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An effective computational design strategy for H_∞ vibration control of large structures with information constraints

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ABSTRACT

In this paper, we present an effective computational strategy to design high-performance decentralized controllers with partial local-state information for vibration control of large building structures. Specifically, the building dynamical model is first decomposed into a set of approximate low-dimensional decoupled subsystems subject to the action of generalized disturbances, which include the effect of external physical disturbances, modeling approximation errors and mechanical subsystem interactions. Next, using the approximate decoupled subsystems, an overall structured state-feedback controller is obtained by designing a proper set of independent local controllers. The proposed computational strategy is applied to obtain two structured control systems for the seismic protection of a 35-story building: (i) a fully decentralized velocity-feedback controller with 35 interstory actuators that can be passively implemented by a set of viscous dampers, and (ii) a decentralized velocity-feedback controller with 15 interstory actuators, which can be implemented with a reduced set of collocated sensors and a system of five independent short-range communication networks. To assess the performance of the obtained structured controllers, the corresponding frequency and time responses are investigated and compared with the responses produced by optimal full-state H_∞ controllers. Moreover, to evaluate the effectiveness of the computational procedure, both structured and full-state controllers are designed for a proper set of buildings with different number of stories and the corresponding computation times are recorded and compared. The obtained results show that the computational cost of the proposed design methodology is remarkably low and also indicate that, despite the severe information constraints, the synthesized structured controllers are practically optimal.

1. Introduction

For vibration control of large structures, the idea of using a distributed control system formed by a large number of smart control devices that work jointly to mitigate the overall vibration response is certainly an appealing concept [1–3]. Considering the current technological means, designing smart control devices that integrate actuation mechanisms, sensors, communication units and computational capabilities is a clearly solvable issue [4,5]. In contrast, designing suitable controllers to drive a large number of such devices is still a challenging and complex open problem, which is characterized by three fundamental elements: large dimensionality, high computational cost and severe information constraints [6–11]. For this kind of problems, design strategies based on linear matrix inequality (LMI) formulations make it possible to compute advanced controllers [12–14]. However, these strategies are only computationally effective in problems of moderate dimension. Moreover, the centralized design of decentralized controllers by setting a particular zero-nonzero pattern on the LMI variables frequently leads to infeasibility issues [15,16].

In this paper, we present a novel controller design methodology for vibration control of large buildings equipped with a distributed system of smart control devices. The main objective is to provide an effective computational strategy to design high-performance decentralized controllers that can operate with partial local-state information. The underlying idea consists in decomposing the overall building model into a set of approximate low-dimensional decoupled subsystems subject to the action of generalized disturbances, which include the effect of physical external excitations, modeling approximation errors and mechanical subsystem interactions. Then, an overall state-feedback structured controller with partial local-state information can be efficiently computed by designing a proper set of independent local state-feedback controllers for the approximate subsystems. To demonstrate

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the effectiveness of the proposed design methodology, two different structured control systems with partial state information are designed for the seismic protection of a 35-story building: (i) a fully decentralized velocity-feedback controller with a complete set of 35 interstory actuators, and (ii) a partially decentralized velocity-feedback controller with an incomplete set of 15 interstory actuation devices implemented at the building bottom levels. The fully decentralized controller admits a passive implementation by means of viscous dampers. This is a simple, robust and reliable solution that can operate without sensors, no communication network and null power consumption [17,18]. The decentralized controller requires an active or semi-active implementation and can operate with a reduced set of 15 interstory-velocity collocated sensors and a system of five independent short-range communication networks. In both cases, local state-feedback H_∞ controllers are designed for the approximate decoupled subsystems and the performance of the overall structured controllers is evaluated by considering the frequency and time-response characteristics, taking as a reference the corresponding active full-state H_∞ controllers. Also, to assess the computational effectiveness of the proposed methodology, the same controller designs are carried out for a set of several building models with different numbers of stories and the corresponding computation times are recorded and compared.

The rest of the paper is organized as follows: In Section 2, the n-story building dynamical model for different actuation schemes is provided. In Section 3, the approximate models for the decoupled subsystems are derived. In Section 4, the structured controllers with partial state information and the reference full-state H_∞ controllers are designed, and the corresponding frequency responses are compared. In Section 5, the seismic time-responses are discussed. Finally, some brief conclusions and future research lines are presented in Section 6.

2. Building model

Let us consider the lateral displacement of an n-story building described by the second-order model

$$\mathbf{M}\ddot{\mathbf{q}}(t) + \mathbf{C}_d\dot{\mathbf{q}}(t) + \mathbf{K}\mathbf{q}(t) = \mathbf{f}_u(t) + \mathbf{f}_w(t) \tag{1}$$

where $\mathbf{q}(t) = [q_1(t),\ldots,q_n(t)]^T$ is the vector of story displacements with respect to the ground, $\mathbf{M}$, $\mathbf{C}_d$ and $\mathbf{K}$ are the mass, damping and stiffness matrices, respectively, $\mathbf{f}_u(t)$ is the vector of structural control forces and $\mathbf{f}_w(t)$ is the vector of external disturbances. The mass matrix has the diagonal form $\mathbf{M} = \mathrm{diag}(m_1,\ \ldots,m_n)$ and the stiffness matrix has the following tridiagonal structure:

$$\mathbf{K} = \begin{bmatrix} k_1+k_2 & -k_2 & & & & \\ -k_2 & k_2+k_3 & -k_3 & & & \\ & \cdots & \cdots & \cdots & & \\ & & \cdots & \cdots & \cdots & \\ & & & -k_{n-1} & k_{n-1}+k_n & -k_n \\ & & & & -k_n & k_n \end{bmatrix}, \tag{2}$$

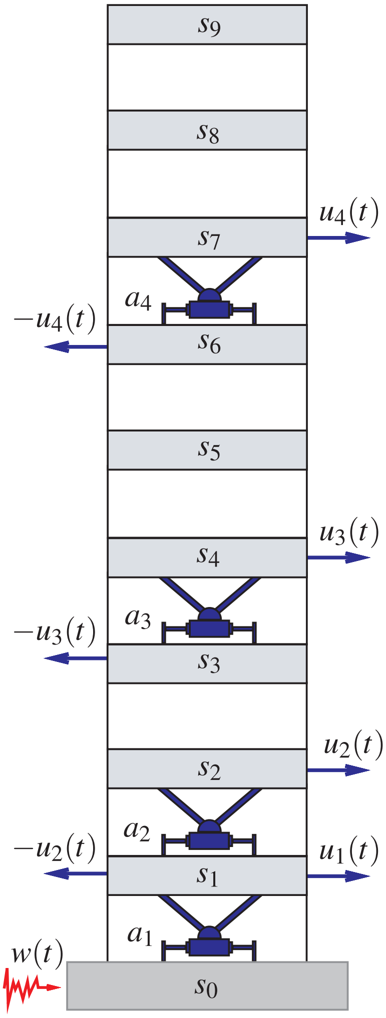

Fig. 1. Multi-story building structure equipped with a system of 4 interstory force-actuation devices. Incomplete actuation scheme corresponding to the location list $L = [1,\ 2,\ 4,\ 7]$.

where m_i and k_i are the mass and stiffness of the ith story, respectively. If the story damping coefficients c_i are known, a tridiagonal damping matrix can be obtained by substituting the stiffness coefficients k_i in Eq. (2) by the corresponding values c_i. Frequently, however, the values c_i are unknown, and the damping matrix $\mathbf{C}_d$ is computed from $\mathbf{M}$ and $\mathbf{K}$ by setting a proper damping ratio on the building modes [19]. For seismically excited buildings, the vector of external disturbances can be written in the form $\mathbf{f}_w(t) = -\mathbf{M}[\mathbf{1}]_{n\times 1}w(t)$, where $w(t)$ is the ground acceleration input and $[\mathbf{1}]_{n\times 1}$ denotes a vector of dimension n with all its entries equal to 1. Finally, the vector of structural control forces has the form $\mathbf{f}_u(t) = \mathbf{T}_u^L\mathbf{u}(t)$, where $\mathbf{u}(t) = [u_1(t),\ldots,u_{n_u}(t)]^T$ is the vector of actuation forces and $\mathbf{T}_u^L$ is the control input matrix, which models the effect of the actuation forces on the structure. In this work, we assume that the n-story building is equipped with a system of $n_u \leqslant n$ interstory force-actuation devices implemented at different levels of the building. An actuation scheme is determined by a list of locations $L = [\ell_1,\ \ldots,\ell_{n_u}]$, where the location ℓ_i indicates that the actuation scheme contains an interstory actuator a_i implemented between the stories s_{ℓ_i-1} and s_{ℓ_i}, which exerts a pair of opposite structural forces of magnitude $|u_i(t)|$ upon these stories. An incomplete actuation scheme, defined by the location list $L = [1,\ 2,\ 4,\ 7]$, and the corresponding structural control forces are schematically depicted in Fig. 1. As it can be seen in the figure, the location $\ell_4 = 7$ indicates that the actuation scheme contains an actuator a_4, implemented between the stories s_6 and s_7, that exerts a pair of opposite structural forces of magnitude $|u_4(t)|$. For a complete actuation scheme, as the one displayed in Fig. 3(a), the location list is $[1,\ 2,\ \ldots,n]$ and the corresponding control input matrix is a square matrix of dimension n that we denote by $\mathbf{T}_u$ and has the following upper-diagonal band structure:

$$\mathbf{T}_u = \begin{bmatrix} 1 & -1 & & & \\ & 1 & -1 & & \\ & & \cdots & \cdots & \\ & & & \cdots & \cdots \\ & & & 1 & -1 \\ & & & & 1 \end{bmatrix}. \tag{3}$$

For an incomplete actuation scheme defined by the location list $L = [\ell_1,\ \ell_2,\ \ldots,\ell_{n_u}]$, $n_u < n$, the control input matrix $\mathbf{T}_u^L$ is a rectangular matrix that contains the columns of $\mathbf{T}_u$ indicated in L. Using the submatrix notations discussed in Appendix A, we can write $\mathbf{T}_u^L = \mathbf{T}_u(1,\ 2,\ \ldots,n;\ell_1,\ \ell_2,\ \ldots,\ell_{n_u})$. The interstory drift $r_i(t)$ is the relative displacement of the adjacent stories s_{i-1} and s_i, more precisely: