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Dynamic output feedback control for seismic-excited buildings

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ABSTRACT

This paper deals with the $\mathcal{H}_\infty$ dynamic output feedback control problem of a seismic-excited building. The control aims to reduce the vibration of a building caused by an earthquake. Instead of system states, the system output measurements are used to design suitable $\mathcal{H}_\infty$ controllers. Depending on whether the system measurements are sampled or not, two kinds of dynamic output feedback control schemes are investigated. By the Lyapunov stability theory, some bounded real lemmas are formulated such that the closed-loop system is asymptotically stable and achieves a prescribed $\mathcal{H}_\infty$ disturbance attenuation level. The cone complementary algorithm is employed to design $\mathcal{H}_\infty$ controllers based on a solution to a nonlinear minimization problem subject to a set of linear matrix inequalities. Finally, a three-storey building model is given to show the effectiveness of the proposed method.

1. Introduction

An earthquake is a natural disaster that usually causes serious damage and destruction of buildings. Thus, it is important to develop effective methods of construction against earthquakes, especially for high-rise buildings due to their inherent susceptibility from earthquakes. Up to date, several methods are proposed to protect buildings against earthquakes, which can be classified into three categories: passive control, semi-active control, and active control. Tuned-mass-dampers (TMD), base isolations, friction and viscous dampers, and structural energy dissipation devises are some examples of passive control techniques [1–5]. Changing the structural parameters such as damping and stiffness is a kind of semi-active control technique [6–8]. Pumping energy to structure by using appropriate actuators is regarded as an active control method [9–11]. Since the effectiveness, this paper focuses on developing an active control method against earthquakes.

The active control of structures was first implemented in Kyobashi Center Building in 1989. Since then, several active control methods are proposed, e.g., for vibration control of buildings [9–14]. Active controllers are designed usually using optimal control methods [7,15,16], robust control methods for the structures in presence of structured and unstructured uncertainties [17–19], and intelligent control methods based on neural networks and fuzzy systems [13,20–22]. Classical control methods such as PID control and sliding mode control are also used to design active controllers [22–24]. The $\mathcal{H}_\infty$ control method is a well-known optimal control strategy that has been used for many years as well as applied for active control of building structures [25–27]. It is worth pointing out that earthquakes have finite frequency spectrum characters, based on which, $\mathcal{H}_\infty$ control for buildings under earthquake excitation is studied [28]. Moreover, active fault tolerant control of buildings is also investigated for seismic loads in finite frequency domain, and recently, equivalent-input-disturbance and energy-to-peak control of structures are proposed [29–31]. However, most methods mentioned above are based on such an assumption that the system state is

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available. This assumption cannot be satisfied for some practical systems due to that only measurement outputs can be used for control design. Thus, it is significant to develop an effective method to design output feedback controllers, especially in the case where system states are not available, which motivates the present study.

In general, there are two ways for measurement signals to be transmitted from a building to a controller: analog signal transmission and digital signal transmission [32–34]. Traditionally, analog signal transmission requires wirings to connect a building to a controller. When the building and the controller are located in the same place, analog signal transmission is a good way to transmit signals from the building to the controller continuously such that some better closed-loop performance can be achieved. However, it is possible that the building and the controller are not located at the same place due to the fact that nobody knows which buildings will suffer earthquakes when earthquakes happen. In this situation, digital signal transmission comes to the fore, in which measurement signals are sampled first in a digital form and then transmitted to the controller through a communication network. Compared with analog signal transmission, digital signal transmission has several advantages, such as no wirings, high reliability, high signal-to-noise ratio (SNR) and suitability for sending data to long distances [35,36]. With the rapid development of communication technology, modern industrial applications are based on digital signal transmission rather than analog signal transmission.

In this paper, two kinds of dynamic output feedback control schemes are investigated for seismic-excited buildings. When the building and the controller are located at the same place, a continuous-signal-based dynamic output feedback control scheme is devised using analog signal transmission. When the building and the controller are located at different places, a sampled-data-based dynamic output feedback control scheme is presented with digital signal transmission. By employing Lyapunov-Krasovskii stability theory, some sufficient conditions on the existence of suitable dynamic output feedback controllers are derived in terms of the solution to a nonlinear minimization problem subject to linear matrix inequalities. Simulation results demonstrate the effectiveness of the proposed control schemes.

This paper is organized as follows. Section 2 describes the dynamic model of n-DOF seismic-excited building. Some useful lemmas are also provided in this section. Two methods are presented in Section 3 to design suitable dynamic output feedback controllers. The simulation results and some comparison with other methods are given in Section 4. Section 5 concludes the paper, and the proofs of theorems proposed in this paper are provided in Appendix.

Notations. The notation in this paper is standard. A symmetric term in a symmetric matrix is denoted by *.

2. Problem statement

Consider a typical n-DOF building model shown in Fig. 1 [34]. The motion equations of the seismic-excited building can be obtained by the Newton's second law, which is given as

$$\mathbf{M}_0\ddot{\mathbf{q}}(t) + \mathbf{C}_0\dot{\mathbf{q}}(t) + \mathbf{K}_0\mathbf{q}(t) = \mathbf{H}_0\mathbf{u}(t) + \xi_0\ddot{x}_g(t), \tag{1}$$

where $\mathbf{q}(t) = \mathrm{col}\{q_1(t), q_2(t), \dots, q_n(t)\} \in \mathbb{R}^n$ denotes the inter-storey relative drift vector between the floors, and $q_i(t)$ is the relative drift between the ith and the $(i-1)$th floor; $\mathbf{u}(t) = \mathrm{col}\{u_1(t), u_2(t), \dots, u_n(t)\} \in \mathbb{R}^n$ is the control force vector produced by n actuators, with each of them installed at the bottom of each storey; $\ddot{x}_g(t) \in \mathbb{R}$ represents the ground acceleration caused by the earthquake. $\mathbf{H}_0$ is an $n \times n$ real matrix; and the matrices $\mathbf{M}_0$, $\mathbf{C}_0$, $\mathbf{K}_0$ and the vector $\boldsymbol{\xi}_0$ are given by

$$\mathbf{M}_0 = \begin{bmatrix} m_1 & 0 & 0 & \cdots & 0 \\ m_2 & m_2 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \ddots & \vdots \\ m_{n-1} & m_{n-1} & m_{n-1} & \ddots & 0 \\ m_n & m_n & m_n & \cdots & m_n \end{bmatrix}, \quad \mathbf{C}_0 = \begin{bmatrix} c_1 & -c_2 & 0 & \cdots & 0 \\ 0 & c_2 & -c_3 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ \vdots & & \ddots & c_{n-1} & -c_n \\ 0 & \cdots & \cdots & 0 & c_n \end{bmatrix}$$

$$\mathbf{K}_0 = \begin{bmatrix} k_1 & -k_2 & 0 & \cdots & 0 \\ 0 & k_2 & -k_3 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ \vdots & & \ddots & k_{n-1} & -k_n \\ 0 & \cdots & \cdots & 0 & k_n \end{bmatrix}, \quad \xi_0 = \begin{bmatrix} -m_1 \\ -m_2 \\ \vdots \\ -m_n \end{bmatrix}$$

where the parameters m_i, c_i, and k_i, $(i = 1,2, \dots, n)$ are the mass, damping, and stiffness of each storey, respectively.

Let $\mathbf{x}(t) = \mathrm{col}\{\mathbf{q}(t), \dot{\mathbf{q}}(t)\}$ and $w(t) = \ddot{x}_g(t)$. Then the state space representation of (1) can be given as

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{F}w(t), \tag{2}$$

where

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}_0^{-1}\mathbf{K}_0 & -\mathbf{M}_0^{-1}\mathbf{C}_0 \end{bmatrix}, \ \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}_0^{-1}\mathbf{H}_0 \end{bmatrix}, \ \mathbf{F} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}_0^{-1}\xi_0 \end{bmatrix}$$