A comparative study of active and semi-active control of building seismic response

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Dedicated to the 70-th anniversary of Professor Constantin Udriste

Abstract. A study of the control of seismically excited building vibrations is presented. The numerical simulations are performed on multi-storey building modeled as a two blocks structure. For determining the active control action a LQG control algorithm was selected and for the semi-active control, an on-off strategy was considered, based on the balance of the elastic force by a sequentially controlled dry friction force in order to cancel or reduce the absolute acceleration. It is shown that during the earthquake motion, the active system is behaving most of the time as a semi-active one, which advocates the choosing of semi-active control as being much simpler to implement.

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Key words: Active control; semi-active control; friction dampers; base isolation.

1 Introduction

The response of a structure to a seismic input can be controlled by placing active elements between storeys and/or between the building and its foundation. In the fully active earthquake protection systems, both elastic and damping forces developed by these elements are modulated according to specific control strategies [6, 4, 8]. If only damping forces are controlled, the protection system is called semi-active. The basic idea of semi-active control strategy "balance logic" is to balance the elastic force by the damping force (as long as these forces act in opposite direction) and to set the damping force to a minimum value (possibly zero) otherwise. This work investigates comparatively the efficiency of active and semi-active base isolation systems used to mitigate the seismic response of buildings. A variety of techniques and semi-active control algorithms have been investigated over the years in order to control structural seismic response [2]. Stammers and Sireteanu [7] carried out experimental work using a servo driven semi-active friction device to control a sprung mass excited by a shake table. The algorithm employed was designed to cancel spring forces whenever possible. As introduced by Federspiel [1], this type of damping modulation is also known as

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sequential damping. Semi-active vibration control devices have received a great deal of attention in recent years because they offer the adaptability of active control devices without requiring large power sources [3]. In contrast to active control devices, semi-active control devices cannot inject mechanical energy into the system and, therefore, they do not have the potential to destabilize (in bounded input/bounded output sense) the controlled system [9]. Most of the semi-active devices produce only modulation of the damping forces in the controlled system according to the control strategy employed. Examples of such devices are variable orifice dampers, controllable friction devices and dampers with controllable fluids (electro and magneto-rheological).

2 Mathematical model

Although an N storey building is envisaged, the model adopted here employs only two masses, each block representing several storey, the aim being to approximate the vibration of the building in the range of its fundamental natural frequency. The objective is to analyze the behavior of the building equipped with a linear viscous damper and a friction damper positioned between the base and the ground in case of an earthquake motion. Only lateral motion is considered, the building being treated as a shear structure. The building represented in Figure 1 is modeled as two masse m_1, m_2, connected by linear springs of stiffness k_2. The lateral stiffness to ground k_1 is governed by the flexibility of the structure and also of the soil. The latter is a function of the type of soil, which can be characterized by the speed ν_s of shear waves. For a building of height h, base area $b \times b$ in plane, fundamental period T_∞ in rigid soil, the fundamental period is taken to be

$$T^2 = T_\infty + 1.47Jb^2(1 + 1.65J^2)/\nu_s^2 \tag{2.1}$$

where J is the building aspect ratio h/b.

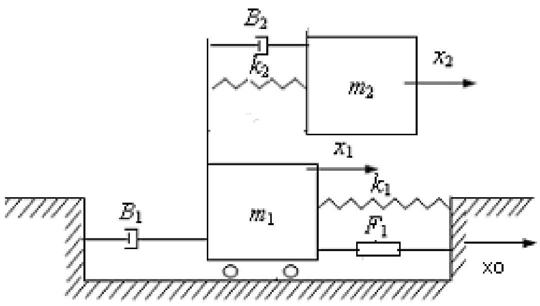


Fig.1. Analytical model.

The period T_∞ in this case is assumed for a square plane building to be $T_\infty = h/c$ where h is the height of the building and c is a constant (having the dimensions of velocity) which depends on the type of construction. For a uniform two mass body, the fundamental frequency is 0.445ω, where ω is the frequency $(k_j/m_j)^{0.5}$ for each of the sub-systems. Hence given a uniform building of a known height, the natural frequency of the two subsystems can be deduced. Soil and structural damping are assumed, as it is usual, to be viscous in nature. The equations of motions are

$$m_1\ddot{x}_1 + k_1 y_1 + B_1\dot{y}_1 - k_2 y_2 - B_2\dot{y}_2 - F_1 = 0 \tag{2.2}$$

$$m_2\ddot{x}_2 + k_2 y_2 + B_2\dot{y}_2 = 0 \tag{2.3}$$

where $y_1 = x_1 - x_0$, $y_2 = x_2 - x_1$ are the relative displacements of the stories m_1 and m_2. As the earthquake action is given by the ground acceleration $\ddot{x}_0$ and the variables x_0, $\dot{x}_0$ are not known (or very difficult to be obtained) then the motion equations are written in terms of y_1, y_2 and $\ddot{x}_0$ [5]. Therefore, the equations (2.2) and (2.3) become:

$$m_1\ddot{y}_1 + k_1 y_1 + B_1\dot{y}_1 - k_2 y_2 - B_2\dot{y}_2 - F_1 = -m_1\ddot{x}_0 \tag{2.4}$$

$$m_2\ddot{y}_2 + k_2 y_2 + B_2\dot{y}_2 = -m_2\ddot{x}_1 \tag{2.5}$$

Next, the notations are introduced (ζ_1 and ζ_2 are the soil and structure damping):

$$\nu = \frac{m_2}{m_1},\ \omega_i^2 = \frac{k_i}{m_i},\ 2\zeta_i\omega_i = \frac{B_i}{m_i},\ i = 1,2 \tag{2.6}$$

In this way the equations (2.4), (2.5) have the form:

$$\ddot{y}_1 = -2\zeta_1\omega_1\dot{y}_1 - \omega_1^2 y_1 + \frac{F_1}{m_1} + \omega_2^2\nu y_2 - 2\zeta_2\omega_2\nu\dot{y}_2 - \ddot{x}_0 \tag{2.7}$$

$$\ddot{y}_2 = 2\zeta_1\omega_1\dot{y}_1 + \omega_1^2 y_1 - \frac{F_1}{m_1} + \omega_2^2(\nu+1)y_2 - 2\zeta_2\omega_2(\nu+1)\dot{y}_2 \tag{2.8}$$

The state-space equation in the case of active control is

$$\dot{z} = Az(t) + Bu(t) + h\ddot{x}_0 \tag{2.9}$$

with

$$z(t) = \begin{pmatrix} y_1(t) & y_2(t) & \dot{y}_1(t) & \dot{y}_2(t) \end{pmatrix}^T, u(t) = F_1 \tag{2.10}$$

The system matrix A and the location matrices B and h (specifying, respectively, the locations of the controller and external excitation) are

$$\begin{gathered} A = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\omega_1^2 & \omega_2^2\nu & -2\zeta_1\omega_1 & -2\zeta_2\omega_2\nu \\ \omega_1^2 & -\omega_2^2(\nu+1) & 2\zeta_1\omega_1 & -2\zeta_2\omega_2(\nu+1) \end{pmatrix}, \\ B = \begin{pmatrix} 0 & 0 & \frac{1}{m_1} & -\frac{1}{m_1} \end{pmatrix}^T, h = \begin{pmatrix} 0 & 0 & -1 & 0 \end{pmatrix}^T \end{gathered} \tag{2.11}$$

The form of the performance index usually chosen for study in structural control is quadratic in $z(t)$ and $u(t)$

$$J = \int_0^{t_f} [z^T(t)Qz(t) + u^T(t)Ru(t)]dt \tag{2.12}$$

with Q a positive semi-definite matrix and R a positive definite matrix. The matrices Q and R are referred to as weighting matrices.
The linear optimal control law is

$$u(t) = G(t)z(t) = -\frac{1}{2}R^{-1}B^T P(t)z(t) \tag{2.13}$$

where $G(t) = -0.5R^{-1}B^T P(t)$ is the control gain, and $P(t)$ is the Riccati matrix. In structural applications, numerical computations have shown that the Riccati matrix remains constant over the control interval, dropping to zero rapidly near t_f[6]. The Riccati equation reduces to

$$PA - \frac{1}{2}PBR^{-1}B^T P + A^T P + 2Q = 0 \tag{2.14}$$

and the control gain is also constant with $G(t) = -0.5R^{-1}B^T P$. In the case of semi-active control, a strategy of type "balance logic" is considered, based on the balance of the elastic force by a sequentially controlled dry friction force in order to cancel or reduce the absolute acceleration [2]. Considering that the structure is equipped with a linear viscous damper and a dry friction damper at the base isolation system, the damping force can be analytically expressed by using the relation

$$F_1 = (-2\zeta\omega_1\dot{y}_1 - \alpha|y_1|sign(\dot{y}_1) + \alpha\omega_1^2 y_1)m_1 \tag{2.15}$$

The equations (2.4) and (2.5) have the form

$$\begin{aligned}\ddot{y}_1 = -2\zeta_1\omega_1\dot{y}_1 - \omega_1^2 y_1 - 2\zeta\omega_1\dot{y}_1 - \alpha|y_1|sign(\dot{y}_1)+\\ +\alpha\omega_1^2 y_1 + \omega_2^2\nu y_2 - 2\zeta_2\omega_2\nu\dot{y}_2 - \ddot{x}_0\end{aligned} \tag{2.16}$$

$$\begin{aligned}\ddot{y}_2 = 2\zeta_1\omega_1\dot{y}_1 + \omega_1^2 y_1 - \omega_2^2(\nu+1)y_2 - 2\zeta_2\omega_2(\nu+1)\dot{y}_2+\\ +2\zeta\omega_1\dot{y}_1 + \alpha|y_1|sign(\dot{y}_1) - \alpha\omega_1^2 y_1\end{aligned} \tag{2.17}$$

3 Numerical results

For the numerical simulations a building of 40 m height and 10 meters square base section was considered. The following values were used for model parameters: $\zeta_1 = 0.02, \zeta_2 = 0.02$, $m_1 = m_2 = 40000$kg, $\omega_1 = 2$Hz, $\omega_2 = 1.5$Hz, $R = 10^{-10}$, $Q = \left(q_{i,j}\right)_{4\times4}$, $q_{i,j} = 1, \forall i,j = 1..4$.
The results are obtained for the seismic acceleration time history, numerically synthesized such as to be compatible with a given design response spectrum.

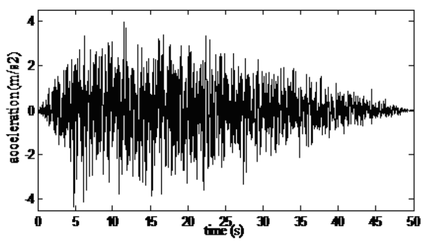
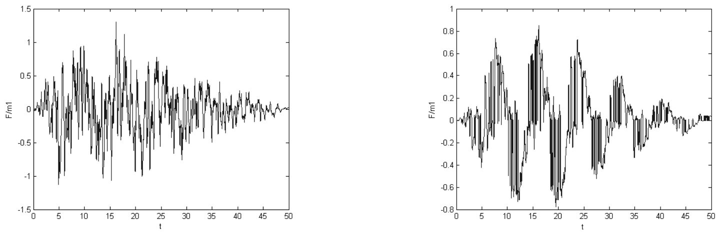


Fig. 2. Synthesized seismic accelerogram.



active control **semi-active control.**

Fig. 3. Control force.

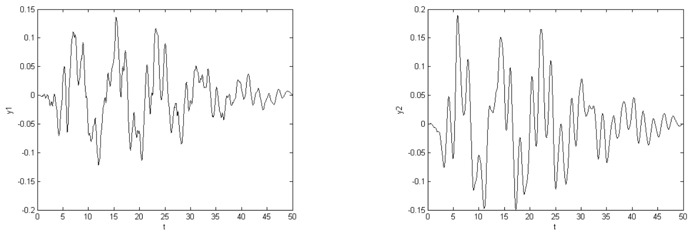


Fig. 4. Relative displacements of structure with active control.

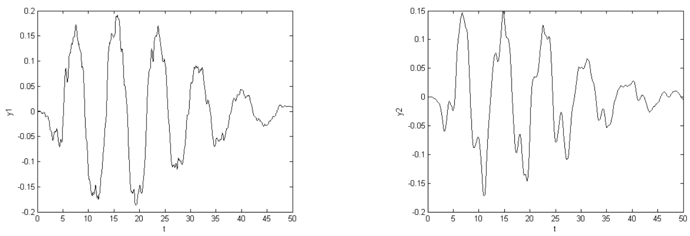


Fig. 5. Relative displacements of structure with semi-active control.

4 Conclusion

The numerical simulation results advocate the advantages of semi-active control of base isolation system for seismic protection:

• The seismic response of both actively and semi-actively controlled structure is lower than that of unprotected structure.

• The semi-active control has almost the same effect on the structural seismic response as the active control, but with much lower energy consumption.

• The results of the numerical simulation have shown that approximately 75.14% of the earthquake duration, the control forces developed by the active system were dissipative forces, i.e., the semi-active sequence is dominant within the active control strategy.

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