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강인 복합제어 시스템
Robust Hybrid Control System

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ABSTRACT

This paper presents a robust hybrid control system for seismic response control of a cable-stayed bridge. Because multiple control devices are operating, a hybrid control system could alleviate some of restirctions and limitations that exist when each system is acting alone. A LQG algorithm with on-off control scheme, H_2 and H_∞ control algorithms with various frequency weighting filters are used to improve the controller robustness of the active control part in the hybrid control system. The numerical simulation results show that control performances of robust hybrid control systems are similar to those of the hybrid control system with LQG algorithm. Furthermore, it is verified that robust hybrid control systems are more robust than the hybrid control system with LQG algorithm and there are no signs of instabilities in the ±5% stiffness matrix perturbed system. Therefore, the proposed hybrid control system have a good robustness for stiffness matrix perturbation without loss of control effectiveness.

1. 서 론

복합제어 시스템은 일반적으로 수동과 능동제어 장치가 결합된 시스템이다. 따라서 복합제어 시스템은 수동이나 능동제어 장치만을 사용할 경우에 발생할 수 있는 문제점을 완화시킬 수 있다. 하지만 복합제어 시스템에 사용되는 능동제어 장치로 인해 전체적인 강인성이 저하될 수 있다. 따라서 복합제어 시스템의 강인성을 향상시키기 위해 능동제어 장치의 강인성을 확보할 수 있는 제어 알고리즘을 사용해야 한다.

본 연구에서는 납고무받침과 유압식 가력기가 결합된 복합제어 시스템을 사용하였다. 또한 능동

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such as small power requirements, reliability, and inexpensive to manufacture (Dyke and Spencer 1996). So that, a number of control algorithms have been adopted for semiactive control systems using MR dampers (Jansen and Dyke 2000).

In the mean time, benchmark problems have been recognized as a means to compare and contrast various structural control strategies. Benchmark structural control problems allow researchers to apply various algorithms, devices, and sensors to a specified problem and make direct comparisons of the results in terms of a specified set of performance objectives. Additionally, theses problems may include control constraints and hardware models to more accurately portray the types of implementation issues and constraints one must consider in reality. Several benchmark studies were posed to help the realization and implementation of innovative control strategies for dynamic hazard mitigation.

In this paper, in an effort to improve applicability, MEDA is applied to benchmark cable-stayed bridge. Jansen and Dyke (2000) suggest MEDA as a variation of the decentralized bang-bang approach proposed by McClamroch and Gavin (1995). However, this approach has not yet been applied to real-size civil engineering structures. Also, their potential for civil engineering applications using semiactive control, especially for MR dampers, has not yet been fully exploited. Thus, we examine the applicabity in point of performance and robustness of the MEDA-based semiactive control system using MR damper through a series of numerical simulations and compare the results with thoses of other control algorithms.

2. Benchmark Cable-Stayed Bridge

At the Second International Workshop on Structural Control (Dec. 18-20, 1996, Hong Kong), the Working Group on Bridge Control developed plans for a "first generation" benchmark study on bridgesand they recently posed a first-generation benchmark structural control problem based upon the Cape Girardeau Bridge.

Figure 1 shows the three-dimensional (3D) view of the Cape Girardeau Bridge. A three-dimensional finite-element analysis of the bridge was completed, and an evaluation model having 419 degrees of freedom (DOF) was developed. The system matrices are provided at the benchmark web site: http://wusceel.cive.wustl.edu/quake

3. Control system

3.1 Control Devices

MR damper with capacity of 1000KN is considered as control devices. To accurately predict the behavior of controlled structure, an appropriate modeling of MR fluid dampers is essential. Several types of control-oriented dynamic models have been investigated for modeling MR fluid dampers. Herein, the Bouc-Wen model is considered. The Bouc-Wen model(Spencer et al, 1997), which is numerically tractable and has been used extensively for modeling hysteretic system, is considered for describing the behavior of the MR damper(Figure 3). The force generated by the damper is given by

$$f = \alpha z + c_0 \dot{x} \tag{1}$$

where the evolutionary variable z is governed by

$$z = -\gamma\,|\dot{x}|\,z\,|z|^{n-1} - \beta\dot{x}\,|z|^{n} + A\dot{x} \tag{2}$$

By adjusting the parameters of the model γ, β, n and A, the degree of linearity in the unloading and the smoothness of the transition from the pre-yield to the post-yield region can be controlled.

Some of the model parameters depend on the command voltage u to the current driver as follows.

$$\alpha = \alpha_a + \alpha_b u \ \text{ and } \ c_0 = c_{0a} + c_{0b} u \tag{3}$$

Parameters for the MR damper are listed in Table 1. Parameters are from Moon et al. (2003).

3.2 Controller Design

This control algorithm is presented as a variation of the decentralized bang-bang approach proposed by McClamroch and Gavin (1995). In the decentralized bang-bang approach, the Lyapunov function was chosen to represent the total vibratory energy in the system. Jansen and Dyke (2000) instead consider a Lyapunov function that represents the relative vibratory energy in the structure as in

$$\boldsymbol{V} = \frac{1}{2}\boldsymbol{x}^T \boldsymbol{K} \boldsymbol{x} + \frac{1}{2}\boldsymbol{x}^T \boldsymbol{M} \boldsymbol{x} \tag{4}$$

where $\boldsymbol{x}$ = vector of the relative displacements of the floors of the structure. The term that can be directly affected by changes in the control voltage is identified, and the following control law is obtained:

$$\boldsymbol{v}_i = \boldsymbol{V}_{\max} \boldsymbol{H}(-\dot{\boldsymbol{x}} \boldsymbol{\Lambda}_i \boldsymbol{f}_i) \tag{5}$$

where $\boldsymbol{\Lambda}_i$ = ith column of the $\boldsymbol{\Lambda}$ matrix; $\boldsymbol{\Lambda}$ = vector determined by the placement of the MR dampers in the structure; $\boldsymbol{f}_i$ = *i*th column of the $\boldsymbol{f}$ matrix; $\boldsymbol{f}$ = $[\boldsymbol{f}_1, \boldsymbol{f}_2, \boldsymbol{f}_n]$ = vector of measured control forces, generated by the *n* MR dampers. Note that this equation is also a bang-bang control law. As in the decentralized bang-bang approach, only local measurements (i.e., the velocity and control force) are required to implement this control law. There is no weighting matrix to be decided in control law as in eq.(5). This is the important benefit of using MEDA for MR damper control. Therefore, it can be said that it is more convenient to use MEDA for structural control, especially for the large-size civil structures for which it is not easy to decide the weighting matrix because of the large DOFs.

4. Numerical Examples

We examine the applicabity in point of performance and robustness of the MEDA-based semiactive control system using MR damper through a series of numerical simulations and compare the result with thoses of other control algorithms.

4.1 Control Performance

The control performane of MEAD-based control system using MR damper for the benchmark problem is demonstrated by numeircal simulatoion. Evaluation of the control performance is carried out using the evaluation criteria provided in the each benchmark problem statement. Table 2 shows the values of the evaluation criteria for the benchmark cable-stayed bridge under various earthquakes. 24 MR dampers are employed between the deck and abutment and the deck and tower of the bridge, all oriented to apply forces longitudinally. Four devices are located between each of the following pairs of nodes on bent 1 and pier 3; and, two devices are located between each of the following pairs of nodes on piers 2 and 4. For comparison, other semiactive control systems, clipped optimal controller(CO; Yoshida and Dyke, 2002) and sliding mode controller(SMC; Moon et. al, 2003), are considered.

The numerical results show that MEDA can reduce the vibration of the seismically excited structure effectively. Though MEDA fails to achieve more reductions over other controllers, it has comparable performance without any controller-design process.

4.2 Controller Robustness

The dynamic characteristics of the real structure may not be identical to those of the evaluation model. Therefore, the controller robustness of the MEDA-based semiactive control system using MR damper was examined for the benchmark cable-stayed bridge. The stiffness matrix is perturbed by some factor , and the resulting bridge model was simulated using the controller for the nominal system. The perturbed stiffness was calculated as

$$\boldsymbol{K}_{pert} = \boldsymbol{K}(1+\varepsilon) \tag{6}$$

where $\boldsymbol{K}$ = nominal stiffness of the bridge, ε = perturbation parameter, and $\boldsymbol{K}_{pert}$ = perturbed stiffness. Perturbations of 7% were considered. The configuration of MR dampers are followings; Four devices are located between each of the following pairs of nodes on bent 1 and pier 4; and, two devices are located between each of the following pairs of nodes on piers 2 and 3. Table 3 shows evaluation criteria for 7% stiffness perturbed system under El Centro earthquake. The robustness of MEDA is compared to that of SMC which is known as robust controller(Moon et al, 2003), and the nominal performance is listed for comparison with the perturbed performance. As you can see, MEDA is stable and performs well for 7% perturbed system.

5. Conclusions

The numerical results show that MEDA can reduce the vibration of the seismically excited structure effectively. Though MEDA fails to achieve more reductions over other controllers, it has comparable performance without any controller-design process. This is the important benefit of using the MEDA. Also, robustness of MEDA is investigated with respect to the uncertainties in stiffness. For 7% perturbed system, MEDA is stable and performs well.

The MR damper is an attractive control device for structural applications. With this study, we confirm the aplicability in point of performance and robustness of the semiactive MR damper system using maximum energy dissipation algorithm for seismic response reduction in large-scale structures.

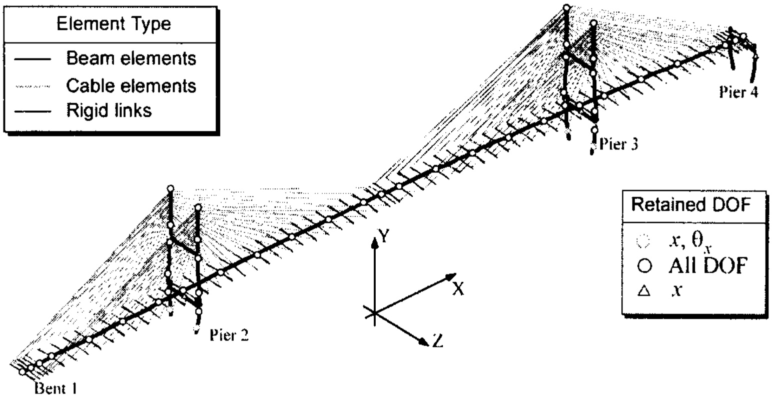

Figure 1. Finite Element Model of the Cape Girardeau Bridge

Table 1. Parameters for MR Damper Model

Parameter	Value	Parameter	Value
	For Cable-Stayed Bridge		For Cable-Stayed Bridge
α_a	500 N/m	γ	300 m^{-2}
α_b	671.41 N/(mV)	β	300 m^{-2}
c_{0a}	0.15 Ns/m	A	120
c_{0b}	1.43 Ns/(cmV)	n	1
η	300 s^{-1}		

Table 2. Comparisons of Evaluation Criteria for Benchmark Cable-Stayed Bridge

Controller	J_1			J_2		
	El Centro	Mexico	Gebze	El Centro	Mexico	Gebze
CO	0.391	0.469	0.415	1.084	1.179	1.376
SMC	0.397	0.453	0.392	1.090	1.068	1.146
MEDA	0.331	0.593	0.453	1.108	1.315	1.447

Controller	J_3			J_4		
	El Centro	Mexico	Gebze	El Centro	Mexico	Gebze
CO	0.267	0.466	0.395	0.537	0.472	0.953
SMC	0.300	0.488	0.382	0.557	0.408	1.053
MEDA	0.255	0.558	0.355	0.464	0.381	0.779

Controller	J_5			J_6		
	El Centro	Mexico	Gebze	El Centro	Mexico	Gebze
CO	0.189	0.060	0.142	0.933	1.282	2.519
SMC	0.205	0.056	0.159	0.880	1.578	2.941
MEDA	0.185	0.079	0.143	0.709	0.694	1.266

Controller	J_7			J_8		
	El Centro	Mexico	Gebze	El Centro	Mexico	Gebze
CO	0.234	0.440	0.328	0.975	1.147	1.331
SMC	0.217	0.372	0.286	0.903	0.902	1.271
MEDA	0.234	0.464	0.318	0.883	1.064	1.128

Controller	J_9			J_{10}		
	El Centro	Mexico	Gebze	El Centro	Mexico	Gebze
CO	0.300	0.393	0.391	0.624	0.656	1.194
SMC	0.193	0.315	0.380	0.577	0.720	1.487
MEDA	0.233	0.453	0.348	0.552	0.552	1.123

Controller	J_{11}		
	El Centro	Mexico	Gebze
CO	0.020	0.007	0.012
SMC	0.018	0.006	0.012
MEDA	0.020	0.011	0.010

Table 3. Evaluation Criteria for 7% Stiffness perturbed System under El Centro Earthquake

	SMC(Moon et al. 2003)		MEDA	
	$\varepsilon = 0$	$\varepsilon = \pm 7\%$	$\varepsilon = 0$	$\varepsilon = \pm 7\%$
J_1	0.394	0.432	0.331	0.395
J_2	1.130	1.323	1.108	1.347
J_3	0.296	0.335	0.255	0.278
J_4	0.560	0.540	0.464	0.443
J_5	0.213	0.224	0.185	0.219
J_6	0.870	0.862	0.709	0.692
J_7	0.218	0.235	0.234	0.233
J_8	0.887	0.901	0.883	0.891
J_9	0.189	0.198	0.233	0.215
J_{10}	0.551	0.556	0.552	0.547
J_{11}	0.016	0.017	0.020	0.020

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