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Vibration control for adjacent structures using local state information

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ABSTRACT

In this paper, a novel strategy for structural vibration control of multi-structure systems is presented. This strategy pays particular attention to mitigating negative interstructure interactions. Moreover, it is based on recent advances in static output–feedback control, which make possible the efficient computation of decentralized velocity-feedback controllers by solving a single-step optimization problem with Linear Matrix Inequality constraints. To illustrate the main ideas, a local velocity-feedback energy-to-peak controller is designed for the seismic protection of a two-building system. This controller is remarkably effective and extremely simple. Moreover, it can also be implemented by a linear passive damper. To assess the effectiveness of the proposed controller, numerical simulations are conducted with positive results.

1. Introduction

One of the main objectives of Structural Vibration Control (SVC) for large structures is to mitigate the vibrational response induced by external natural disturbances, such as wind gusts, earthquakes, or ocean waves. For multi-structure systems, the overall response must include not only the vibrational response of individual substructures, but also the possible interactions between adjacent substructures.

The seismic protection of closely adjacent buildings is an excellent example of SVC for multi-structure systems. In this case, the action of seismic excitations can produce interbuilding collisions (*pounding*), which can cause severe structural damage. Moreover, the large acceleration pulses generated in the quick and massive pounding impacts can also produce a serious damage in the buildings' content [1–5]. Consequently, a twofold objective must be considered in SVC designs for this kind of multi-structure systems: (1) mitigating the structural vibrational response of the individual buildings and (2) providing protection against pounding events.

The Connected Control Method (CCM) consists in linking together adjacent buildings by coupling devices to produce appropriate reaction control forces. Over the last years, a number of passive, active, and semiactive control strategies based on the CCM approach have been proposed for seismic protection of adjacent buildings with positive results (see for example [6–15]). It should be highlighted, however, that all these works only deal with the vibrational response of the individual buildings.

An attempt of setting a more comprehensive formulation of the problem can be found in [16,17], where two different kinds of output variables are considered. In these papers, together with the *interstory drifts* typically used to describe the relative displacement of adjacent stories in the same building, the *interbuilding approaches* are introduced to describe the approaching between stories placed at the same level in adjacent buildings.

In contrast with previous works, the present paper is principally focused on the interactions between adjacent buildings. More precisely, the main goal is to design a control system to provide a suitable protection against negative interbuilding interactions produced by seismic excitations. This should also be done without introducing negative side effects in the structural vibration response of the individual buildings. Moreover, the control system should be as simple as possible to facilitate its practical implementation. In terms of the output variables, these controller design objectives can be formulated as follows: (1) to produce a significant reduction of the interbuilding approach peak values, while (2) helping to keep the peak values of the interstory drifts in the individual buildings within acceptable levels. Additionally, the simplicity constraint is a broad concept which may involve a variety of different design elements, such as partial state information requirements, reduced information exchange, or low power consumption.

Decentralized velocity-feedback controllers can be efficiently designed using recent developments on static output–feedback control presented in [18]. This approach has been successfully applied to design decentralized velocity-feedback controllers and

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optimal passive-damping systems for seismic protection of single buildings [19,20]. In the present work, these new ideas are applied to design a local velocity-feedback energy-to-peak controller which satisfies the proposed design objectives.

For clarity and brevity, a particular two-building system formed by a four-story building adjacent to a five-story building has been selected to present the main ideas. A minimal actuation system has also been chosen, which consists in a single actuation device linking both buildings at the fourth story level, as schematically depicted in Fig. 1. For this two-building system, a velocity-feedback controller that only uses the relative velocity of the fourth stories as feedback information is designed. This controller attains a remarkable reduction of the interbuilding approach peak values and, also, a moderate attenuation of the interstory drift peak values in both buildings. Moreover, it can be implemented in practice using a linear passive damper, that is, without sensors, no communication system, and null power consumption. A state-feedback LQR controller and a state-feedback energy-to-peak controller, which require the complete two-building state as feedback information, are also computed and used as a reference.

To assess the effectiveness of the proposed controllers, numerical simulations are conducted using the full scale North–South El Centro 1940 seismic record as ground acceleration disturbance. To avoid the computational complexity associated to the pounding impacts, the numerical simulations are carried out under the assumption that the interbuilding separation is large enough to avoid collisions. In this case, the maximum values of the interbuilding approaches can be understood as lower bounds of *safe interbuilding separation*.

The paper is organized as follows: In Section 2, a second-order model and a first-order state-space model for the two-building system are provided. In Section 3, the theoretical results on static output–feedback control presented in [18] are applied to derive an effective computational strategy to design static output–feedback energy-to-peak controllers. In Section 4, the different controllers are computed and numerical simulations are conducted to compare their effectiveness. Finally, some conclusions and future research directions are presented in Section 5.

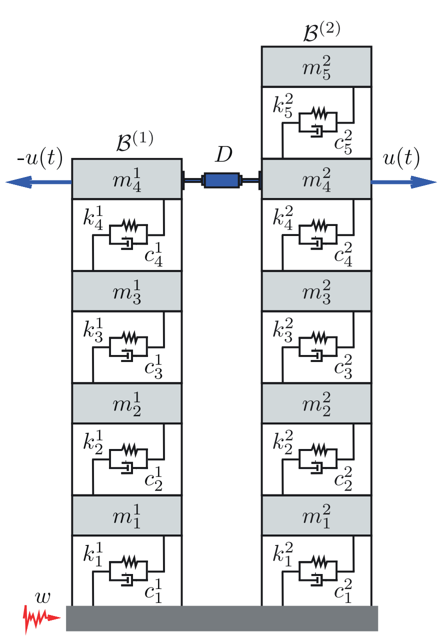

Fig. 1. Two-building system with interbuilding actuation device.

2. Two-building mathematical model

2.1. Second-order model

Let us consider the two-building system schematically displayed in Fig. 1. The buildings motion can be described by the second-order model

$$\mathbf{M}\ddot{\mathbf{q}}(t) + \mathbf{C}\dot{\mathbf{q}}(t) + \mathbf{K}\mathbf{q}(t) = \mathbf{T}_u u(t) + \mathbf{T}_w w(t), \tag{1}$$

where $\mathbf{M}$ is the mass matrix, $\mathbf{C}$ is the damping matrix, and $\mathbf{K}$ is the stiffness matrix. The vector of story displacements with respect to the ground is

$$\mathbf{q}(t) = \begin{bmatrix} \mathbf{q}^{(1)}(t) \\ \mathbf{q}^{(2)}(t) \end{bmatrix}, \tag{2}$$

where

$$\mathbf{q}^{(1)}(t) = \left[q_1^1(t), q_2^1(t), q_3^1(t), q_4^1(t)\right]^T, \tag{3}$$

$$\mathbf{q}^{(2)}(t) = \left[q_1^2(t), q_2^2(t), q_3^2(t), q_4^2(t), q_5^2(t)\right]^T, \tag{4}$$

and $q_i^j(t)$ represents the displacement of the ith story in the jth building corresponding to the time t. We assume that an active control device D has been implemented between the fourth stories of both structures. The control force $u(t)$ delivered by D produces a pair of opposite forces as indicated in Fig.1. This actuation scheme is modeled by means of the control location matrix $\mathbf{T}_u$. Finally, the ground acceleration disturbance is denoted by $w(t)$, and $\mathbf{T}_w$ is the disturbance input matrix. The mass matrix $\mathbf{M}$ has the following block diagonal structure:

$$\mathbf{M} = \begin{bmatrix} \mathbf{M}^{(1)} & [\mathbf{0}]_{4\times5} \\ [\mathbf{0}]_{5\times4} & \mathbf{M}^{(2)} \end{bmatrix}, \tag{5}$$

where $[\mathbf{0}]_{r\times s}$ is a zero matrix of dimensions $r \times s$,

$$\mathbf{M}^{(1)} = \begin{bmatrix} m_1^1 & 0 & 0 & 0 \\ 0 & m_2^1 & 0 & 0 \\ 0 & 0 & m_3^1 & 0 \\ 0 & 0 & 0 & m_4^1 \end{bmatrix}, \tag{6}$$

$$\mathbf{M}^{(2)} = \begin{bmatrix} m_1^2 & 0 & 0 & 0 & 0 \\ 0 & m_2^2 & 0 & 0 & 0 \\ 0 & 0 & m_3^2 & 0 & 0 \\ 0 & 0 & 0 & m_4^2 & 0 \\ 0 & 0 & 0 & 0 & m_5^2 \end{bmatrix}, \tag{7}$$

and m_i^j denotes the mass of the ith story in the jth building. The stiffness matrix has the form

$$\mathbf{K} = \begin{bmatrix} \mathbf{K}^{(1)} & [\mathbf{0}]_{4\times5} \\ [\mathbf{0}]_{5\times4} & \mathbf{K}^{(2)} \end{bmatrix}, \tag{8}$$

where

$$\mathbf{K}^{(1)} = \begin{bmatrix} k_1^1 + k_2^1 & -k_2^1 & 0 & 0 \\ -k_2^1 & k_2^1 + k_3^1 & -k_3^1 & 0 \\ 0 & -k_3^1 & k_3^1 + k_4^1 & -k_4^1 \\ 0 & 0 & -k_4^1 & k_4^1 \end{bmatrix}, \tag{9}$$

$$\mathbf{K}^{(2)} = \begin{bmatrix} k_1^2 + k_2^2 & -k_2^2 & 0 & 0 & 0 \\ -k_2^2 & k_2^2 + k_3^2 & -k_3^2 & 0 & 0 \\ 0 & -k_3^2 & k_3^2 + k_4^2 & -k_4^2 & 0 \\ 0 & 0 & -k_4^2 & k_4^2 + k_5^2 & -k_5^2 \\ 0 & 0 & 0 & -k_5^2 & k_5^2 \end{bmatrix}, \tag{10}$$