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Active Control of a Seismic Soil-Structure Interaction System

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ABSTRACT

This study proposes an active control method to reduce seismic vibrations of a soil-structure interaction system. The proposed control technique is a synthesis of the adaptive input estimation method (AIEM) and the linear quadratic Gaussian (LQG) controller. The AIEM can estimate online the unknown input and optimal states by measuring the dynamic displacement, the optimal estimated states into the feedback control; thereby optimal control forces to reduce vibrations of a soil-structure interaction system. Active vibration control of a soil-structure interaction (SSI) system is performed to verify the feasibility and effectiveness of the proposed algorithm. The simulation results demonstrate that the proposed method is more efficiently than the conventional LQG method.

1. INTRODUCTION

Recent many strong earthquake disasters have occurred all around the world, causing heavy casualties and property loss. Earthquake-resistant technique is very important part in the structure design. During the two last decades, passive and active controls of civil engineering structures have been rapidly developed in the earthquake engineering field. Passive techniques are normally performed by devices known as absorbers or isolators. (Chaudhary 2001) have identified the structural and geotechnical parameters of four base-isolated bridges using available theoretical models and data from recent earthquakes. (Liang 2002) proposed a method for habitability analysis of base-isolated buildings under fluctuating wind loads in the time domain. (Spyrakos 2002) and (Vlassis 2001) performed analytical studies of SSI effects on the longitudinal response of base-isolated bridge piers. (Sarrazin 2005) proposed the response of base-isolated bridges for ambient vibration tests and earthquake excitations in Chile. (Spyrakos 2009) investigated the effect of SSI on the response of base-isolated buildings. In terms of passive control technique, the unwanted vibration problem can be effectively solved using passive control techniques.

In general, active control technique are designed on the Linear Quadratic Regulator (LQR) and LQG theory or H-infinite control theory. Optimal LQR controllers

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have been developed and used in practical implementations (Pourzeynali 2007, Gabbert 2002, Aldawod 2001). Yang (1975) applied the optimal control theorem to control the vibrations of civil engineering structures under stochastic dynamic loads such as earthquakes and wind loads. The traditional optimal controller has difficulty maintaining robust control performance while the external load influence is not considered in the optimal controller design.

This study is to investigate the active control technique application to reduce the SSI response when subjected to earthquake excitation. a synthesis of the AIEM algorithm and LQG controller was proposed in the active control technique. The traditional LQG controller was applied and the performances were compared. Proposed the active LQG controller can apply the same inverse control forces on a structural system in the control procedure. The proposed method control results are effective in suppressing vibration in a SSI system

2. SMART SOIL-STRUCTURE INTERACTION MODEL

The simulated model is shown in Fig. 1. The active control of a seismic soil-structure interaction system movement equation can be written as follows (Wang 2009):

$$M\ddot{X} + C\dot{X} + KX = M\ddot{x}_g(t) + DF(t) \tag{1}$$

where M is the diagonal mass matrix, C is the damping matrix and K is the restoring force vector. $\ddot{x}_g(t)$ is the ground motion acceleration. D is the control force distribution matrix, $F(t)$ is the control force vector. X, $\dot{X}$ and $\ddot{X}$ is the displacements, velocities and accelerations, respectively.
The continuous-time measurement equation is shown below:

$$Z(t) = HX(t) + v(t) \tag{2}$$

where $Z(t)$ is the observation vector, H is the measurement matrix and $v(t)$ is the measurement noise.
The continuous-time state equation of the structural system equation is presented as follows (Tuan 1996):

$$\dot{X}(t) = AX(t) + BG(t) + EF(t) \tag{3}$$

where $A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}_{2(n+2)\times 2(n+2)}$, $B = \begin{bmatrix} 0 \\ -M^{-1}M \end{bmatrix}_{2(n+2)\times 2(n+2)}$,

$$G(t) = \left[\ddot{g}(t) \quad \ddot{g}(t) \quad \cdots \quad \ddot{g}(t)\right]^T_{1\times(n+2)},\ E = \begin{bmatrix} 0 \\ M^{-1}D \end{bmatrix}_{2(n+2)\times 2(n+2)},$$

where $X(t)$ is the modal state vector. A is the coefficient matrix. $F(t)$ is the control force inputs. B and E are the coefficient vectors of $G(t)$ and $F(t)$, respectively. Using the sampling time, Δt, to sample the continuous-time state Eq. (3) and assuming that the system model error, $w(k)\lim\limits_{x\to\infty}$ is Gaussian white noise with zero mean, the discrete-time equation can be obtained as follows (Tuan 1996).

$$X(k+1) = \Phi X(k) + \Gamma G(k) + \Lambda F(k) + v \tag{4}$$

$$X(k) = \left[x_1(k) \quad x_2(k)\right]^T, \quad \Phi = \exp(A\Delta t), \quad \Gamma = \int_{k\Delta t}^{(k+1)\Delta t} \exp\left\{A\left[(k+1)\Delta t - \tau\right]\right\} B d\tau$$

$$\Lambda = \int_{k\Delta t}^{(k+1)\Delta t} \exp\left\{A\left[(k+1)\Delta t - \tau\right]\right\} D d\tau$$

where Φ is the state transition matrix. Γ and Λ are the coefficient matrices of $G(k)$ and $F(k)$, respectively. $G(k)$ is the certain input array. $F(k)$ is the control array. The discrete-time measurement equation of Eq. (2) is shown below:

$$Z(k) = HX(k) + v(k) \tag{5}$$

$Z(k)$ is the discrete observation vector. $v(k)$ represents the measurement noise vector and is assumed as the Gaussian white noise with zero mean and the variance, $E\left\{v(k)v^T(k)\right\} = R\delta_{kj}$, $R = R_v \times I_{2n\times 2n}$, R is the discrete-time measurement noise covariance matrix.

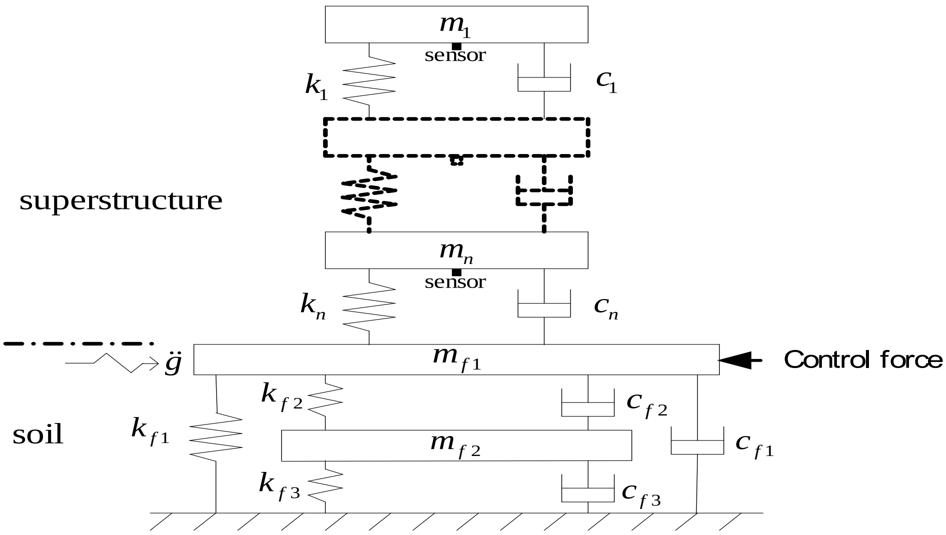

Fig. 1 The active control of a smart soil-structure interaction model

For standard linear quadratic Gaussian problems, the system under control is assumed to be described by the stochastic discrete-time state space equations as below (Lewis 1972):

$$X(k) = \Phi X(k-1) + \Lambda F(k-1) + \Gamma w(k-1) \tag{6}$$

where $w(k)$ is zero-mean white noises with variances Q. The input forces sequence $F(k)$ are neglected or assumed to be zeros in the conventional LQG controller design. From Eq. (6), the conventional LQG control methodology for a system without input forces term is obvious. That is to say, Eq. (6) is not satisfactory for modeling most dynamic structures because there are usually external excitation forces. We therefore considered the case where the input forces are not zeros, i.e., Eq. (4) and (5). However, the conventional LQG control methodology is not applicable to structures without neglecting the input disturbance forces, because the entire input dynamic loads histories are not known a priori. This study proposes combining the AIEM with the LQG control technique for SSI system active vibration control to resolve this situation. The AIEM can estimate the unknown dynamic inputs while the active LQG controller can apply the same inverse control forces on the structural system.The combination of AIEM and the LQG controller is illustrated in Fig. 2.

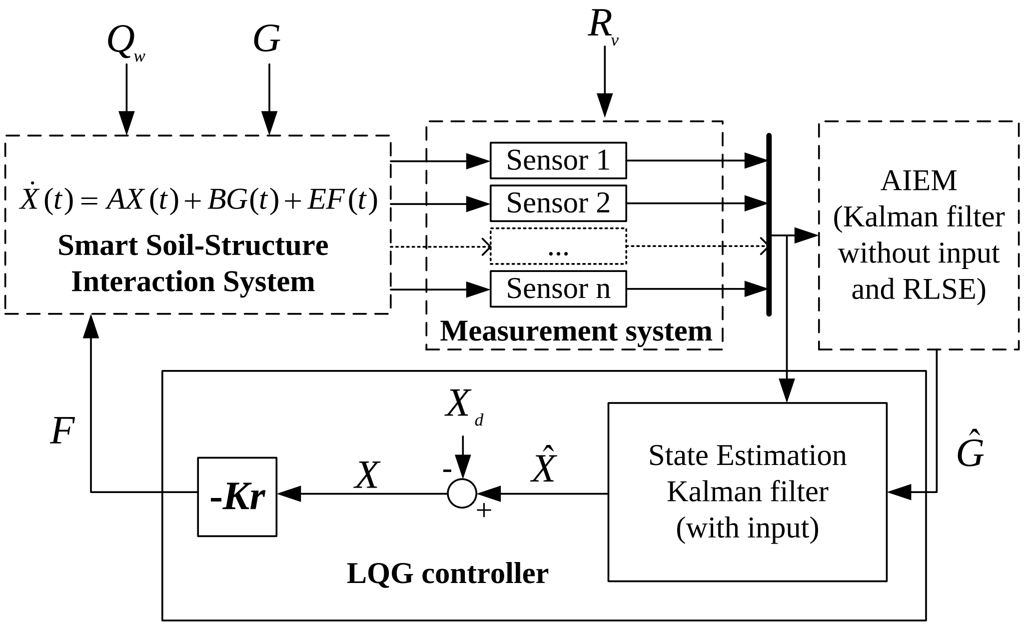

Fig. 2 Flowchart of the AIEM combined with the LQG.

3. CASE STUDY

The simulated case model is shown in Fig. 1. A 5-story building founded on a semi-infinite foundation was used for simulations. The soil was simulated using the lumped parameters developed fallowing section. The experimental structure can also be idealized into mass blocks, springs and dashpots. The foundation associated parameters in Eq. (1) have the following relationship with unified mass, damping and stiffness:

$$m_{fi} = M_{fe} \cdot m^{*}; \quad c_{fi} = C_{fe} \cdot c^{*}_{fi}; \quad k_{fi} = K_{fe} \cdot k^{*}_{fi} \tag{7}$$

where M_{fe}, C_{fe} and K_{fe} are the unified mass, damping and stiffness, respectively. In the case of a strip footing on the elastic foundation, the unified parameters can be calculated according to the following formulas [Wolf 1985]:

$$K_{fe} = K_s = \pi \rho c_s^2; \quad C_{fe} = K_s \frac{r_0}{c_s}; \quad M_{fe} = K_s \cdot \left(\frac{r_0}{c_s}\right)^2 \tag{8}$$

where K_s is the static stiffness, C_s is the shear wave velocity of soil and r_0 is the characteristic length of the foundation. The dynamic-stiffness coefficient of the lumped parameter model is defined and determined using eight parameters: $m^{*}_{f1} \cdots c^{*}_{f3}$. Based on the dynamic stiffness coefficient as developed by (Oien 1971), the eight parameters in this lumped parameter model can be obtained through multiple regression analysis. Table 1 shows the eight coefficients obtained through multiple regression analysis.

Table 1. The parameters of the lumped parameter model

m^*_{f1}	m^*_{f2}	k^*_{f1}	k^*_{f2}	k^*_{f3}	c^*_{f1}	c^*_{f2}	c^*_{f3}
0.035	0.150	1.423	0.716	-0.202	1.724	0.126	0.815

The structure has the following properties: the story mass $m_{1\sim5} = 5.28\times10^4 kg$, the stiffness $k_{1\sim5} = 5.46\times10^7 N/m$, and damping $c_{1\sim5} = 1.47\times10^5 Ns/m$. The structure is built on the surface of a semi-infinite soil foundation with a Poisson's ratio $\nu = 1/3$ and a mass density $\rho = 2000kg/m^3$. To consider the soil foundation stiffness effect, the shear wave velocity, $c_s = 200m/s$ is adopted for soft soil foundation. Substituting the parameters into equation (3), the unified mass, stiffness, and damping of the lumped parameter model can be calculated as follows: $K_{fe} = 2.513\times10^8 N/m$, $C_{fe} = 3.016\times10^7 Ns/m$ and $M_{fe} = 3.619\times10^6 kg$. To further verify that the presented method is feasible for vibration control, we consider the EI CENTRO earthquake. The time histories of the responses for a soil-structure interaction system with and without control are shown in Figs. 3 and 4. The conventional LQG controller has the issue that the unknown input cannot be obtained and the control reaction is slower. The AIEM estimates the unknown input in on-line and combined with the LQG controller (which computes the optimal control force) can be used to obtain better results.

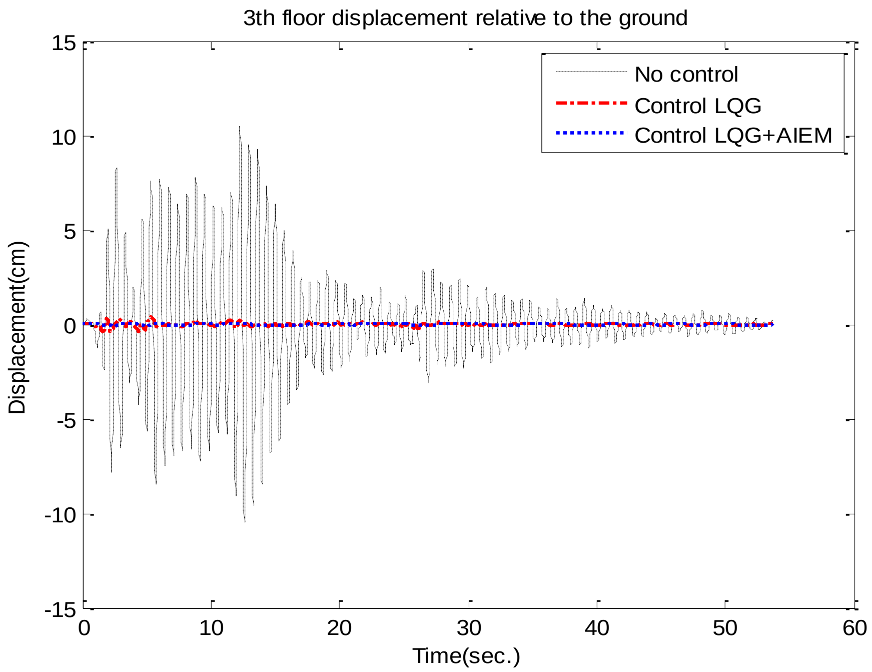

Fig. 3 Comparison of 3th floor displacement control caused by the EI CENTRO earthquake.

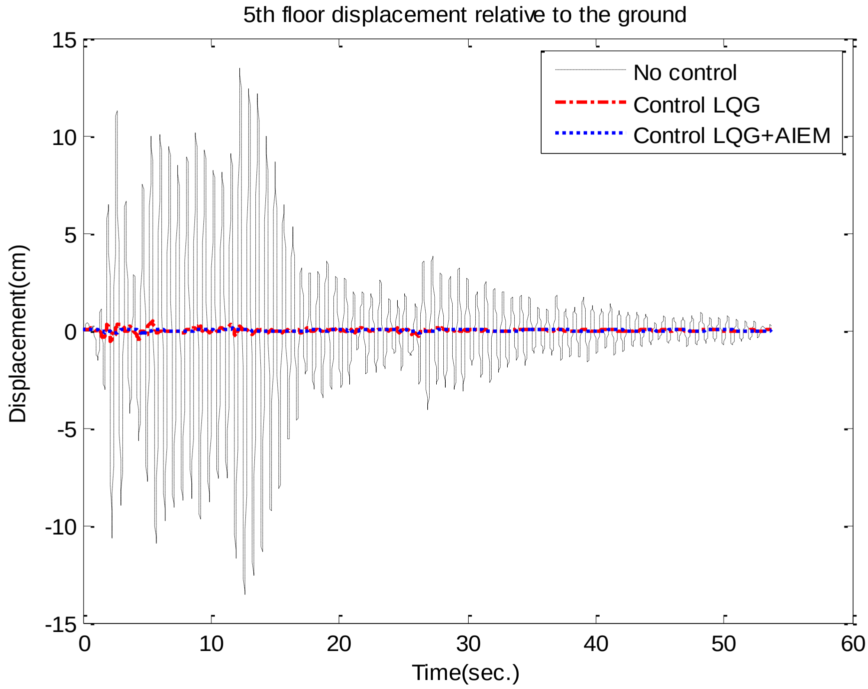

Fig. 4 Comparison of 5th floor displacement control caused by the EI CENTRO earthquake.

4. CONCLUSIONS

An active control technique was proposed for active ground motion acceleration control in a smart soil-structure interaction system. This active control technique demonstrated excellent performance by solving the earthquake-excitation control problem. The simulation results demonstrate that this technique has better active vibration control than the conventional LQG controller. In addition, this technique is effective and useful for active vibration control of a soil-structure interaction system.

5. ACKNOWLEDGMENT

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