Experimental Evaluation of the Performance of a Nonlinear Dual-Mode Vibration Isolator/Absorber System

Puthynan Bin and P. Scott Harvey Jr.

School of Civil Engineering & Environmental Science
Gallogly College of Engineering
University of Oklahoma, 202 W. Boyd St., Norman, OK 73019

ABSTRACT

Floor isolation systems (FISs) are used to mitigate earthquake-induced damage to sensitive building contents and equipment. Traditionally, the isolated floor and the primary building structure (PS) are analyzed independently, assuming the PS response is uncoupled from the FIS response. Dynamic coupling may be non-negligible when nonlinearities are present under large deflections at strong disturbance levels. This study investigates a multi-functional FIS that functions primarily as an isolator (i.e., attenuating total acceleration sustained by the isolated equipment) at low-to-moderate disturbance levels, and then passively adapt under strong disturbances to function as a nonlinear (vibro-impact) dynamic vibration absorbers to protect the PS (i.e., reducing inter-story drifts). The FIS, therefore, functions as a dual-model vibration isolator/absorber system, with displacement-dependent response adaptation. A scale experimental model—consisting of a three-story frame and an isolated mass—is used to demonstrate and evaluate the design methodology via shake table tests. The properties of the 3D-printed rolling pendulum (RP) bearing, the seismic gap, and the impact mechanism are optimized to achieve the desired dual-mode performance. A suite of four ground motions with varying spectral qualities are used, and their amplitudes are scaled to represent various hazards—from service level earthquake (SLE), to design basis earthquake (DBE), and even maximum considered earthquake (MCE). The performance of the multi-functional FIS is established and is described in this paper.

Keywords: vibration isolation, vibration absorption, TMD, energy sink

INTRODUCTION

Isolation systems have shown promise for suppressing and controlling the total transferred acceleration to buildings and their contents. The basic premise behind seismic isolation is to elongate the natural period, which results in larger displacements and smaller accelerations. This reduction of acceleration results in the reduction of downtime and uninterrupted operation of mission-critical facilities, which indirectly improve the resilience of the serving community. To date, several approaches to protecting equipment housed in buildings have been used: (1) using base isolation of the entire building to elongate the natural period of building [1]; (2) isolating an object or equipment housed inside a building or industrial facilities [2]; and (3) isolating a group of objects or a floor inside a building [3]. This study focuses on the third approach, in particular floor isolation systems (FISs).

An alternative solution for vibration mitigation is the tuned mass damper (TMD). This type of vibration absorber consisting of a mass that is connected to the primary structure through a spring and/or a dashpot. Linear TMDs' application is usually limited by its constant natural frequency. That is, only one targeted mode can be considered for suppression. The vibration of the primary structure dissipates due to the resonant of the TMD at the tuned frequency. On the other hand, nonlinear TMDs are able to be tuned for a broader frequency range in the vicinity of the targeted frequency. Recently, nonlinear TMDs with hardening gained attention as energy pumping devices (i.e., nonlinear energy sink) [4, 5].

Both FISs and vibration absorbers involve a secondary system supported by the primary structure (PS), but these two approaches differ in their function. FISs protect the isolated objects, whereas vibration absorbers protect the supporting PS. In this study, these two concepts are merged in a nonlinear dual-mode vibration isolator/absorber system. The same system is used to act as a vibration isolator when the PS motion is small, and as a vibration absorber when the PS motion is large. The transition is achieved by an impact, and the system is experimentally investigated in this study.

COUPLED EQUATIONS OF MOTION FOR PS-FIS SYSTEM

The FIS horizontal force is formulated using a Lagrange multiplier approach and derived as

$$f_{\mathrm{FIS}} = \mu N \frac{1}{\sqrt{1 + [h'(u)]^2}} Z(t) + k_c u(t)[1 - u_o/|u(t)|] + N \frac{h'(u)}{\sqrt{1 + [h'(u)]^2}} \tag{1}$$

where

$$\dot{Z}(t) = \dot{u}(t)\sqrt{1 + [h'(u)]^2}\{A - [\beta(Z(t)\dot{u}(t)) + \gamma]\,|Z(t)|^n\}/s_y \tag{2}$$

The first term in Eq. (1) is the frictional component of the FIS force where μ is the friction coefficient between the roller bearing and the curved track. Circular elevation profile is denoted by $h(u)$ and is given by $h(u) = R - \sqrt{R^2 - u^2}$ where R is the radius of curvature and u is the horizontal displacement. The normal force, N, changes depending on the displacement $u(t)$ of the FIS. The dimensionless hysteretic parameter $Z(t)$ is described by the nonlinear differential equation shown in Eq. (2) where A, β, γ, and n are Bouc-Wen parameters taken to be 1, 1/2, 1/2, and 3.2 respectively in this study, and s_y denotes the yield displacement of the FIS. The second term comes from the elastic impact force when FIS displacement exceeds its displacement capacity. Parameter k_c denotes the contact stiffness and u_o is a seismic gap allowing FIS to displace without impact. The last term corresponds to the restoring force of the FIS.

In this experimental study, the PS is a three-story shear building, which can be modeled as a 3 degree of freedom (DOF) system with the equation of motion as shown:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = -\mathbf{M}\mathbf{1}\ddot{u}_g(t) \tag{3}$$

where $\mathbf{x}(t)$ is the floor level's horizontal displacement and $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are 3×3 mass, Rayleigh damping, and stiffness matrices, respectively. Vector $\mathbf{1}$ distributes the force coming from the horizontal ground acceleration $\ddot{u}_g(t)$ to each of the floors. The total acceleration of the floor at the isolation system's location is given by $\ddot{x}^t(t) = \mathbf{p}^{\mathrm{T}}(\ddot{\mathbf{x}}(t) + \mathbf{1}\ddot{u}_{\mathrm{g}}(t))$ where $\mathbf{p}$ is a vector identifying the position of the FIS on the structure.

With the force of the FIS shown in Eq. (1), the dynamics of the coupled PS-FIS system is given by

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = -\mathbf{M}\mathbf{1}\ddot{u}_{\mathrm{g}}(t) + \mathbf{p}f_{\mathrm{FIS}}(u, \dot{u}, \ddot{u}) \tag{4a}$$

$$m\ddot{u}(t) + f_{\mathrm{FIS}}(u, \dot{u}, \ddot{u}) = -m\mathbf{p}^{\mathrm{T}}(\ddot{\mathbf{x}}(t) + \mathbf{1}\ddot{u}_{\mathrm{g}}(t)) \tag{4b}$$

Thus, Equations (1), (2), and (4) can be solved and integrated simultaneously to obtain the quantities of interest, $\mathbf{x}(t)$ and $u(t)$.

PERFORMANCE OPTIMIZATION CRITERIA

To optimize the performance of this dual-mode system, seismic gap (u_o) is the parameter being optimized while contact stiffness (k_c), radius of curvature (R), and friction coefficient (μ) are set constant. Other parameters such as FIS location and mass, along with PS properties, are also fixed quantities. The isolation performance is evaluated based on the peak total acceleration transmitted from the floor, in which the FIS is attached, to the isolated content. The vibration absorption performance is evaluated based on the peak inter-story drift of the PS. Thus, the optimization criteria are set based on two objective functions as defined below:

$$J_{\mathrm{FIS}} = \max_{\text{SLE-scaled GMs}} \frac{|a_{\mathrm{FIS}}|}{a_2} \tag{5}$$

$$J_{\mathrm{PS}} = \max_{\text{DBE-scaled GMs}} \frac{\delta_{\max}^{\text{controlled}}}{\delta_{\max}^{\text{uncontrolled}}} \tag{6}$$

where

$$\delta_{\max} = \max_{\text{GMs}} \max_{i=1,2,3} \max_{t} |d_i(t)/h_i| \tag{7}$$

where $d_i(t)$ is the inter-story drift in the ith story, and h_i is the height of the associated story. Total acceleration of the FIS and the second floor (on which the FIS is installed) are denoted as a_{FIS} and a_2, respectively.

Four historic ground motions (GMs) – Elcentro, Hachinohe, Kobe and Northridge – are used in this experiment. They are scaled in similitude and also scaled to have a spectral acceleration of $0.739g$ at 1 second period. The performance of this system is also considered at three hazard levels—service level earthquake (SLE), design-basis earthquake (DBE) and maximum considered

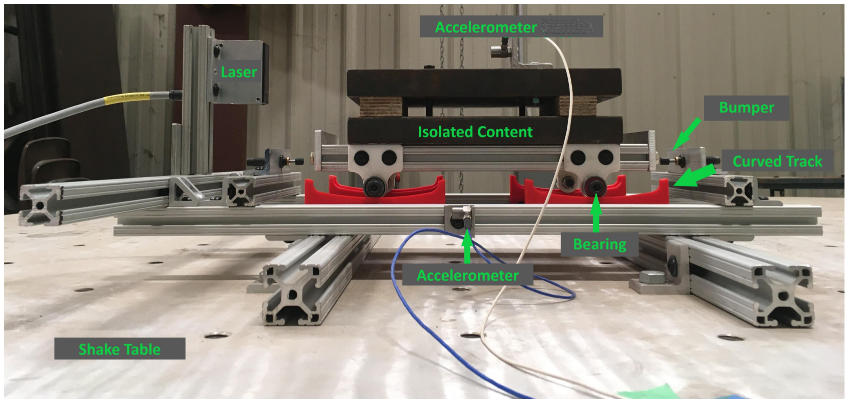

Figure 1: Experimental setup showing the FIS with rolling pendulum bearings.

earthquake (MCE). SLE and MCE are used for the evaluation criterion of the system's performance in isolation and vibration absoprtion respectively. However, MCE is not the main consideration of the optimization, but could potentially be looked at when evaluating J_{PS}.

EXPERIMENTAL SETUP

The PS is a three-stories shear structure with plan dimensions, and a total floor-to-floor height of 31.25 in.. Properties of the PS were obtained from the system identification method, which results in mass and stiffness of the first, second and third floor to be $m_1 = 56.06$ kg, $m_2 = 56.29$ kg, $m_3 = 56.20$ kg, $k_1 = 112.83$ N/mm, $k_2 = 135.64$ N/mm, and $k_3 = 158.35$ N/mm. Damping ratios in the first, second and third mode were also identified to be $\zeta_1 = 0.1\%$, $\zeta_2 = 0.1\%$, and $\zeta_3 = 0.2\%$. The FIS is characterized from the displacement and acceleration response of a sine sweep test with the setup shown in Figure 1. Bumpers are placed on both sides of the system to provide smooth elastic impact when the system's displacement exceeds its capacity.

The experimentation conducted to study the dual-mode performance of the FIS is still in progress. The setup shown in the figure is to be installed on the second floor the PS. A total of five accelerometers are each to be installed on the shake table, first floor, second floor, third floor, and the isolated content to measure the acceleration response when the structure is subjected to the above-mentioned earthquakes. Cameras are also installed on the underside of the floor decks to measure the inter-story drift of each story. After optimal gap values are obtained from the optimization, bumpers will be easily moved along the rail to the design gap. Within this range, the FIS is expected to exhibit an isolation behaviour (low accelerations). When high intensity ground motion causes the FIS to move above its displacement capacity, the system will hit the bumper and dissipate energy. During impacting regimes, the FIS is expected to behave as a vibration absorber (low inter-story drifts).

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