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A gain-scheduling-based LQR control method for active structural control of base-isolated buildings with bilinear oil dampers

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Active structural control Base-isolated building
Bilinear oil damper LQR control Gain-scheduling

1. Introduction

In Japan, thousands of base-isolated buildings have been constructed since the 1995 Kobe earthquake. Many of them are installed with dampers. An investigation in Japan [1] shows that 64% of the investigated base-isolated buildings use oil dampers (ODs), of which 86% are bilinear oil dampers (BODs).

Recently, active structural control (ASC) has been studied for enhancing the control performance of base-isolated buildings. The linear quadratic regulator (LQR) control method is one of the most widely studied methods for ASC of base-isolated buildings and has been demonstrated to be effective [2-3]. However, LQR is a linear control method, cannot be directly used for base-isolated buildings with nonlinear dampers. This limits the application of LQR control for base-isolated buildings.

This paper presents a gain-scheduling-based LQR (GSLQR) control method for ASC of base-isolated buildings with BODs. We separate the BODs from the plant and regard them as a passive part of a total controller to use LQR method. The damper force of BODs is expressed as a multiplication of a state-dependent matrix and the state vector. A GS controller that uses a varying gain based on the defined scheduling variables [4] is used as an active part of the LQR controller. It is designed to ensure that the sum of the active gain and the state-dependent matrix of BODs equals the gain of the LQR controller. This makes LQR control of base-isolated buildings with BODs possible. A design example demonstrates the feasibility of the method.

2. Mathematical model

Consider a base-isolated building equipped with BODs and ASC devices in isolation layer, which is described as a multi-degree-of-freedom (MDOF) model. The dynamic equation is

$$M\ddot{x}(t)+C\dot{x}(t)+Kx(t)+Ef_{\mathrm{d}}(t)=-E_{\mathrm{g}}\ddot{x}_{\mathrm{g}}(t)-Eu(t)\,, \qquad (1)$$

where $x(t)$, $\dot{x}(t)$, and $\ddot{x}(t)$ are respectively the relative displacement, velocity and acceleration; $\ddot{x}_{\mathrm{g}}(t)$ is the ground acceleration; $u(t)$ is the control force; $f_{\mathrm{d}}(t)$ is the damper force of BODs; M, C, and K are the mass, damping, and stiffness matrices, respectively; E represents the input location of $u(t)$ and $f_{\mathrm{d}}(t)$; E_{g} represents the input location of $\ddot{x}_{\mathrm{g}}(t)$. The damper force, $f_{\mathrm{d}}(t)$, is expressed as

$$f_{\mathrm{d}}(t)=\begin{cases} c_{\mathrm{d}}\dot{x}_0(t), & \left|\dot{x}_0(t)\right|<\dot{x}_{\mathrm{y}}, \\ (1-p)c_{\mathrm{d}}\dot{x}_{\mathrm{y}}\operatorname{sgn}(\dot{x}_0(t))+pc_{\mathrm{d}}\dot{x}_0(t), & \left|\dot{x}_0(t)\right|\ge\dot{x}_{\mathrm{y}}, \end{cases} \qquad (2)$$

where $\dot{x}_0(t)$ is the velocity of isolation layer, c_{d} is the initial damping coefficient of BODs, p is the proportional coefficient, $\dot{x}_{\mathrm{y}}$ is the yield velocity.

The state-space representation of the system is

$$\dot{z}(t)=Az(t)+Bu(t)+B_{\mathrm{d}}f_{\mathrm{d}}(t)+B_{\mathrm{g}}\ddot{x}_{\mathrm{g}}(t)\,, \qquad (3)$$

where $z(t)=\begin{bmatrix}x(t) & \dot{x}(t)\end{bmatrix}^{\mathrm{T}}$, $A=\begin{bmatrix}0 & I\\ -M^{-1}K & -M^{-1}C\end{bmatrix}$, $B=\begin{bmatrix}0 & -M^{-1}E\end{bmatrix}^{\mathrm{T}}$, $B_{\mathrm{g}}=\begin{bmatrix}0 & -M^{-1}E_{\mathrm{g}}\end{bmatrix}$. z is the state vector, A is the system matrix, B is the input matrix for $u(t)$ and $f_{\mathrm{d}}(t)$, B_{g} is the input matrix for $\ddot{x}_{\mathrm{g}}(t)$.

The active control force $u(t)$ is based on state feedback:

$$u(t)=K_{\mathrm{A}}z(t)\,, \qquad (4)$$

where K is the gain of the active controller.

3. Gain-scheduling-based LQR control method

We regard both the active controller (active part) and the BODs (passive part) as parts of an LQR controller. Define the sum of the active control force and the damper force of BODs to be a total control input, $u_{\mathrm{T}}(t)$,

$$u_{\mathrm{T}}(t)=u(t)+f_{\mathrm{d}}(t)\,. \qquad (5)$$

Then, the system is expressed as

$$\dot{z}(t)=Az(t)+Bu_{\mathrm{T}}(t)+B_{\mathrm{g}}\ddot{x}_{\mathrm{g}}(t)\,, \qquad (6)$$

which can be considered as a linear system with $u_{\mathrm{T}}(t)$ as the control input. We optimize $u_{\mathrm{T}}(t)$ by minimizing the following performance index [2]:

$$J=\int_0^{\infty}\left[z^{\mathrm{T}}(t)Qz(t)+2z^{\mathrm{T}}(t)Su_{\mathrm{T}}(t)+Ru_{\mathrm{T}}^2(t)\right]dt\,, \qquad (7)$$

where Q, S, and R are the weight matrices. The total control force $u_{\mathrm{T}}(t)$ minimizing (8) is

$$u_{\mathrm{T}}(t)=K_{\mathrm{LQR}}z(t)\,, \qquad (8)$$

$$K_{\mathrm{LQR}}=-R^{-1}(B^{\mathrm{T}}P+S^{\mathrm{T}})\,, \qquad (9)$$

where K_{LQR} is the gain of the LQR controller, P is the solution to the algebraic Riccati equation

$$A^{\mathrm{T}}P+PA-\left(PB+S\right)R^{-1}\left(B^{\mathrm{T}}P^{\mathrm{T}}+S^{\mathrm{T}}\right)+Q=0\,. \qquad (10)$$

Remark 1: (7) transforms the control of a nonlinear system into the control of a linear system by separating the nonlinear dampers from the plant and incorporating them into a total controller.

We describe the damper force of BODs as the following form:

$$f_{\mathrm{d}}(t)=c_{\mathrm{LT}}(t)\dot{x}_0(t)=\Xi(z(t))z(t)\,, \qquad (11)$$

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$$c_{\mathrm{LT}}(t)=\begin{cases} c_{\mathrm{d}}, & |\dot{x}_0(t)|<\dot{x}_{\mathrm{y}}, \\ \left[\dfrac{(1-p)\dot{x}_{\mathrm{y}}}{|\dot{x}_0(t)|}+p\right]c_{\mathrm{d}}, & |\dot{x}_0(t)|\geq \dot{x}_{\mathrm{y}}, \end{cases} \tag{12}$$

where $c_{\mathrm{LT}}(t)$ is the linear time-varying damping coefficient, $\Xi(z(t))$ is a state-dependent matrix. From (6), we have

$$K_{\mathrm{LQR}}z(t)=K_{\mathrm{A}}z(t)+\Xi(z(t))z(t). \tag{13}$$

Thus, the gain of the active controller, K_{A}, can be derived as

$$K_{\mathrm{A}}(t)=K_{\mathrm{LQR}}-\Xi(z(t)). \tag{14}$$

Remark 2: (15) is the gain of a GS controller with respect to $\Xi(z(t))$, the scheduling variable. The boundedness of $\Xi(z(t))$ and K_{LQR} ensures that $K(t)$ is bounded.

Remark 3: In this control method, $\Xi(z(t))$ is regarded as the gain of the passive part of the LQR controller, while $K_{\mathrm{A}}(t)$ is the gain of the active part, as shown in Fig. 1.

4. Design example

Consider a base-isolated building with BODs modelled as a shear 11-degree-of-freedom (11-DOF) model. The design conditions and design criteria are shown as follows.

Design conditions:

Ground motion component: Art Kobe (Fig. 2).

Mass per story: $m_i=9.8\times10^5$ kg.

Natural period of superstructure: $T_{\mathrm{s}}=2$ s.

Damping ratio of superstructure: $\zeta_{\mathrm{s}}=0.02$.

Natural period of bearings: $T_0=4$ s.

Damping ratio of bearings: $\zeta_0=0.05$.

Design criteria:

Limitation of displacement: $x_{\mathrm{lim}}=0.65$ m.

Limitation of velocity: $\dot{x}_{\mathrm{lim}}=1$ m/s.

Limitation of acceleration: $\{\ddot{x}+\ddot{x}_{\mathrm{g}}\}_{\mathrm{lim}}=1$ m/s^2.

In this example, the parameters of installed BODs are predetermined as

$$c_{\mathrm{d}}=1.02\times10^7\ \mathrm{Ns/m},\quad p=0.05,\quad \dot{x}_{\mathrm{y}}=0.4\ \mathrm{m/s}.$$

The LQR controller is designed to satisfy the design criteria for the base-isolated building without BODs. Then, we obtain $c_{\mathrm{LT}}(t)$ and $\Xi(z(t))$ by using (13). Finally, the gain of the active controller, $K_{\mathrm{A}}(t)$, is obtained by (15). The 12th element of $K_{\mathrm{A}}(t)$, denoted as $K_{\mathrm{A},12}(t)$, is a time-varying gain with respect to $\dot{x}_0(t)$,

$$K_{\mathrm{A},12}(t)=\begin{cases} 1.77\times10^7, & |\dot{x}_0(t)|\leq 0.4\ \mathrm{m/s}, \\ 2.74\times10^7-\dfrac{3.88\times10^6}{|\dot{x}_0(t)|}, & |\dot{x}_0(t)|>0.4\ \mathrm{m/s}. \end{cases}$$

The maximum seismic responses of the building are shown in Fig. 3. As can be seen, the design results satisfy all design criteria.

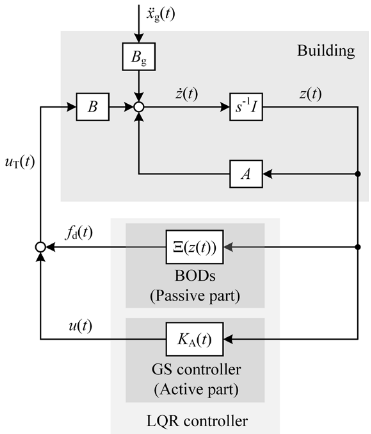

Fig. 1. Block diagram.

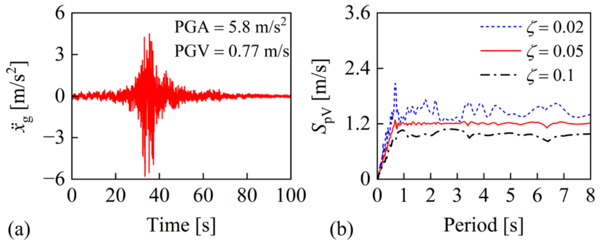

Fig. 2. Art Kobe: (a) accelerogram and (b) pseudo velocity response spectrum

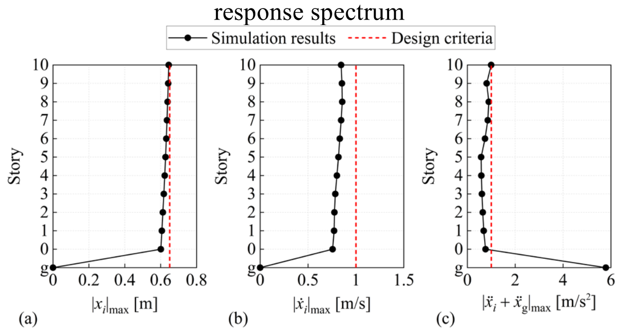

Fig. 3. Maximum responses: (a) displacement, (b) velocity, and (c) acceleration.

5. Summary

This paper presented a GSLQR control method for ASC of base-isolated buildings with nonlinear dampers. This method makes LQR control of base-isolated buildings with BODs possible. An example demonstrates the feasibility of the method.

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