MAXIMUM ENERGY DISSIPATION ALGORITHM FOR SEISMIC RESPONSE REDUCTION OF LARGE SCALE STRUCTURES USING MR DAMPERS

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ABSTRACT : This paper proposes the implementation of the meximum energy dissipation algorithm for seismic structures using magnetorheological (MR) dampers. Numerous control algorithms have been adopted for semiactive systems including MR dampers. In spite of some advantages of each algorithm, there are not much differences in the performance. Among many control algorithms, the meximum energy dissipation algorithm represents one control class which employs the Lyapunov's direct approach to stability analysis in the design of a feedback controller. Although the meximum energy dissipation algorithm was introduced 15 years ago, their potential for civil engineering applications using semiactive control, especially for MR dampers, has not yet been fully exploited. This paper investigates the applicability of the maximum energy dissipation algorithm for civil engineering structures through the large-scale numerical examples. The numerical examples contain the cable-stayed bridge and nonlinear building. Through the numerical examples, the performance is compared with that of other control algorithms which are previously proposed. In simulation, various earthquakes are used to excite the system and the reduction in the drifts, accelerations, and relative displacements throughout the structure is examined according to the evaluation criteria.

KEYWORDS: Maximum energy dissipation algorithm, semiactive control, MR damper, robustness, nonlinear control, benchmark cable-stayed bridge, Benchmark problem

1. INTRODUCTION

Growing number of large-scale structures give rise to more research on the seismic protection of structures. Passive and active control systems are representative supplemental damping strategies for response reduction in civil engineering structures subjected to earthquakes and winds. On the other hand, semiactive control systems combine the advantages of both approaches. Magnetorheological (MR) dampers one of quite promising semiactive control devices, which use MR fluids to provide controllable damping forces. MR dampers are suitable to civil engineering applications, since they have many attractive features 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

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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 those benchmark structures. 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 of benchmark problems and compare the result with thoses of other control algorithms.

2. BENCHMARK PROBLEM

2.1 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 bridges and they recently posed a first-generation benchmark structural control problem based upon the Cape Girardeau Bridge. **Figure 1** shows the three-dimensional (3–D) 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

2.2 Nonlinear Benchmark Building

During the 2nd World Conference on Structural Control(June 28 – July 1, 1998, Tokyo), as a result of the success of the linear benchmark's presented, it was decided to pursue the nonlinear analysis for the seismically excited buildings. Nonlinear benchmark building considered here is the 20-story benchmark building specified in the benchmark problem statement (http://wusceel.cive.wustl.edu/quake). This benchmark study focuses on an in-plane (2–D) analysis of the benchmark structures. **Figure 2** shows the schematic of the 20-story nonlinear benchmark building.

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 both benchmark problems are listed in **Table 1**. Each parameter is from Yoshida and Dyke(2002) for nonlinear benchmark building and from Moon et al.(2003) for cable-stayed bridge.

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

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

where 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:

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

where Λ_i = *i*th column of the Λ 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; $\boldsymbol{f} = [\boldsymbol{f}_1, \boldsymbol{f}_2, \ldots, \boldsymbol{f}_n]$ = 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 decide or design in control law in eq.(5). This is the important benefit of using MR damper with the EMI system. Therefore, it can be said that it is more convenient to use MEDA for structural control, especially for the large-size civil structures.

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 of benchmark problems 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 problems 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 damper 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.

Table 3 shows evaluation criteria for the nonlinear benchmark building. The total number of MR damper is 65. Four devices are located on the first eight stories, three devices are located on the next nine stories, and two devices are located on the top three stories. For comparison, clipped optimal controller is considered. The building was subjected to the four earthquakes specified in the benchmark paper with various intensity.

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 designed controller.

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 ε, and the resulting bridge model was simulated using the controller for the nominal system. The perturbed stiffness was calculated as

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

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 4** shows evaluation criteria for ±7% stiffness perturbed system under El Centro earthquake. SMC is known as robust controller(Moon et al, 2003). So, the robustness of MEDA is compared to that of SMC and the nominal performance is listed 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 designed controller. 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.

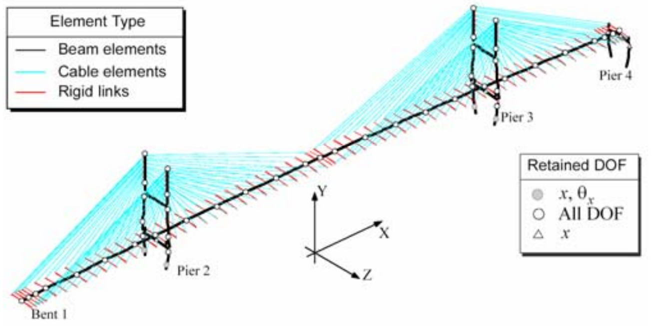

Figure 1. Finite Element Model of the Cape Girardeau Bridge

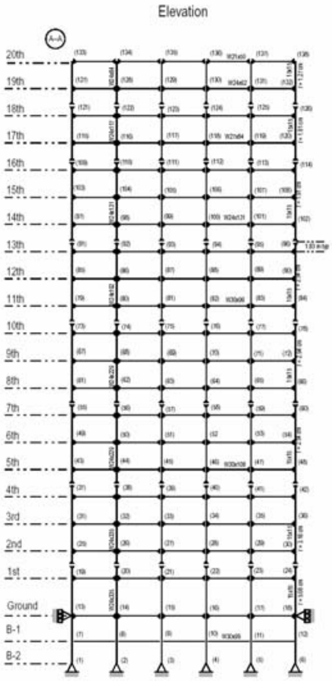

Figure 2. Schematic of 20-story benchmark building

Table 1. Parameters for MR Damper Model

Parameter	Value		Parameter	Value	
	For Non-linear building	For Cable-Stayed Bridge		For Non-linear building	For Cable-Stayed Bridge
α_a	1.087e5 N/cm	500 N/m	γ	3 cm^{-2}	300 m^{-2}
α_b	4.962e5 N/(cm·V)	671.41 N/(m·V)	β	3 cm^{-2}	300 m^{-2}
c_{0a}	4.40 N s/cm	0.15 N s/m	A	1.2	120
c_{0b}	44.0 N s/(cm·V)	1.43 N s/(cm·V)	n	1	1
η	50 s^{-1}	300 s^{-1}			

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

	J1			J2		
Controller	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
	J3			J4		
Controller	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
	J5			J6		
Controller	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
	J7			J8		
Controller	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
	J9			J10		
Controller	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
	J11					
Controller	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. Comparisons of Evaluation Criteria for Nonlinear Benchmark Building

	Clipped Optimal Controller (Yoshida and Dyke, 2002)				Maximum Energy Dissipation Algorithm			
Earthquake Intensity	Elcentro 0.5/1.0/1.5	Hachinohe 0.5/1.0/1.5	Northridge 0.5/1.0	Kobe 0.5/1.0	Elcentro 0.5/1.0/1.5	Hachinohe 0.5/1.0/1.5	Northridge 0.5/1.0	Kobe 0.5/1.0
J_1	0.747 0.748 0.748	0.883 0.887 0.907	0.859 0.942	0.816 0.728	0.639 0.642 0.658	0.713 0.683 0.745	0.666 0.796	0.497 0.636
J_2	0.648 0.646 0.664	0.746 0.743 0.833	0.807 0.904	0.702 0.839	1.653 1.049 0.828	2.410 1.550 1.257	0.965 0.911	0.796 0.849
J_3	0.780 0.782 0.909	0.977 0.982 1.010	0.885 0.969	0.925 1.070	1.267 0.996 1.025	1.440 1.223 1.172	0.988 1.122	0.789 1.258
J_4	0.662 0.663 0.670	0.885 0.884 0.903	0.724 0.929	0.648 0.230	0.455 0.468 0.486	0.724 0.735 0.768	0.442 0.986	0.273 0.271
J_5	0.563 0.560 0.578	0.658 0.652 0.661	0.592 0.637	0.579 0.713	1.328 0.961 0.812	2.081 1.370 1.091	0.712 0.761	0.624 0.691
J_6	0.724 0.723 0.729	0.849 0.848 0.858	0.776 0.841	0.689 0.840	0.710 0.622 0.600	0.933 0.818 0.797	0.474 0.724	0.401 0.638
J_7	0.772 0.722 0.722	0.955 0.959 0.943	0.728 0.978	0.688 0.688	0.695 0.648 0.613	0.796 0.807 0.752	0.559 0.809	0.334 0.603

J_8	- - 0.078	- - 0.714	0.220 0.548	0.144 0.323	- - 0	- - 0.008	0 0.328	- 0.058
J_9	- - 0.372	- - 0.791	0.542 0.906	0.308 0.810	- - 0	- - 0.233	0 0.760	- 0.595
J_{10}	0.733 0.733 0.656	0.847 0.847 0.890	0.632 0.944	0.777 0.227 0.656	0.480 0.492 0.449	0.700 0.711 0.730	0.325 0.984	0.248 0.309
J_{11}	0.002 0.003 0.501	0.002 0.004 0.005	0.007 0.008	0.005 0.009	0.009 0.009 0.009	0.009 0.009 0.009	0.009 0.009	0.009 0.009

Table 4. Evaluation Criteria for ±7% Stiffness perturbed System under El Centro Earthquake

	SMC(Moon et al. 2003)		MEDA	
	$\varepsilon = 0$	$\varepsilon = \pm 7\%$	$\varepsilon = 0$	$\varepsilon = \pm 7\%$
J1	0.394	0.432	0.331	0.395
J2	1.130	1.323	1.108	1.347
J3	0.296	0.335	0.255	0.278
J4	0.560	0.54	0.464	0.443
J5	0.213	0.224	0.185	0.219
J6	0.870	0.862	0.709	0.692
J7	0.218	0.235	0.234	0.233
J8	0.887	0.901	0.883	0.891
J9	0.189	0.198	0.233	0.215
J10	0.551	0.556	0.552	0.547
J11	0.016	0.017	0.020	0.02

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