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A new performance index of LQR for combination of passive base isolation and active structural control

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ABSTRACT

This paper considers the problem of designing a state-feedback controller with both passive base isolation (PBI) and active structural control (ASC). In order to improve control performance, state-feedback gains are designed based on the linear quadratic regulator (LQR) method that optimizes a new performance index containing absolute acceleration, and inter-story drifts and velocity. Simulations on a model of an eleven degree-of-freedom shear building for four earthquake accelerograms are used to verify this method. Comparison studies show that, compared with PBI, the combination of PBI and ASC improves control performance; and this method yields better control results than the conventional ASC, which considers relative displacement and relative velocity of each story. The results are also discussed from the viewpoint of control system structure regarding the location of system zeros. In addition, the effect of weights in the LQR on control performance is discussed. A method for selecting the weights is presented by using the infinity norm of a system as a criterion to visualize their effect.

1. Introduction

Passive base isolation (PBI) installed in buildings not only suppresses vibrations, but also ensures safe use of the buildings after earthquakes [1,2]. The Kobe earthquake on January 17, 1995 triggered a demand for PBI in Japan, and the number of passive-base-isolated high-rise buildings has been steadily increasing in the last two decades [3].

A new base isolation system called a rubber-layer rolling bearing was presented in [4,5].

As the installation of PBI enlarges the natural period of a building, it results in a reduction in the absolute acceleration of buildings. However, it increases displacement of the PBI story and may force it beyond its allowable range.

Some aluminum or steel devices were also used as passive energy dissipating systems for a building to suppress the displacement [6–8]. If a building employs these kinds of devices, its stiffness increases and the natural period becomes short. This may increases the absolute acceleration of the building.

Active structural control (ASC) is a strategy for vibration reduction that incorporates control engineering and civil engineering. The first full-scale ASC in the world was installed in the Kyobashi Center Building in 1989 in Japan. Studies in this field have been showing rapid progress since then, and ASC is now widely used in civil structures all over the world [9,10].

The linear-quadratic regulator (LQR) is one of the most commonly used design methods in control theory. It designs a state-feedback gain by minimizing a performance index that considers the weighted state and control input of a plant. This method has been used in the design of ASC and semi-active structural control systems. Loh at el. conducted an experiment using a real-scale active tendon to demonstrate the validity of ASC [11].

The selection of a performance index for the LQR is a key to designing a satisfactory ASC system. While most studies selected relative displacement and velocity of each story [12–15], some studies considered kinetic energy [16,17], inter-story drifts [18,19], or absolute acceleration [19,20]. In the structural control of a building, suppressing inter-story drifts prevents the exfoliation of exterior materials and the plastic behavior of a building. On the other hand, suppressing absolute acceleration not only protects a building by reducing story shear-force from an earthquake, but also protects people and property by preventing things such as furniture and equipment inside the facility from falling. Thus, it is important to build a performance index that considers the inter-story drifts, the relative velocity, and the absolute acceleration of all stories of a building for the design of a practical ASC system. A new performance index that contains those items is presented in this

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paper.

The method utilized to weights to integrate evaluation items in a performance index is also an important issue for system design. However, only few attempts have so far been made to accomplish it such methods. Most studies selected weights rather subjectively and determined them by trial and error [12]. Regarding this issue in structural control, a study examined the effect of different weights for a single-degree-of-freedom system [21]. However, buildings are usually multi-degree-of-freedom (MDOF) systems. Therefore, it is of practical value to investigate weight selection for an MDOF system.

PBI enlarges the natural period. This may result in a large displacement. On the other hand, ASC generally increases the apparent stiffness of a building by suppressing the displacement. It shortens the apparent natural period, and may cause a large absolute acceleration. Thus, a good combination of PBI and ASC provides satisfactory structural control performance with small control energy. Focusing on this characteristic, this paper considers the problem of structural control using the combination of PBI and ASC for high-rise buildings. A new performance index is used to design a suitable ASC system. The superiority of the method over PBI or conventional ASC is demonstrated through simulations, and the analysis of control inputs and the control system structure.

In this paper, I is an identity matrix with appropriate dimension. For simplicity, a system only with PBI is called NC (no control); a conventional ASC system that minimizes the displacement and velocity of each story is called a conventional LQR; and an ASC system that minimizes the absolute acceleration, and inter-story drift and velocity of each story presented in this paper is called AD-LQR for short.

2. Structures and base-isolation models

This study used three building models with heights of 250 m, 150 m, and 50 m. The floor areas of the models were all 40 m× 40 m (Fig. 1). Each was described as a 10-DOF shear building model (Fig. 2). PBI was installed under the structure. The ASC device was located at the PBI story. Thus, the models have 11 DOFs (10 DOFs for the superstructure and 1 DOF for the base isolation).

The parameters are as follows (Fig. 1):

Mass per unit area of base isolation: 2551 kg/m^2.
Damping for period of PBI (ζ_b): 0.05.
Damping of superstructure: stiffness-proportional damping model (the damping ratio for the first mode, ζ_u, is assumed to be 0.02).
Natural periods of superstructure of first mode (T_u): 1.0 s for the 50-m-high building, 3.0 s for the 150-m-high building, and 5.0 s for the 250-m-high building.
Density of superstructure (for all floors): 175 kg/m^3.
Height of superstructure (h_u): = T_u/0.02 m.
Stiffness of the *i*-th story of superstructure [22]:

$$\begin{cases} k_i = \dfrac{\omega^2 m_i \phi_i + k_{i+1}(\phi_{i+1} - \phi_i)}{\phi_i - \phi_{i-1}}, \quad i = 2,\dots,9, \\ k_1 = \dfrac{\omega^2 m_1 \phi_1 + k_2(\phi_2 - \phi_1)}{\phi_1}, \qquad k_{10} = \dfrac{\omega^2 m_{10}\phi_{10}}{\phi_{10} - \phi_9}, \end{cases} \tag{1}$$

where ω is the first natural circular frequency; and for the i-th story (i = 1,2,…,10), ϕ_i is the first natural mode, and m_i is the mass.

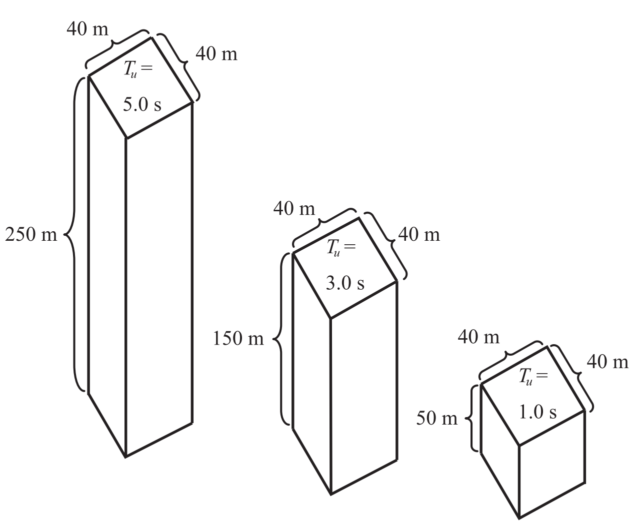

Fig. 1. Models of structures.

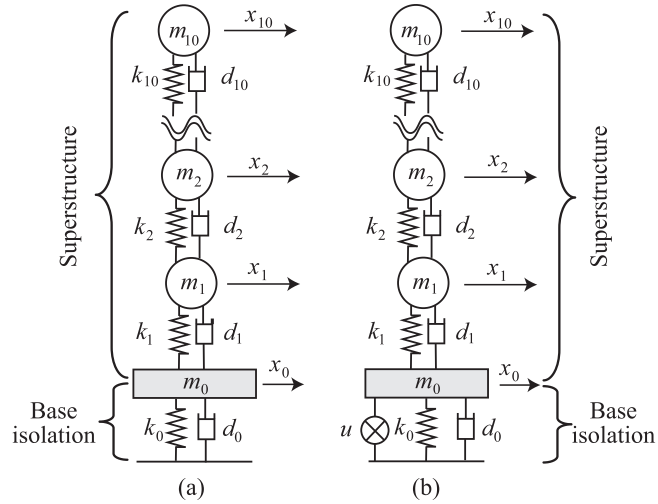

Fig. 2. 11-DOF model of [(a) NC and (b) LQR or AD-LQR].

To use the LQR method, which is a linear control strategy [27], the laminated rubber in the PBI is modeled as a linear spring (Fig. 3), and the viscous damper in the PBI is modeled as a linear dashpot (Fig. 4). The stiffness, k_0, and the damping coefficient, d_0, of the PBI are given by

$$k_0 = \frac{4\pi^2(m_u + m_0)}{T_0^2}, \quad d_0 = 2\zeta_b\sqrt{(m_u + m_0)k_0}, \tag{2}$$

respectively, where m_u is the total mass of the superstructure; and m_0 is given by the product of the density of the base and the floor area.

Let T_0 be the period of the PBI with the superstructure being assumed to be a rigid body. The combinations of the parameters of buildings (Table 1) are used to verify the validity of the method presented in this paper and to perform a comparison with other methods. In the table, T is the period of the first mode of the building with the base isolation.

3. Design of LQR controllers

The dynamics of an 11-DOF building with an ASC device and the PBI are described by

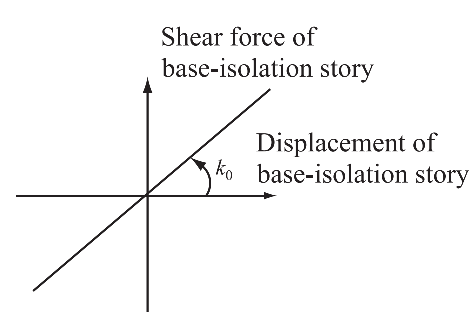

Fig. 3. Linear spring model of laminated rubber.