고층 빌딩의 진동에 대한 능동제어기의 개발

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A Development of Active Controller for the Vibration of Tall Civil St

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Abstract - This paper is attempt to develop an active controller for the vibration of tall civil structures due to earthquake-induced ground acceleration. Various active control methods are applied to an 8 story base isolated system(BIS) with a turned mass damper(TMD) at the base of the building. The results are also investigated.

1. Introduction

In the recent past, the construction of high-rise buildings has been increasing with the use of lighter and more flexible construction materials. The motion of the tall buildings due to an earthquake could lead to the collapse of the building and the possible loss of the human life. To limit the displacement of the structure within an acceptable range during an earthquake, active control devices can be used. At present, active control of tall civil structures is becoming one of the more important fields of the motion control applications in electrical engineering. The aim of the application of an active control to these structures is to reduce undesirable structural vibrations due to earthquake-induced ground acceleration.

In this study, various active control methods including the proportional control, optimal control and variable structure control as a sliding mode control are applied to an 8 story base isolated system with a tuned mass damper at the base of the building. The various control techniques and its results are compared from the view of the displacement of the structure and applied control force[1].

2. System Description and Modeling

Fig. 1 shows the system model as a BIS having a TMD in the base of the building. Under the assumption that the building structure is sensitive only to horizontal translation vibration and merely one direction of the horizontal translation vibration needs to be considered. The building can then be resolved into a 20th order system model as described below. Also the effects of a TMD system is to provide excellent control by an optimal adjustment subjected to mass, spring, and damper elements for the earthquake-induced ground[2].

Consider the base-isolated structure with TMD in the base floors. Assume that the system is initially to be linear, the equations of motion for the system model subject to the wind-induced excitation at the each floors can be expressed in matrix form as follows:

$$M\ddot{z} + C\dot{z} + Kz = f + u \qquad (1)$$

where

z = vector of building displacements (DOFs)
f = vector of external excitations
u = vector of control forces
M = mass matrix
C = damping matrix
K = stiffness matrix

Eq. (1) can be transformed to first order state space form as

$$\dot{x} = Ax + Bu + Wf \qquad (2)$$

where

$$A = \begin{bmatrix} O & I \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad B = \begin{bmatrix} O \\ M^{-1} \end{bmatrix}, \quad x = \begin{bmatrix} z \\ \dot{z} \end{bmatrix},$$

$$W = \begin{bmatrix} O \\ M^{-1} \end{bmatrix}$$

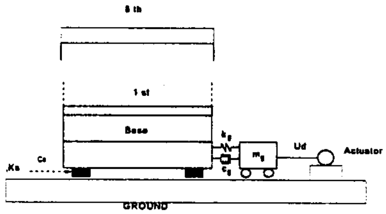

Fig. 1 Building system model.

3. Active Controls of the Tall Civil Stru

3.1 Proportional Control

At a first cut at deal with the active control of the 8 story building, the proportional(P) control is considered. The simplicity of the approach of the P control as one of the active control methods is attractive from both the control and the practical points of view.

3.2 Optimal Control

To solve the optimal control problem, it is required to minimize the response of the closed-loop system and the control effort simultaneously. The form of the performance index usually chosen is the quadratic cost function

$$J = \int^{t_f} \frac{1}{2}\left(x^T Q x + u^T R u \right) dt \tag{3}$$

where Q and R are the performance index matrices which are based on the relative importance of each state and control force. It is required that Q be a semi-positive definite matrix and R be positive definite[3].

For closed-loop control where the control vector is governed by the state vector only, the resulting solution to the optimal control problem takes the form known as the matrix Riccati equation(MRE) as given in basic texts[1] to be

$$\dot{P}(t) = -P(t)A - A^T P(t) + P(t)BR^{-1}B^T P(t) - Q \tag{4}$$

After solving for P, the optimal control force for closed-loop control can be written as

$$u(t) = -R^{-1}B^T P x(t) = -Gx(t) \tag{5}$$

where $G(= R^{-1}B^T P)$ is the control gain matrix.

3.3 Variable Structure Control

Variable Structure Control(VSC) is one of the active control methods applied to the system. Here the equations based on the general linear time-invariant system are given as a procedure of the design of the controller for the system. In general, there are two possible method to find the switching surface, S, a pole-placement (PP) method and a quadratic minimization (QM) method. For a PP method, a system is required for controllable system because the eigenvalues of the transformed system cant be placed arbitrarily in the left-hand side of the complex plane by the S. For the given system, it is impossible to use the PP method due to uncontrollable system.

To find the switched feedback gains for the VSC controller, the state trajectory have to follow the switching surface and eventually maintain the trajectory on the surface. The control function is chosen as

$$u_i = \begin{cases} u_i^+ & \sigma_i(x) > 0 \\ u_i^- & \sigma_i(x) < 0 \end{cases} \tag{6}$$

where

$$u = [u_1 \ \ u_2 \ \ . \ . \ \ u_m]^T$$

$$\sigma(x) = [\sigma_1(x) \ \ \sigma_2(x) \ \ . \ . \ \ \sigma_m(x)]^T \tag{7}$$

After chosen the control function, the sliding surface is previously chosen as

$$\sigma(x) = Sx \tag{8}$$

After choosing the appropriate matrix Q, the new control law is given by

$$u^* = Q^{-1}[SB]u = Kx \tag{9}$$

To compute the gains,

$$\dot{\sigma} = SAx + u^* \tag{10}$$

Thus, the control u(x) can be solved by constraining the switching function to the following condition

$$\sigma\dot{\sigma} < 0 \tag{11}$$

To satisfy the existence conditions, the elements of the gain matrix K_{1i} are derived. Therefore, the actual control vector is given by

$$u = (SB)^{-1}Qu^* = (SB)^{-1}QKx \tag{12}$$

Finally the obtained actual control vector is applied to the state equation as following.

$$\dot{x} = Ax(t) + Bu(t) + E y_0 \qquad (13)$$

To solve the $\dot{x}$, there are some possible ways to find the $\dot{x}$. In this study, the Runge-Kutta method is applied.

4. Simulation Results and Discussions

4.1 Responses of the building for acceleration with no control

Fig. 2(a)-(b) shows the response of the building during an earthquake. Each of the floor displacements, base displacement and damper stroke are plotted. The base has a maximum displacement swing of about 24.11 cms. Fig. 2(c)-(f) shows the energy and power developed by the building during an earthquake.

4.2 Proportional Control

One of the several simulations is presented to Fig. 3 for gain K = 620.56. The maximum displacement swing is seen to reduce by about 2.4cms and control force has a peak of about 75 kN. But the most important aspect of this gain is that there are sustained oscillations of the magnitude greater than that of the building with no control and the reduction of the peak displacement by about 10 % cant justify the magnitude of the sustained oscillations later in the simulation.

4.3 Optimal Control

To examine the control performance, the LQR controller is designed using the weighting matrix Q and R. In the LQR design, finding best choice of Q and R is one of the most difficult steps. Here the weighting matrix is chosen by the based on the verification of the system dynamics using the trial and error method subject to the control concepts. But a closed form result for the optimal control law is not available. To find the proper Q and R, the lqr and lsim commands in the MATLAB program is repeated until these value is smaller than without LQR.

As shown in Fig. 4, an intuitive approach would demand that the focus is on the base displacement and accordingly the Q matrix was chosen as a zero matrix with only the element Q(2,2) = 2,000,000. This particular selection results in the reduction of the base displacement by about 25% and the control force required is about 1,000 kN peak. It can be argued that the focus of the selection of Q was 1 dimensional, but if we are to restrict ourselves to a reasonable control force, the selection of the one element gives rise to a very good performance.

4.4 Variable Structures Control (VSC)

VSC seems to provide a much better control option than any of the methods discussed above provided accurate tuning is done. As shown in Fig. 5 as one of results through VSC, when the Q matrix is chosen as an Identity Matrix with Q(2,2) = 3,950, the maximum displacement swing has been considerably reduced when compared to the optimal control. The maximum control force has a maximum value of less than 2,500 kN. Also the base displacement and the damper position seem to be reaching a more acceptable steady state value. This means that accurate selection of the Q matrix is required but once the selection is done the control methodology is superior to the other methods.

5. Conclusions

This study presented above brings us to the following conclusions: 1) Proportional control would be of no use in active control of tall civil structures when the external force is an earthquake. 2) Optimal control seems to be an excellent strategy for the control of the linear model but the fact that all the states may not be available to the user and proper estimation of states may have to be done should be taken into consideration. 3) Variable structure control is an effective strategy providing accurate tuning of the system is done. This model may also require estimation of states.

6. References

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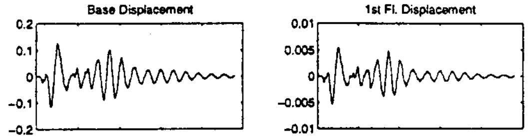
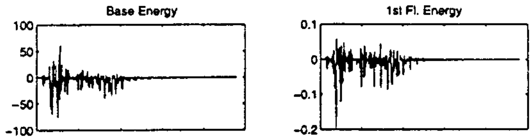
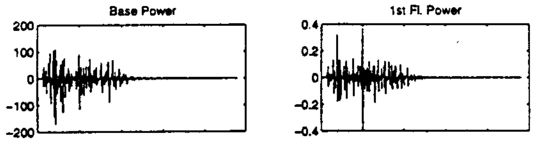


(a) Base Displacement [m] (b) 1st Floor Displacement [m]

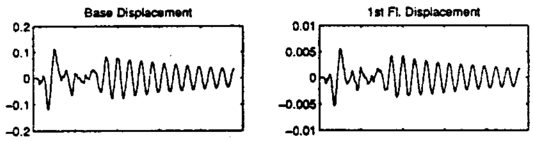


(c) Base Energy [kJ] (d) 1st Floor Energy [kJ]

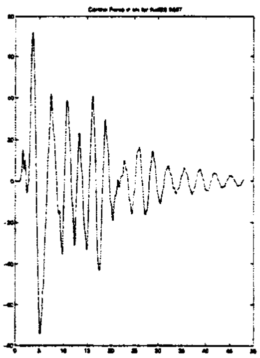


(e) Base Power [kW] (f) 1st Floor Power [kW]

Fig. 2 No Control.

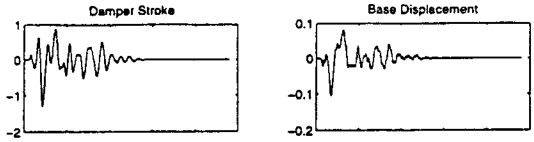


(a) Base Displacement [m] (b) 1st Floor Displacement [m]

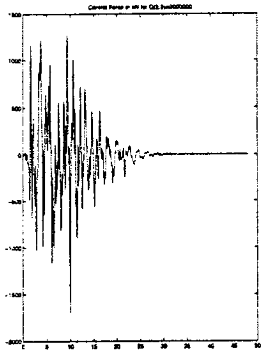


(c) Control Force [kN]

Fig. 3 Proportional Control with K = 620.56.

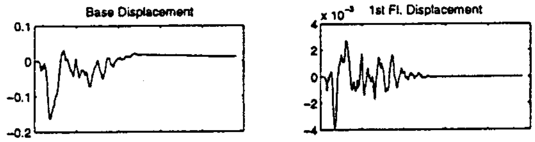


(a) Base Displacement [m] (b) 1st Floor Displacement [m]

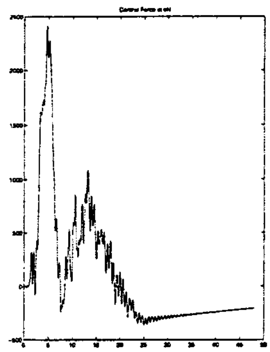


(c) Control Force [kN]

Fig. 4 Optimal Control with Q(2,2) = 2,000,000.



(a) Base Displacement [m] (b) 1st Floor Displacement [m]



(c) Control Force [kN]

Fig. 5 Variable Structures Control with Q(2,2) = 3,950.