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Equivalent-input-disturbance approach to active structural control for seismically excited buildings

Kou Miyamoto [a], Jinhua She [b,*], Junya Imani [c], Xin Xin [d], Daiki Sato [a]

[a] School of Environment and Society, Architecture and Building Engineering, Tokyo Institute of Technology, Yokohama, Kanagawa 226-8503, Japan
[b] School of Engineering, Tokyo University of Technology, Hachioji, Tokyo 192-0982, Japan
[c] Department of Mechanical Systems Engineering, Tokyo University of Agriculture and Technology, Tokyo 184-8588, Japan
[d] Faculty of Computer Science and Systems Engineering, Okayama Prefectural University, Soja, Okayama 719-1197, Japan

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ABSTRACT

A new method of active structural control, which suppresses vibrations in civil structures due to seismic shocks, has been developed. It is based on the equivalent-input-disturbance (EID) approach, which estimates the effect of a seismic shock and produces an equivalent control signal on the control input channel to compensate for it. A system designed by this method can be viewed as a conventional state-feedback control system with an EID estimator plugged in. Unlike conventional control systems, this one has two degrees of freedom, which yields better control performance. Simulations on a model of a ten-degree-of-freedom building demonstrated the validity of the method. In addition, the effect of the parameters of the low-pass filter in the EID estimator on the vibration suppression performance was examined. A comparison revealed that this method is superior to a linear-quadratic regulator and sliding-mode control.

1. Introduction

The first full-scale implementation of active structural control (ASC) was in Kyobashi Center Building in 1989 [1]. Progress in ASC has been rapid, and it is now widely used in civil structures [2]. Since ASC pumps energy into a system to suppress vibrations, it is effective for all types of vibrations.

A variety of control strategies have been employed to design ASC systems, including the extensively used linear-quadratic regulator (LQR) [3,4], PID control [5], computational-intelligence-based control [6–11], predictive control [12], sliding-mode control (SMC) [13], and robust control [14–17]. However, the resulting systems generally have only one degree of freedom (DOF). Note that, while the DOF is defined to be the number of modes of a building model in structural engineering, the DOF of a control system is defined to be the number of closed-loop transfer functions that can be adjusted independently in control engineering [18]. The control objective is to minimize the sensitivity function of the control system, but there are trade-offs between the sensitivity function and other aspects of control performance for a one-DOF control system.

On the other hand, She et al. devised the equivalent-input-disturbance (EID) approach, which rejects both matched and unmatched disturbances [19,20]. An EID-based control system has two DOFs: one is used to tune the disturbance rejection performance, and the other is used to tune the feedback performance. This relaxes the trade-off between different aspects of control performance. Unlike a one-DOF system, an EID-based control system directly estimates the effect of disturbances and produces a control input that actively suppresses that effect. This makes the system more effective than a one-DOF system in suppressing vibrations due to seismic shocks, even when the same actuators are used for both systems. Some of the distinctive features of the method are that the control system has a simple structure, that it does not require the derivative of measured output, and that it avoids the cancellation of unstable poles and zeros. She et al. previously applied this method of controlling seismic vibrations to a model of a three-story building with an actuator for each story and with an input dead zone in each actuator, and presented some preliminary results in a conference paper [21].

This paper considers EID-based ASC for a seismically excited building, and examines the internal operation of the EID method for ASC. Since actuators are expensive, the fewer there are, the better. Unlike the system described in [21], the one considered in this study has fewer actuators than stories. The design of the control

* Corresponding author.
E-mail address: she@stf.teu.ac.jp (J. She).

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Nomenclature

ASC	active structural control
DOF	degree of freedom
EID	equivalent input disturbance
LQR	linear-quadratic regulator
NC	no control
PID	proportional integral derivative
SMC	sliding-mode control
m_i	mass of ith DOF $(i = 1, \ldots, n)$
k_i	stiffness of ith DOF $(i = 1, \ldots, n)$
c_i	damping of ith DOF $(i = 1, \ldots, n)$
M_S	mass matrix of structure
K_S	stiffness matrix of structure
C_S	damping matrix of structure
ω_m	maximum angular frequency for vibration suppression
I_k	k-dimensional identity matrix
$0_{j\times k}$	j-by-k matrix with all entries being zero
$x_i(t)$	displacement of ith DOF $(i = 1, \ldots, n)$
$\dot{x}_i(t)$	velocity of ith DOF $(i = 1, \ldots, n)$
$\ddot{x}_i(t)$	acceleration of ith DOF $(i = 1, \ldots, n)$
$\ddot{x}_g(t)$	acceleration of ground
$q(t)$	displacement vector $(= [x_1(t), x_2(t), \ldots, x_n(t)]^T)$
$\dot{q}(t)$	velocity vector $(= [\dot{x}_1(t), \dot{x}_2(t), \ldots, \dot{x}_n(t)]^T)$
$\xi(t)$	state vector $(= [q^T(t), \dot{q}^T(t)]^T)$
$\theta_i(t)$	interstory-drift angle of ith DOF $(i = 1, \ldots, n)$
$\Delta\dot{x}_i(t)$	relative speed of ith DOF $(i = 1, \ldots, n)$
$\ddot{x}_i(t) + \ddot{x}_g(t)$	absolute acceleration of ith DOF $(i = 1, \ldots, n)$
$\Vert u\Vert_2$	2-norm of signal $u(t)$, which is defined as $\Vert u\Vert_2 = \left\{\int_{-\infty}^{\infty} u^T(t)u(t)dt\right\}^{1/2}$
$\Vert G\Vert_\infty$	H_∞ norm of system $G(s)$, which is defined as $\Vert G\Vert_\infty = \sup_{0\leqslant\omega\leqslant\infty}\sigma_{\max}[G(j\omega)]$
$\sigma_{\max}(G)$	maximum singular value of G

system is explained, and the validity of the method is demonstrated through simulations using data from five earthquakes with different kinds of seismic waves, and through a comparison with the LQR and SMC methods. The relationship between the effectiveness of vibration suppression and the input energy of the control system is examined. Most reports have shown control results only for the displacement or drift of stories. However, the velocity and acceleration of a story strongly impact the people on that floor. To better assess damage reduction and the impact on humans, this study investigated not only interstory-drift angles, but also relative velocity and absolute acceleration.

2. Structural model

The dynamics of an n-DOF building (Fig. 1) are described by the equation

$$M_S\ddot{q}(t) + C_S\dot{q}(t) + K_S q(t) = E_u u(t) + E_g\ddot{x}_g(t), \tag{1}$$

where

$$q(t) = [x_1(t), x_2(t), \ldots, x_n(t)]^T$$

is the displacement vector; $u(t) \in \mathbb{R}^l$ is the control force produced by an actuator; $\ddot{x}_g(t)$ is the acceleration of the ground; M_S is the mass matrix; C_S is the damping factor matrix; K_S is the stiffness matrix; and E_u and E_g are input matrices for $u(t)$ and $\ddot{x}_g(t)$, respectively.

The state-space variable, $\xi(t)$, is defined to be

$$\xi(t) = \begin{bmatrix} q(t) \\ \dot{q}(t) \end{bmatrix}, \tag{2}$$

and note that M_S is positive definite. Thus, the state-space representation of (1) is

$$\begin{cases} \dot{\xi}(t) = A\xi(t) + B_u u(t) + B_g\ddot{x}_g(t), \\ y(t) = C\xi(t), \end{cases} \tag{3}$$

where

$$A = \begin{bmatrix} 0 & I_n \\ -M_S^{-1}K_S & -M_S^{-1}C_S \end{bmatrix}, \quad B_u = \begin{bmatrix} 0 \\ M_S^{-1}E_u \end{bmatrix}, \quad B_g = \begin{bmatrix} 0 \\ M_S^{-1}E_g \end{bmatrix},$$

C is the output matrix, and $y(t) \in \mathbb{R}^p$ is the measured output of the system.

Now, we define three terms in the basic vocabulary of control engineering.

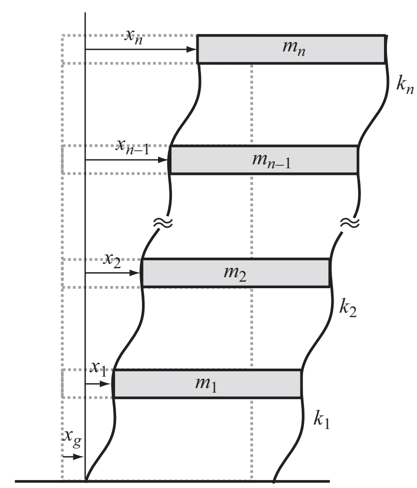

Fig. 1. n-DOF model of building.

Plant: A plant is a physical object to be controlled.

Controllable: Controllable means that the current state of the plant can be moved by an admissible control input in the state space.

Observable: Observable means that the current state of the plant can be determined in finite time from the input and output.

For simplicity, the plant is usually described using the parameters in (3). For the plant (A, B_u, C), it is easy to verify that (A, B_u) is controllable, and (C, A) is observable. Note that (A, B_u, C) is a minimum-phase system[1] and there are no zeros on the imaginary axis. This characteristic enables us to employ the results in [19] to design an EID-based ASC system.

3. Design of EID-based ASC system

This section explains the configuration and design of an EID-based ASC system.

[1] A minimum-phase system has all its poles and zeros on the complex open left-half plane.