horizontal displacement of the upper support of the isolation system was recorded, for which the video was analyzed with the modeling tool Tracker video.

3.1 Free vibration tests

To evaluate the dynamic behavior of the isolator coupled to the energy dissipation system, free vibration (FV) tests were performed with and without the installation of the damping system. The FV tests consisted of bringing the upper support to the end of the inclined surface and releasing suddenly it to simulate initial displacement and velocity conditions. The average initial displacement was 0.11m, while the mass is represented by two books supported on the top plate of the isolator as shown in Fig. 1(d).

In this testing stage, three cases were considered, the first one corresponds to the testing of the isolator under FV conditions without the damping system, while the second and third tests correspond to the isolator coupled to the damping system with conductor spacings of $6mm$ and $2mm$, respectively. Fig. 1(d) shows the setup and performance of the FV tests.

The mass applied in the first test has a value of $2{,}536kg$, while for the second and third tests, the measured mass was $2{,}980kg$, this increase is explained by the magnetic system installed in the performance of these tests. As mentioned above, we used the Tracker Video software to record and track the horizontal displacement of the damping system. Fig. 2 shows the record of the typical displacements, obtained with the video processing in the three cases corresponding to the free vibration tests.

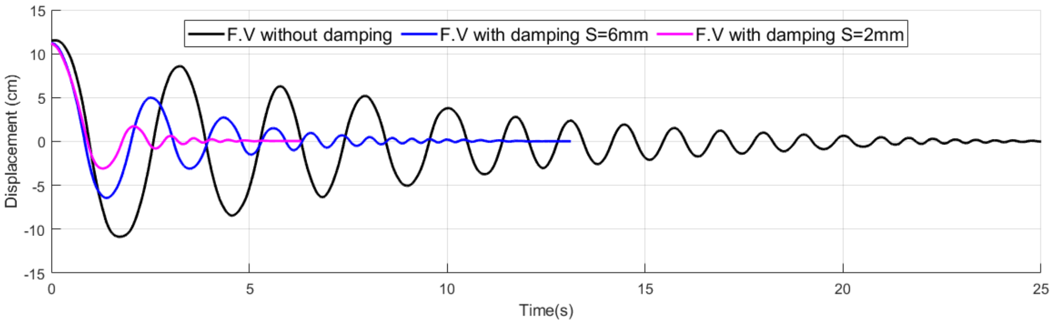


Figure 2. Time series of displacement response in free vibrations.

A qualitative examination of Fig. 2 shows the stiffening of the isolation system with the installation of the damping system, being stiffer the isolator with energy dissipation system, where the conductor and the magnetic system is 2 mm gap. Despite the stiffening, the vibrations remain underdamped. This behavior is beneficial for the isolation system.

Analyzing two cycles of the displacement response of the isolator with dissipation system (Fig. 2), the effectiveness of the application of eddy currents is verified, finding reductions in the displacement of the isolator of 76% and 94% for a separation of 6mm and 2mm, respectively.

3.2 Seismic Excitation Tests

Concerning the dynamic behavior of the isolator coupled to the damping system, harmonic seismic excitation (HSE) tests were performed with and without the installation of the damping system. The HSE tests consist of placing the isolator on a vibrating table and placing the system in its equilibrium state; additionally, initial amplitude and frequency data are set to generate a periodic sinusoidal motion.

In this testing stage, two cases were considered, the first one corresponds to the testing of the isolation system under HSE conditions without the damping system, while the second one corresponds to the isolator coupled to the damping system with a conductor spacing of $2mm$. Fig. 1(b) shows the assembly and performance of the HSE tests.

The mass applied in the first test has a value of $2{,}809kg$, while for the second one the measured mass was $3{,}212kg$, this increase is explained by the magnetic system installed in the performance of these tests. As mentioned above, we used the Tracker Video software to record and track the horizontal displacement of the isolator. Fig. 3 shows the record of the typical displacements, obtained with the video processing in the two cases corresponding to the HSE tests.

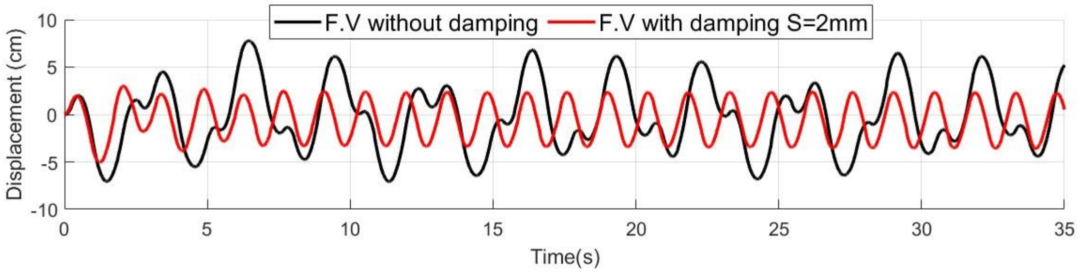


Figure 3. Time series of displacement response in free vibrations.

Analyzing these results, the effectiveness in the reduction of displacements with the application of the eddy current damping system is verified. According to these results, a 64% reduction is presented for the $2mm$ separation. This section enabled to verify the efficiency of eddy currents in the reduction of the displacements in the isolator under harmonic seismic excitation conditions. All of this in an experimental context. In a later phase of this study, the numerical correlation will be included considering the parameters identified in the FV tests described in section 4.2.

4 Characterization of the dynamic model of the isolation coupled to the damping system

4.1 Equation of motion

To characterize the dynamic behavior of the seismic isolator coupled with the damping system, this study considers the equations formulated by Ortiz-Cano et al. [15]. According to that research work, the motion of an isolator made up of roller supports, coupled to a damping system and subjected to a seismic excitation, is governed by the nonlinear second order differential equation, Eq. (1), in which m represents the mass applied on the roller seismic isolation bearing; u, $\dot{u}$, $\ddot{u}$, displacement, velocity and acceleration of the isolator, respectively. In addition, f_s , f_{Dr} and f_{Ds} correspond to the self-centering force, roller friction force and eddy current induced damping force. Finally, the seismic excitation is represented by the term $\ddot{u}_g$.

$$m\ddot{u} + f_s sign(u) + f_{Dr} sign(\dot{u}) + f_{Ds} sign(\dot{u}) = -m\ddot{u}_g \tag{1}$$

In the equation of motion (1) the magnitude of the self-centering forces f_s and roller friction force f_{Dr} can be calculated with equations (2) and (3).

$$f_s = 0.5mg\, sin\, \theta \tag{2}$$

$$f_{Dr} = \mu_r m_1 g \tag{3}$$

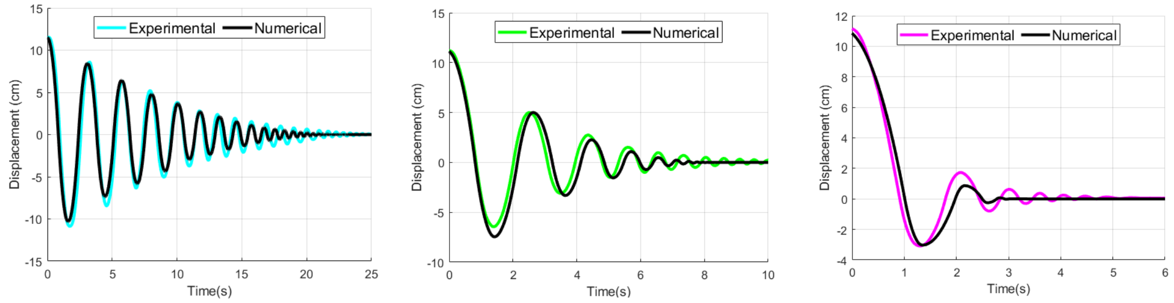
In these equations, g represents the acceleration of gravity, θ the angle of inclination of the bearing surfaces, μ_r coefficient of roller friction. On the other hand, the function sign present in Eq. (1), corresponds to a continuum function proposed by Ortiz-Cano et al. [15] that allows to reduce the computational cost and maintain numerical stability when solving the equation of motion with conventional numerical integration methods. This function defined by sections is established with Eq. (4), where d refers to the yield displacement, which indicates the movement of the roller supports around the vertex where the inclined surfaces intersect.

$$Sign(x) = \begin{cases} 1 & if \quad x \geq d \\ x/d & if \quad -d < x < d \\ -1 & if \quad x \leq -d \end{cases} \tag{4}$$

4.2 Validation of the dynamic model of the isolator coupled to the damping system

To validate the dynamic model of the roller support isolation system coupled to the eddy current damping system, we solved by numerical integration the equation of motion, Eq. (1), the solution of the nonlinear second order differential equation was solved considering the experimental conditions formulated in section 3 of this paper. The ODE45 integrator in a Matlab® programming environment was implemented for this purpose.

The first validation of the dynamic model of the isolator was performed under FV conditions without eddy current damping. In this sense, the rolling friction coefficient and the yield displacement were calibrated by comparing the experimental displacement response of the isolator and the numerical response. Fig. 4 (a) shows the correlation of results. To obtain the numerical displacement, the following parameters were considered $m = 2.536\,kg$, $\mu = 0.00219601$, $d = 0.185\text{x}10^{-3}m$, $\theta = 4°$, $u_0 = 0.1151m$, $v_0 = 0\,m/s$, $g = 9.81\,m/s^2$, $\ddot{u}_g = 0\,m/s^2$.



(a) Roller seismic isolation bearings without damping system

(b) Roller seismic isolation bearings with damping system S=6mm

(c) Roller seismic isolation bearings with damping system S=2mm

Figure 4. Numerical and experimental displacement (Free vibrations conditions)

The second validation of the dynamic model is presented with the numerical correlation of the isolator coupled to the damping system with $6mm$ and $2mm$ spacings. This validation phase allowed to identify the magnitude of the damping force f_{Ds} imposed by the dissipation system constituted by the eddy currents. The adjustment of the displacement response was determined by considering the magnitudes$f_{Ds} = 0.156\,N$ for the damping system with a separation of $6mm$ and $f_{Ds} = 0.534\,N$ for a separation of $2mm$. In addition, the parameters $m = 2.98\,kg$, $\mu = 0.001096$, $d = 0.925\text{x}10^{-4}m$, $\theta = 4°$, $u_0 = 0.112m$, $v_0 = 0\,m/s$, $g = 9.81\,m/s^2$, $\ddot{u}_g = 0\,m/s^2$ were considered.

The difference in mass with the first validation is explained by the increase in mass with the installation of the magnetic system. On the other hand, the adjustment in the friction coefficient μ and in the yielding displacement d were necessary, since the rolling conditions of the supports were modified by the raise of the mass applied on the isolation system.

The excellent correlation of the results shown in Fig. 4 indicates that the dynamic behavior of the isolation system with and without the damping system is represented by the equations of motion, Eq. (1)-(4), however, some differences are present in the transition of the roller supports (vertex of the inclined surfaces), this could be improved with the provision of a smooth transition surface. For the case of the damping system with 2 mm gap, the test should be improved by further control of the spacing distance.

5 Conclusions

This research work analyzes a roller seismic isolation bearing coupled to an eddy current damping system under conditions of free vibration and seismic excitation. According to the experimental results and the numerical correlation, the following conclusions were obtained:

1. The use of eddy currents as a damping system mechanism reduces the horizontal displacements of the roller bearing isolator. With proper design of the magnetic system separation from the conductor, it is possible to maintain dynamic behavior in the underdamped vibration range.
2. The excellent correlation of the dynamic response of the isolator with and without the damping system under free vibration conditions allows us to conclude that the experimental and numerical analysis methodologies are appropriate in the characterization of the isolator system.
3. The dynamic behavior of the isolator system is represented by the equations of motion presented in section 4, however, the construction of the isolator prototype in the transition zone of the inclined surfaces should be improved.
4. According to the setting of the design parameters of the isolation system, we estimate a magnitude of the damping force at 0.16N and 0.53N, for conductor separations of 6 mm and 2 mm, respectively.
5. According to the results of this study, the eddy current damping system is viable for use in seismic isolation systems, however, we suggest adding other studies where higher power magnetic systems are tested and including a numerical analysis under real earthquake recording conditions.

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