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Nonlinear damping based semi-active building isolation system

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ABSTRACT

Many buildings in Japan currently have a base-isolation system with a low stiffness that is designed to shift the natural frequency of the building below the frequencies of the ground motion due to earthquakes. However, the ground motion observed during the 2011 Tohoku earthquake contained strong long-period waves that lasted for a record length of 3 min. To provide a novel and better solution against the long-period waves while maintaining the performance of the standard isolation range, the exploitation of the characteristics of nonlinear damping is proposed in this paper. This is motivated by previous studies of the authors, which have demonstrated that nonlinear damping can achieve desired performance over both low and high frequency regions and the optimal nonlinear damping force can be realized by closed loop controlled semi-active dampers. Simulation results have shown strong vibration isolation performance on a building model with identified parameters and have indicated that nonlinear damping can achieve low acceleration transmissibilities round the structural natural frequency as well as the higher ground motion frequencies that have been frequently observed during most earthquakes in Japan. In addition, physical building model based laboratory experiments are also conducted, The results demonstrate the advantages of the proposed nonlinear damping technologies over both traditional linear damping and more advanced Linear-Quadratic Gaussian (LQG) feedback control which have been used in practice to address building isolation system design and implementation problems. In comparison with the tuned-mass damper and other active control methods, the proposed solution offers a more pragmatic, low-cost, robust and effective alternative that can be readily installed into the base-isolation system of most buildings.

1. Introduction

Traditional building base-isolation systems are designed to shift the structural resonant frequencies to a range that is well below the frequencies of ground motions during earthquakes [1,2]. To ensure a significant reduction of vibration transmitted to a building over the isolation range which covers the frequencies of the estimated earthquake ground motions, low

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horizontal-stiffness bearings are fitted into the isolation layer of the building. The current building regulations in Japan place limits on the design response spectrum with respect to the ground motion for a duration of up to 60 s. However, during the most severe earthquake in Japanese records that occurred off the Pacific coast of Tohoku in 2011, strong ground motions with a very long period lasted for about 3 min. Although the current seismic protection systems performed reasonably well during the Tohoku earthquake as described in Ref. [3], structural engineers are becoming more vigilant towards the potential damage that the long-period waves may cause in the future. Since the occurrence of this unprecedented earthquake, greater emphasis has naturally been placed to the building response to these long-period waves in future seismic protection designs.

To reduce the building vibration, a wide range of active control techniques have been discussed in Refs. [4,5]. In all these cases, the controller, designed by various methods such as classical and optimal control, deliver control signals to the actuators that apply forces to the structure. One major drawback of active control in structural protection is the large power consumption that leads to a high maintenance cost. Stability could be a concern when energy is added to the system. In contrast, passive control designs do not draw any external power and do not affect the system stability. For example, a conventional passive solution is to introduce damping into the isolation system to suppress the impact of the long-period waves.

However, the intrinsic properties of linear damping inevitably lead to a compromised performance over the higher frequencies which unfortunately overlap the frequency range of the ground motions observed during most earthquakes in Japan [6]. Recently, the authors have exploited the special characteristics of nonlinear damping [7,8] to create a vibration isolation system that has low transmissibilities over both low and high frequencies [9–11]. As buildings in Japan now require base-isolation systems that can reduce the effects of ground motion with frequencies in the traditional isolation range, which is usually a frequency range over $\sqrt{2}$ times building major resonance frequency, as well as lower frequencies around the resonant regions (about 0.2–0.4 Hz in Japan), the introduction of nonlinear damping would be hugely beneficial.

This paper presents the realization of nonlinear damping using valve-controlled semi-active dampers in a building base-isolation system to protect the building against lateral vibration caused by the long-period waves while maintaining sufficient isolation over the higher frequency spectrum of most of the historical earthquakes ground motions. Although applicable to other multi-storey buildings, the analysis and simulation results presented in this paper are based on the nine-storey Sosokan Building at Keio University. Currently, the building is protected by an optimal control system implemented by semi-active dampers [12]. The solution proposed in this paper offers an alternative method that only requires a software update without any hardware changes. In addition to the numerical model based simulation studies, the laboratory experimental studies on a two storey physical building model are also conducted. The experimental results confirm the results of the numerical simulation studies and demonstrate the advantages of the proposed nonlinear damping technologies over traditional linear damping as well as currently operating LQG feedback control.

The paper is arranged as follows. In Section 3, control methods developed for electrorheological dampers [13,14] are applied to the semi-active dampers to realize the designed nonlinear damping function [15]. The closed-loop controlled semi-active dampers are then incorporated into the building model under a single-tone sinusoidal ground excitation in Section 4. Comparisons between the transmissibility curves of a linearly and nonlinearly damped base-isolation system confirm the theoretical advantages of nonlinear damping in a vibration control application. The simulation results of the proposed system are also shown against the current control system operating in the Sosokan Building that is based on a LQG design. In Section 5, the set-up of the laboratory experiments is introduced. The experimental results and the advantages of nonlinear damping technologies over other techniques are discussed. Finally, conclusions are drawn in Section 6.

2. Semi-active damping system for the Sosokan Building

2.1. The Sosokan Building and its model representation

Sosokan, a symbolic nine-storey tower located in the Yagami campus of Keio University, was completed in 2000. Its isolation layer under B2F, is composed of sixty-five laminated rubber bearings, one set of twelve passive hydraulic dampers and four semi-active dampers oriented horizontally in the east-west direction and another identical set of dampers in the north-south direction. The lateral dynamics of the building subject to the horizontal ground acceleration as shown in Fig. 1 can be modelled by a system of mass-spring-damper in series given by

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{E}\mathrm{u} + \mathbf{F}\ddot{\mathrm{z}} \tag{1}$$

where u represents the force of the semi-active damper,

$$\mathbf{x} = [x_1, x_2, x_3, \ldots, x_{10}]^{\mathrm{T}} \tag{2}$$

$$\mathbf{M} = \mathrm{diag}[m_1, m_2, m_3, \ldots, m_{10}] \tag{3}$$