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Energy-to-peak performance controller design for building via static output feedback under consideration of actuator saturation

Haiping Du [a,*], James Lam [b]

[a] Control and Power Group, Department of Electrical & Electronic Engineering, Imperial College London, Exhibition Road, London SW7 2AZ, UK
[b] Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong

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Abstract

The paper presents a static output feedback controller design approach for seismic-excited structures. An energy-to-peak control performance is used and actuator saturation is taken into consideration. By combining the linear matrix inequality (LMI) technique and the random search results of genetic algorithm (GA), a desirable static output feedback controller can be computed. Two building structures under seismic loads are used to validate the effectiveness of the proposed method in reducing the structural vibration. Simulation results also show that the energy-to-peak performance based controller can well realize the peak response suppression requirement and the static output feedback controller can achieve the same level of control performance as that of a full-state feedback controller.

Keywords: Energy-to-peak performance; Saturation; Static output feedback; Structural systems; Vibration control; Genetic algorithms

1. Introduction

Active control of civil engineering structures to reduce the excessive vibration due to strong winds or earthquakes has received considerable attention in recent years [1]. Various control strategies, such as H_2 (LQR) and H_∞ control, neural network control, fuzzy logic control, adaptive control, sliding mode control, independent modal space control etc., have been proposed and developed to attenuate the effects of structural vibration. More recently, the international structural control community has placed a lot of emphases on certain benchmark problems in view of the many issues that must be dealt with before the wide-spread use of active control techniques can be made possible [2]. In response to these challenges, many fundamental problems involving the technical aspects of active control have been studied [2–4].

There is a trend to move toward performance-based control system designs of civil engineering structures [3]. The idea is to guarantee that the performances related to peak response quantities, such as the peak interstorey drifts, peak floor accelerations, peak shear forces, are required to be smaller than some allowable values in the design specifications. Unfortunately, the control theories used for civil engineering structures up to date do not guarantee that the selected peak response quantities to be smaller than specified allowable values except the two control strategies presented in [3]. Simulation results of [3] have shown that the performance-based controllers are very effective in comparison with LQG control method. One of the performance-based control strategy is referred to as the energy-to-peak based control method. The objective is to minimize the peak values of the output for all possible bounded energy disturbances [5,6]. This control strategy is capable of satisfying the design requirements for the peak response quantities.

One issue that is always encountered in controlling civil structures is the actuator saturation problem, which has

* Corresponding author.
E-mail address: h.du@imerial.ac.uk (H. Du).

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been a topic of considerable interest over the past several years [2,4,7–10]. Due to the stochastic nature of seismic and wind loadings, it is conceivable that the required control force may exceed the capacity of the actuator in civil engineering applications, resulting in actuator saturation. Actuator saturation may lead to serious deterioration in the performance of the closed-loop system, and may also lead to instability. Numerous proposed solutions to the actuator saturation problem include the anti-windup technique, Riccati and Lyapunov-type local and semi-global stabilization methods, and absolute stability theory. In some recent papers [2,11–13], methods that can provide guaranteed performance levels and employ large gains of control input are developed. These methods are particularly suitable to structural applications, in which the main objective of the control is to reduce the response (for instance, interstorey drifts) due to the disturbance such as ground motion or wind gusts.

Another issue is concerned with the realization of the controller. Most of the previous studies require full-state feedback or observer-based feedback controllers. In practice, installing sensors to measure the entire state vector is not practical from an implementation standpoint for civil engineering structure control. Moreover, an observer-based controller may require a significant amount of on-line computational effort due to the complexity of the structures, thus resulting system in time delays [14]. Therefore, it is desirable to implement static output feedback control using a limited number of sensors from the standpoints of cost and complexity. Efforts have been made to design static output feedback controllers for civil engineering structures [4,14,15]. However, output feedback controller designs involving fixed order or static gain can be computationally demanding [16,17] although several different approaches based on linear matrix inequalities (LMIs) and other properties of convex analysis [18,19] have been presented. Nevertheless, the genetic algorithms (GAs) are found to be useful in searching possible solutions to this problem [15].

Although performance-based controllers have been investigated for civil engineering structures in [3], only full state feedback is considered and no other practical constraints are imposed. In this paper, the energy-to-peak performance for building structures is shown to be realizable by using static output feedback control in presence of actuator saturation. Sufficient conditions for designing such a controller are given in terms of matrix inequalities based on the preliminary results in [5,12]. Due to nonconvexity, an approach that combines the feasible solutions of linear matrix inequalities (LMIs) with the random search of GAs is developed to find the possible solutions of the static gain matrix. The designed controllers are applied to reduce the vibration of seismic-excited building structures. Simulation results show that in spite of the actuator saturation, the designed static output feedback controllers can achieve peak response performances as good as those using full state feedback.

The rest of this paper is organized as follows. Section 2 gives the problem formulation. The design of the static output feedback controller for the civil engineering structures to achieve energy-to-peak performance under actuator saturation is expressed in terms of matrix inequalities. The procedure that combines the LMIs and GAs to find the possible solutions of the static gain matrix is presented in Section 3. Section 4 provides two illustrative examples to further validate the effectiveness of the approach developed in this paper. Finally, conclusions are given in Section 5.

2. Problem formulation

2.1. Structural motion equation

Consider an n degree-of-freedom (DOF) linear building structure equipped with control system and subject to earthquake excitation, the equation of motion can be written as

$$\overline{M}\ddot{x} + \overline{C}\dot{x} + \overline{K}x = Hu + E\ddot{x}_{\mathrm{g}} \tag{1}$$

where $x = [x_1, x_2, \ldots, x_n]^{\mathrm{T}}$, x_n is the interstorey relative drift of the nth floor; $u = [u_1, u_2, \ldots u_r]^{\mathrm{T}}$, u_r is the rth control force; $H \in \mathbb{R}^{n\times r}$ gives the location of the r controllers; $\ddot{x}_{\mathrm{g}}$ is the earthquake ground acceleration; $E \in \mathbb{R}^n$ is a vector representing the influence of the earthquake excitation; $\overline{M}, \overline{C}, \overline{K} \in \mathbb{R}^{n\times n}$ are the mass, damping, and stiffness matrices of the building, respectively.

Using the state variable $q = [x^{\mathrm{T}} \quad \dot{x}^{\mathrm{T}}]^{\mathrm{T}}$, the system in (1) can be expressed in state space form:

$$\dot{q} = Aq + B_1 w + B_2 u \tag{2}$$

where

$$A = \begin{bmatrix} 0 & I \\ -\overline{M}^{-1}\overline{K} & -\overline{M}^{-1}\overline{C} \end{bmatrix}, \quad B_1 = \begin{bmatrix} 0 \\ \overline{M}^{-1}E \end{bmatrix}, \quad B_2 = \begin{bmatrix} 0 \\ \overline{M}^{-1}H \end{bmatrix}$$

w represents the disturbance (that is, the earthquake ground acceleration $\ddot{x}_{\mathrm{g}}$).

In this paper, for a real vector v, we denote its magnitude by $|v| = \sqrt{v^{\mathrm{T}}v}$. The disturbance signal $w(t)$ is assumed to bounded and with finite energy, that is,

$$\|w\|_\infty = \sup_{t\in[0,\infty)} |w(t)| < \infty$$

$$\|w\|_2 = \sqrt{\int_0^\infty |w(t)|^2 \mathrm{d}t} < \infty$$

2.2. Actuator saturation

When considering the actuator saturation, system (2) is expressed as

$$\begin{aligned} \dot{q} &= Aq + B_1 w + B_2 \mathrm{SAT}(u) \\ z &= C_1 q + D_{12}\mathrm{SAT}(u) \\ y &= C_2 q \end{aligned} \tag{3}$$