MR Damper를 이용한 지진하중을 받는 구조물의 모드 제어

Implementation of Modal Control for Seismically Excited Structures Using MR Damper

조상원* · 정형조** · 오주원*** · 이인원****

Cho, Sang-Won · Jung, Hyung-Jo · Oh, Ju-Won · Lee, In-Won

1. 서 론

Magnetorheological (MR) dampers are one of semi-active control devices, which use MR fluids to provide controllable damping forces. A number of control algorithms have been adopted for semi-active systems including the MR damper. Jansen and Dyke (2000) discussed recently proposed semi-active control algorithms and formulated these algorithms for use with MR dampers and evaluated and compared the performance of each algorithm. Modal control represents one control class, in which the motion of a structure is reshaped by merely controlling some selected vibration modes. The motion of the structure can be effectively suppressed by merely controlling these few modes. A modal control scheme, which uses modal state estimation, is desirable (Meirovitch 1990).The purpose of this study is to implement modal control for seismically excited structures that use MR dampers and to compare the performance of the proposed method with that of other control algorithms previously studied.

2. Modal Control Scheme for MR dampers

2.1 Modal Control

Consider a seismically excited structure controlled with m MR dampers. In modal control, only a limited number of lower modes are controlled. Hence, l controlled modes can be selected with $l < n$ and the displacement may be partitioned into controlled and uncontrolled parts as $x(t) = x_c(t) + x_R(t)$, where x_c and x_R represent the controlled and uncontrolled displacement vector, respectively. We refer to the uncontrolled modes as residual. Considering orthogonal condition between eigenvectors, we obtain

$$\ddot{\eta}_r + 2\zeta_r\omega_r\dot{\eta}_r + \omega_r^2\zeta_r = \phi_r^T\Lambda f - \phi_r^T\Gamma\ddot{x}_g\ , \quad r = 1,\ 2,\ldots,\ l \tag{1}$$

where $\eta_r(t)$ is r th modal displacement; ϕ_r is the r th natural frequency; Φ is a eigenvector set; η is a modal dispacement; ζ_r are modal damping ratios;and ω_r is a natural frequency; $f = [\ f_1,\ f_2, \cdot,\ f_m\ ]^T$ is the vector of measured control forces generated by m MR dampers; $\ddot{x}_g$ is ground acceleration; Γ is the column vector of ones; and Λ is the matrix determined by the placement of MR dampers in the structure. Then, Equation (1) can be rewritten in state-space form such as

$$\dot{w}_c(t) = A_c(t)\,w_c(t) + B_c f(t) + E_c\ddot{x}_g,\ y_c(t) = C_c w_c(t) \tag{2}$$

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* 한국과학기술원 건설및환경공학과 박사과정 · 공학석사 · 042-869-3658(E-mail:kimbw@kaist.ac.kr)
** 정회원 · 한국과학기술원 건설및환경공학과 연구조교수 · 공학박사 · 042-869-5658(E-mail:hjung@mail.kaist.ac.kr)
*** 정회원 · 한남대학교 토목환경공학과 교수 · 공학박사 · 042-629-7560(E-mail:ohjw@mail.hannam.ac.kr)
**** 정회원 · 한국과학기술원 건설및환경공학과 교수 · 공학박사 · 042-869-3618(E-mail:iwlee@kaist.ac.kr)

where w_c is a $2l$-dimensional modal state vector by the controlled modes and

$$A_c=\begin{bmatrix} 0 & I_c \\ -\Omega_c^2 & -\Delta_c \end{bmatrix},\ B_c=\begin{bmatrix} 0 \\ B'_c \end{bmatrix},\ E_c=\begin{bmatrix} 0 \\ E'_c \end{bmatrix} \tag{3}$$

are the $2l\times 2l$, $2l\times m$ matrixes and a $2l\times 1$ vector, respectively, and Δ_c is the diagonal matrix listing $2\omega_r\zeta_r$; Ω_c^2 is the diagonal matrix listing $w_1^2,\ldots, w_n^2$; $B_c'=\Phi^T\Lambda$; and $E_c'=\Phi^T\Gamma$. For feedback control, the control vector is related to the modal state vector according to

$$f(t)=-K_c w_c(t) \tag{4}$$

where K_c is an m×$2l$ control gain matrix. Because the force generated in the i th MR damper depends on the responses of the structural system, the MR damper cannot always produce the desired optimal control force f_{Ci}. Thus, the strategy of a clipped-optimal control(Dyke et al. 1996) is used. Referring to the discussions in above section, control gain matrix K_c should be decided. Although a variety of approaches may be used to design the optimal controller, H2/LQG (Linear Quadratic Gaussian) methods are advocated because of their successful application in previous studies (Dyke et al. 1996).

2.2 Modal State Estimation

To estimate the modal state vector $w_c(t)$ from the measured output $y(t)$, we consider a Kalman-Bucy filter as an observer(Meirovitch, 1990). Not only, in this paper, the state feedback including velocities or displacements is considered, but also the acceleration feedback is implemented for the modal state estimation using a Kalman-Buch filter. Then we can write the observer equation in the form

$$\dot{\hat{w}}_c(t)=(A_c-B_cK_c)\,\hat{w}_c(t)+LC_c(w_c-\hat{w}_t)+LC_Rw_R(t)+E_c\,\ddot{x}_g \tag{5}$$

where $w_c(t)$ is the estimated controlled modal state and L is the optimally chosen observer gain matrix by solving a matrix Riccati equation, which assumes that the noise intensities associated with earthquake and sensors are known. C_c is changeable according to the signals which are used for the feedback and D_c is generally zero except the acceleration feedback. The error vector is defined such as $e_c(t)=\hat{w}_c(t)-w_c(t)$. Then the Equations can be written in the matrix form

$$\begin{bmatrix} \dot{w}_c(t) \\ \dot{w}_R(t) \\ \dot{e}_c(t) \end{bmatrix}=\begin{bmatrix} A_c-B_cK_c & 0 & -B_cK_c \\ -B_RK_c & A_R & -B_RK_c \\ 0 & LC_R & A_c-B_cK_c \end{bmatrix}\begin{bmatrix} w_c(t) \\ w_R(t) \\ e_c(t) \end{bmatrix}+\begin{bmatrix} E_c \\ E_R \\ E_c \end{bmatrix}\ddot{x}_g \tag{6}$$

Note that the term $-B_RK_c$ in Eq. (6) is responsible for the excitation of the residual modes by the control forces and is known as control spillover. If C_R is zeros, which means the sensor signal only include controlled modes, the term $-B_RK_c$ has no effect on the eigenvalues of the closed-loop system. Hence, we conclude that control spillover cannot destabilize the system. Normally, however, the above system can not satisfy the separate principle because the term LC_R affects eigenvalues of the controlled system by the observer. This effect is observation spillover and can produce instability in the residual modes. However, a small amount of damping inherent in the structure is often sufficient to overcome the observation spillover effect.

3. 수치 예제

To evaluate the proposed modal control scheme for use with the MR damper, a numerical example is considered in which a model of a six-story building is controlled with four MR dampers (그림 1.). This numerical example is the same with that of Jansen and Dyke (2000) and is adopted for direct comparisons between the proposed modal control scheme and other control algorithms. In simulation, the model of the structure is subjected to the NS component of the 1940 El Centro earthquake. Because the building system considered is a scaled model, the amplitude of the earthquake was scaled to ten percent of the full-scale earthquake. The various control algorithms were evaluated using a set of evaluation criteria based on those used in the second generation linear control problem for buildings (Spencer and Sain 1997) such as

$$J_1 = \max\left(\frac{|x_i(t)|}{x^{\max}}\right),\ J_2 = \max\left(\frac{|d_i(t)/h_i|}{d_n^{\max}}\right),\ J_3 = \max\left(\frac{|\ddot{x}_{ai}(t)|}{\ddot{x}_a^{\max}}\right),\ J_4 = \max\left(\frac{|f_i(t)|}{W}\right) \tag{5}$$

For modal control, three cases of the structural measurements are considered; displacements, velocities and accelerations. Using each structural measurement, a Kalman filter estimates the modal states. 그림 2. represents the variations of each evaluation criteria for increasing weighting parameters in a 3-dimensional plot. J_T is the summation of evaluation criteria, J_1, J_2 and J_3. We can find the weighting for reduction of overall structural responses from the variations of JT, whereas we can find the weighting for reduction of related responses from J_1, J_2 and J_3, Designer can decide which to use according to control objectives. By using the controller (H2/LQG) with designed weighting matrices from 그림 2. we can get the results in 표 1.

4. 결론

In this paper, modal control was implemented to seismically excited structures using MR dampers. To this end, a modal control scheme was applied together with a Kalman filter and a low-pass filter. A Kalman filter considered three cases of the structural measurement to estimate modal states: displacement, velocity, and acceleration, respectively. Moreover, a low-pass filter was used to eliminate spillover problem. In designing phase of controller, the size of weighting matrix $\boldsymbol{Q}$ was reduced because the lowest one or two modes were controlled. Therefore, it is more convenient to design the smaller weighting matrix of modal control. This is one of the important benefits of the proposed modal control scheme. The numerical results show that the motion of the structure was effectively suppressed by merely controlling a few lowest modes, although resulting responses varied greatly depending on the choice of measurements available and weightings. The modal controller $\boldsymbol{A}$ and $\boldsymbol{V}$ achieved significant reductions in the responses. The modal controller $\boldsymbol{A}_{J2}$, $\boldsymbol{V}_{J2}$ and $\boldsymbol{V}_{J3}$ achieve reductions (39%, 30%, 30%) in evaluation criteria J_1, J_2 and J_3, respectively, resulting in the lowest values of all cases considered here. The modal controller $\boldsymbol{A}_{JT}$ and $\boldsymbol{V}_{JT}$ fail to achieve any lowest value of evaluation criteria, but have competitive performance in all evaluation criteria. Based on these results, the proposed modal control scheme is found to be suited for use with MR dampers in a multi-input control system.

표 1. Normalized Controlled Maximum Responses of the Various Feedback due to the Scaled El Centro Earthquake

Control strategy	**Weighting parameters**	***J1***	***J2***	***J3***	***J4***
Passive-off	-	0.862	0.801	0.904	0.00292
Passive-on	-	0.506	0.696	1.41	0.0178
Modal control **A**J1	qmd=400, qmv=1500	0.310(-39)	0.529(-24)	1.07(+18)	0.0178
Modal control **A**J2	qmd=1, qmv=500	0.398(-21)	0.485(-30)	0.870(-4)	0.0178
Modal control **A**J3	qmd=2200, qmv=100	0.549(+8)	0.618(-11)	0.697(-23)	0.0176
Modal control **A**JT	qmd=500, qmv=600	0.380(-25)	0.488(-30)	0.823(-9)	0.0178
Modal control **D**J1	qmd=100, qmv=4900	0.403(-20)	0.560(-20)	0.765(-15)	0.0177
Modal control **D**J2	qmd=100, qmv=4900	0.403(-20)	0.560(-20)	0.769(-15)	0.0178

Modal control **D**J3	qmd=200, qmv=4900	0.702(+39)	0.728(+5)	0.671(-26)	0.0178
Modal control **D**JT	qmd=3300, qmv=4700	0.408(-19)	0.566(-19)	0.721(-20)	0.0178
Modal control **V**J1	qmd=700, qmv=800	0.327(-35)	0.554(-20)	1.06(+17)	0.0178
Modal control **V**J2	qmd=1, qmv=400	0.383(-24)	0.487(-30)	0.874(-3)	0.0177
Modal control **V**J3	qmd=1300, qmv=100	0.541(+7)	0.611(-12)	0.632(-30)	0.0178
Modal control **V**JT	qmd=600, qmv=500	0.354(-30)	0.502(-28)	0.825(-9)	0.0176

그림 1. 예제구조물

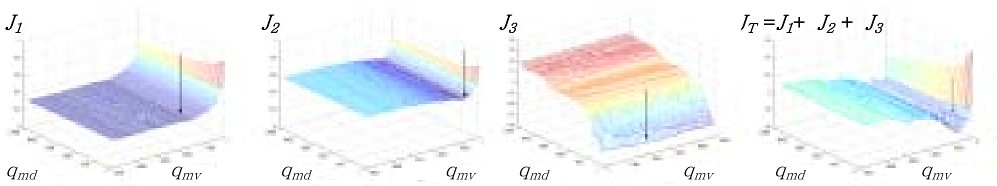

그림 2. Variations of Evaluation Criteria with Weighting Parameters

감사의 글

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