Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 890

SHAKING TABLE TEST OF SEMI-ACTIVE MASS DAMPING SYSTEM USING MR DAMPER

Pei-Yang Lin[1] Hung-Wei Chiang[2]

ABSTRACT

A semi-active mass damping system (SMD) utilizing magnetorheological (MR) damper is proposed in this paper. The main purpose of this study is to integrate the reliable characteristic of the traditional tuned mass damper (TMD) and the superior performance of the active mass damper (AMD). A full-size three-story steel building is used as the benchmark structure to verify its performance in both the numerical simulation and shaking table test. To accurately predict the behavior of the MR dampers, serious of performance test with various excitation and command voltages are done. According to the performance test data, a modified Bouc-Wen model is identified and been used to represent the nonlinear behaviors of the MR damper. Unlike the clipped-optimal control, the LQR with the continuous-optimal control, which can generate the continuous varying command voltage, is used to online calculate the optimal command voltage to the MR damper. Both numerical simulation and shaking table test results demonstrated the superior mitigation ability of the proposed SMD. In addition, the control effect of the proposed SMD system is compatible to the traditional bracing system with passive dampers. The proposed SMD system provides the alternative solution and has been demonstrated to implement easily in practice.

Introduction

Over the last decade, the concept of semi-active tuned mass dampers (STMD) has been widely discussed. The idea of the STMD is to try and integrate the advantages from both the TMD and the ATMD, thereby optimizing the frequency and the damping ratio in an adaptive and reliable manner. Based on this premise, a large amount of research was conducted to try and offer protection for civil structures [1~8]. The research by T. Pinkaew [9] proved that the utilization of STMDs could be equivalent to increasing the TMD's mass in the structure, which was the main constraint in designing a TMD system [10]. Even though all the numerical studies have shown satisfactory results for the STMD [11~13], one basic condition has always been assumed in the research: the stiffness and the damping of the STMD must be varied in a reasonably short period of time. This has proven to be the bottleneck confining the practicability of the STMD.

[1]Research Fellow, National Center for Research on Earthquake Engineering, Taiwan
[2]Assistant Research Fellow Assistant, National Center for Research on Earthquake Engineering, Taiwan

A series of researches including the investigation and simulation of the MR damper, as well as applying specific MR dampers to control an isolated structure were conducted by the authors. Kim et al [14] proposed a neuro-fuzzy model to describe the behavior of a hybrid system with friction pendulum system (FPS) bearings and MR damper. Different control algorithms were then compared in order to offer strong protection to the main structure. Moreover, the possibility of utilizing resettable semi-active stiffness dampers was also investigated [15]. Although the results have shown that the utilization of MR dampers can provide a vastly superior next generation control system, however, the MR dampers were mainly considered as bracing-type equipment and may not be feasible to practical structures when a large amount of MR damper is needed.

A semi-active mass damping system (SMD) using MR dampers is proposed in this paper. With the implementation of varying the stiffness and the damping of the MR damper in a short interval, the mass block on the top of the structure does not need to be tuned precisely in advance as the aforementioned STMD system while satisfactory control result can still be achieved. The remainder of this paper is organized as follows. First, the main concept of the proposed system is described. Next, in order to precisely evaluate the behavior of the MR damper used in the research and to guarantee its application we compare the performance test result of a specific MR damper with the numerical model developed. Then a numerical analysis and experimental verification are carried out to demonstrate the performance of the proposed SMD system. A summary and the conclusions are drawn in the final section.

Performance Test of MR Dampers

The primary concept of the smart SMD is to suppress the response of the main structure by sacrificing as much as possible the reaction of the mass added on top of the building. To achieve this goal, the stroke of the MR damper used becomes the most critical point in the system. A designated MR damper (7kN/300mm))manufactured by National Center for Research on Earthquake Engineering (NCREE) is used in this research. The basic property of the MR damper is shown in Table1.

The robust numerical model of the MR damper for describing its hysteresis behavior under arbitrary excitation is essential for developing the smart system. Unlike the previous neuro-fuzzy model proposed by the authors [14], a modified Bouc-Wen model is developed in this study for both the theoretical and the experimental stages. According to the previous studies by Spencer et al 1997[16], the Bouc-Wen model is suitable to describe the nonlinear behavior of the MR damper. To simplify the mathematic model, a modified Bouc-Wen model, as shown in Equations (1) and (2), is used. Four parameters (C, α, β and γ) are used to express the performance of the MR damper under a fixed command voltage.

$$F_{MR}(t) = C * \dot{x}(t) + z(t) \tag{1}$$

$$\dot{z}(t) = \alpha * \dot{x}(t) + \beta|\dot{x}(t)||z(t)| + \gamma\dot{x}(t)|z(t)|^2 \tag{2}$$

Where F_{MR} represents the force, and $\dot{x}(t)$ represents the velocity of the MR damper.

Generally the nonlinear curve fitting method is used to find the relationship between the model parameters and the command voltages. However, the time required as well as the complex coefficients make this method impractical. Therefore, this study simplifies the relationship between the model parameters and the command voltage using a new technique of interpolation.

First, the performance test data of the MR damper with random displacement and seven constant voltage levels (0, 0.2, 0.4, 0.6, 0.8, 1 and 1.2 V) are used to identify the individual model parameters (C, α, β and γ) for each constant command voltage level. These parameters can be identified using Matlab/Optimization toolbox [17]. The identified model parameters of the seven constant voltage levels are shown in Table 1. The theoretical force of the MR damper with command voltage different from these seven levels can then be obtained by interpolating the model parameters from the two adjacent levels it locates.

Table 2. Identified model parameters of MR damper (Unit: kN-m-s).

Voltage (Volt)	C	α	β	γ
0	12.955	4628.659	-742.499	-187.583
0.2	16.729	5314.937	-690.171	422.641
0.4	20.887	8175.300	-201.144	108.644
0.6	24.048	10384.40	-139.423	65.465
0.8	27.756	6386.549	-107.805	68.691
1.0	25.319	8469.352	-99.669	57.789
1.2	26.274	9345.521	-87.724	46.546

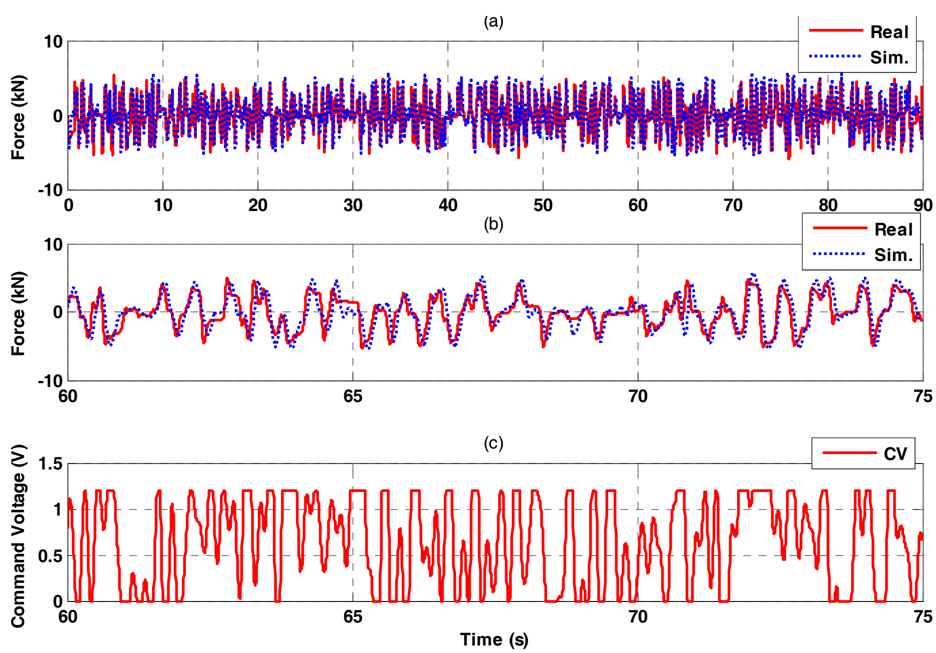

Figure 1. Comparison of the real and the simulated MR damper force in the performance test (random displacement and random voltage)；(a) the whole history; (b) the time history 60~75 sec; (c) Command voltage to the MR damper

The numerical model of the MR damper established was verified through a performance test of the MR damper at NCREE. A banded white noise (0-5Hz) was used as the velocity and voltage of the MR damper. Ninety seconds of damping force were recorded, and the result is shown in Figure 1 where subplot (a) shows the time history of the damping force; subplot (b) focuses on the period between 60 to 75 seconds; and subplot(c) indicates the given command voltage. The numerical simulation, shown in red color, substantially matches the measured response in blue color, and the peak values and phases of the damping force can be expressed precisely by the proposed method. This result strongly supports the understanding that the modified Bouc-Wen model can be applied in the present study.

Semi-active control algorithm of the SMD System

A four degree-of-freedom (DOF) model is used to express a three-story structure representing a typical low-rise building with rolling pendulum system (RPS) and MR damper in this research. As shown in figure 2, only the horizontal movement is considered where X1, X2, and X3 are the displacement of the main structure, and X4 is the response of the SMD on the roof. The first three fundamental frequencies of the main structure are set to 1.085, 3.277, and 5.165 Hz, and the mass on the first and second floor is 6t (m1, m2). The total mass of m3 and m4 is also set to 6t where m4 is the tunable mass block of the control system. The stiffness and period of the RPS used in this study are 1.049 kg/mm and 2.77 s..

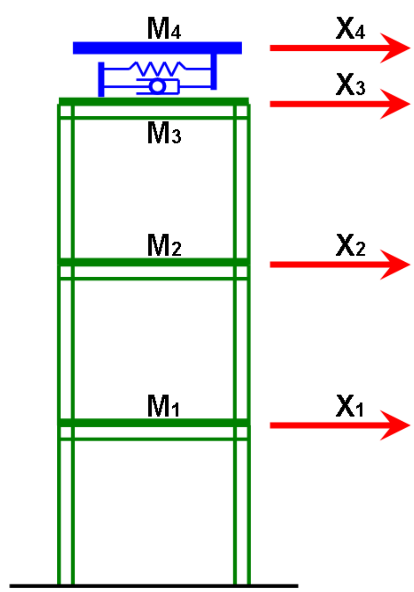

Figure 2. Illustration of the Three-story Structure with SMD.

To offer a strong protection to the structure, a special control algorithm combining the LQR method and a continuous–optimal control concept is proposed. In this study, the most common active control algorithm, the LQR method, is used to calculate the optimal control force with designated control objectives to make the SMD system both simpler and more flexible. Meanwhile, unlike the previous developed neural-network-based MR damper model [21], the continuously-optimal control concept is utilized to transfer the desired control voltage from the optimal active control force obtained to improve the time-consuming and extrapolation problems. To reach this goal, seven modified Bouc-Wen models with different constant voltages are built to form the database for a comparison. Seven damper forces calculated from these voltages are compared to the optimal control force. The command voltage is then interpolated proportionally from the two adjacent MR damper models it locates. The LQR method with the continuous–optimal control concept will be able to provide an easy and stable way to calculate the suitable command voltage in each time step. The traditional LQR control algorithm is used to calculate the desired control force $F_{desired}$ (active control force). Then, the continuous–optimal control is used to translate the desire control force to the command voltage to drive the MR damper. The flowchart of the continuous-optimal control concept is shown in figure 3.

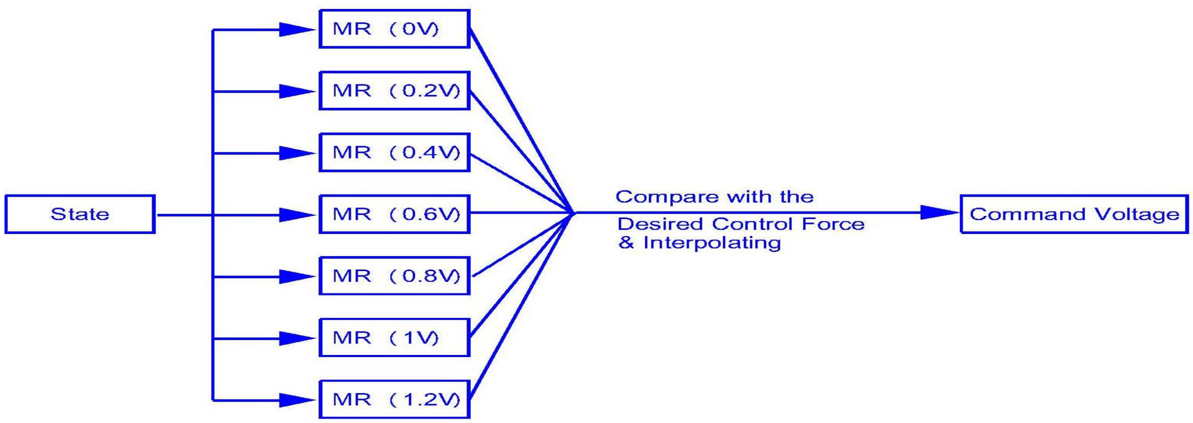

Figure 3. Flow chart of the semi-active control strategy

To implement the strategy of the continuous-optimal control, seven voltages ranging from 0V to 1.2V in increments of 0.2V are used as the references. The desired control force, calculated from the LQR control algorithm, is then used for comparison with all the estimated MR damper forces from these models. According to the desired control force, the command voltage is yielded by the interpolation between the best two voltage levels as shown in Eq. (3). It is expected that a better and smoother control effect can be achieved by the new proposed control algorithm.

$$V = V_j * \frac{F_{desired} - F_{MR\_V_i}}{F_{MR\_V_j} - F_{MR\_V_i}} + V_i * \frac{F_{MR\_V_i} - F_{desired}}{F_{MR\_V_j} - F_{MR\_V_i}} \tag{3}$$

Where V is the command voltage; V_i and V_j are the two closest voltages; $F_{MR\_V_i}$ and $F_{MR\_V_i}$ are the corresponding force of V_i and V_j; and $F_{desired}$ is the force calculated by the specific LQR method.

Shaking Table Test of the SMD System

The feasibility of implementing the proposed system in practice was verified through a shaking table test conducted at NCREE. A full-size three-story steel structure measuring 3m (length) x 2m (width) x 3m (height) in each floor with the MR damper on the roof was used to form the four degree-of-freedom model in the theoretical analysis. In order to approach the assumption of a shear-type structure, the beams and the columns of the specimen were constructed using H-beams measuring 150(mm) x 150(mm) x 7(mm) x 10(mm) while the floor thickness was set as 25mm and was welded on extremely strong diaphragms. Additional blocks with a mass of 3.5 tons were mounted on every floor to satisfy the requirement of fundamental frequency. The first three fundamental frequencies of the main structure are set to 1.085, 3.277, and 5.165 Hz. The mass the SMD system is 2 tons. The SMD system combines the Rolling Pendulum System (RPS) and semi-active controlled MR damper. The stiffness and period of the RPS used in this study are 1.049 kg/mm and 2.77 s. The set-up, including the specimen, the MR damper, and the RPS, is shown in figure 4.

Figure 4: Set-up of the three-story benchmark structure

A traditional instrumentation system was deployed for the specimen to measure the response of the structure during earthquake excitation. As shown in figure 4, the absolute displacement, velocity, and acceleration of each floor of the main structure as well as the reaction of the MR damper were recorded by the linear variable differential transformer (LVDT) for comparison. The stroke of the MR damper was carefully monitored to avoid any collision between the MR damper and the specimen. The optimal control voltage was calculated by the embedded Simulink/dSPACE code [18] with the necessary feedback signals and then sent to the MR damper. The Control flow-chart of the smart SMD system is shown in figure 5.

Four diverse earthquakes including the 1940 El Centro earthquake (NS direction), the 1995 Kobe earthquake, the TCU 068 site record, and the TCU129 site record in the 1999 Chi-Chi earthquake, representing the typical far-field and near-fault earthquakes were used to examine the practical performance of the smart SMD system. For each testing case, the PGA value started from 50 gal with increments of 50 gal until the maximal allowable stroke of the MR damper, set to be 12 cm in the experiment, was reached. To demonstrate the advantage of applying the smart system, all four control modes comprising the UC (uncontrolled structure), PMD (passive mass damper / max. power of MR damper), PMD-off (passive mass damper / power-off of MR damper), and the SMD (Semi-active mass damper / semi-active controlled MR damper) were executed. The experimental data were collected by the data acquisition system for further comparison.

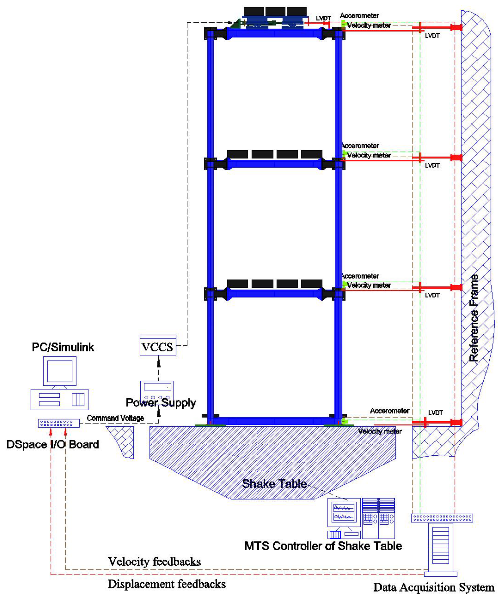

Figure 5. Control flow-chart of the SMD damping system

The overall presentation of the four modes under different PGA levels of the El Centro earthquake is illustrated in figure 6. It should be noted that the red line, which is the PMD-off mode, can be treated as a failure mode of SMD. Apparently, the blue line, which represents the performance of the proposed SMD method, occupies the lowest position under almost every PGA value. This trend proves that the MR damper can be manipulated smartly by the proposed control algorithm with on average an improvement of 40-50% from the uncontrolled state. Moreover, a 20-30% efficiency increase over the PMD system can be easily achieved by this robust control system.

Figure 7 show the comparisons of the time history responses of the relative displacement and absolute acceleration of three stories with and without SMD under El Centro earthquake excitation (normalized to 200gals). The relative displacements in each story are dramatically reduced. In the same time, the absolute acceleration time histories are smaller. According to the over all comparisons and time history comparisons, the semi-active controlled mass damping system with MR damper shows the excellent control effect. Comparing to the traditional TMD system, the proposed SMD has much more control efficiency and the most important, it is stable robust. Only one semi-active controlled mass damping system is used on the top floor, the over all control effect is compatible to the traditional bracing system with passive damper. Not only the high-raised building but also the middle-raised building can use the SMD to increase the seismic behavior. The 2ton's mass seems to be too heavy for the high raised building, but it is reasonable for the middle-raised building.

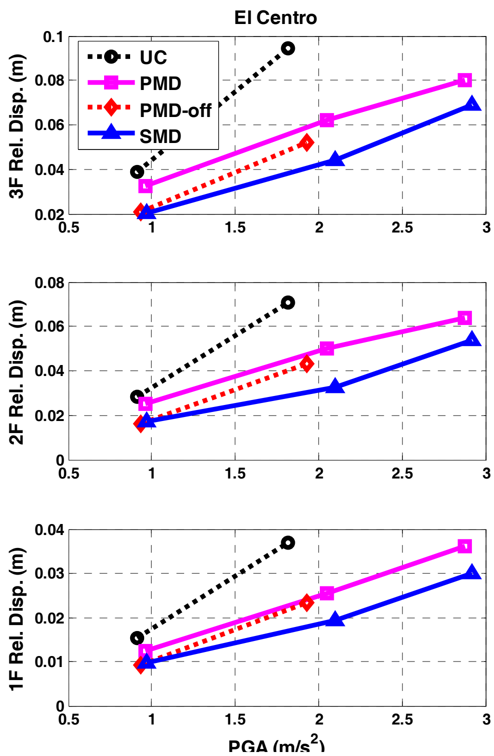

Figure 6. Overall presentation of all modes under different PGA levels of the El Centro earthquake

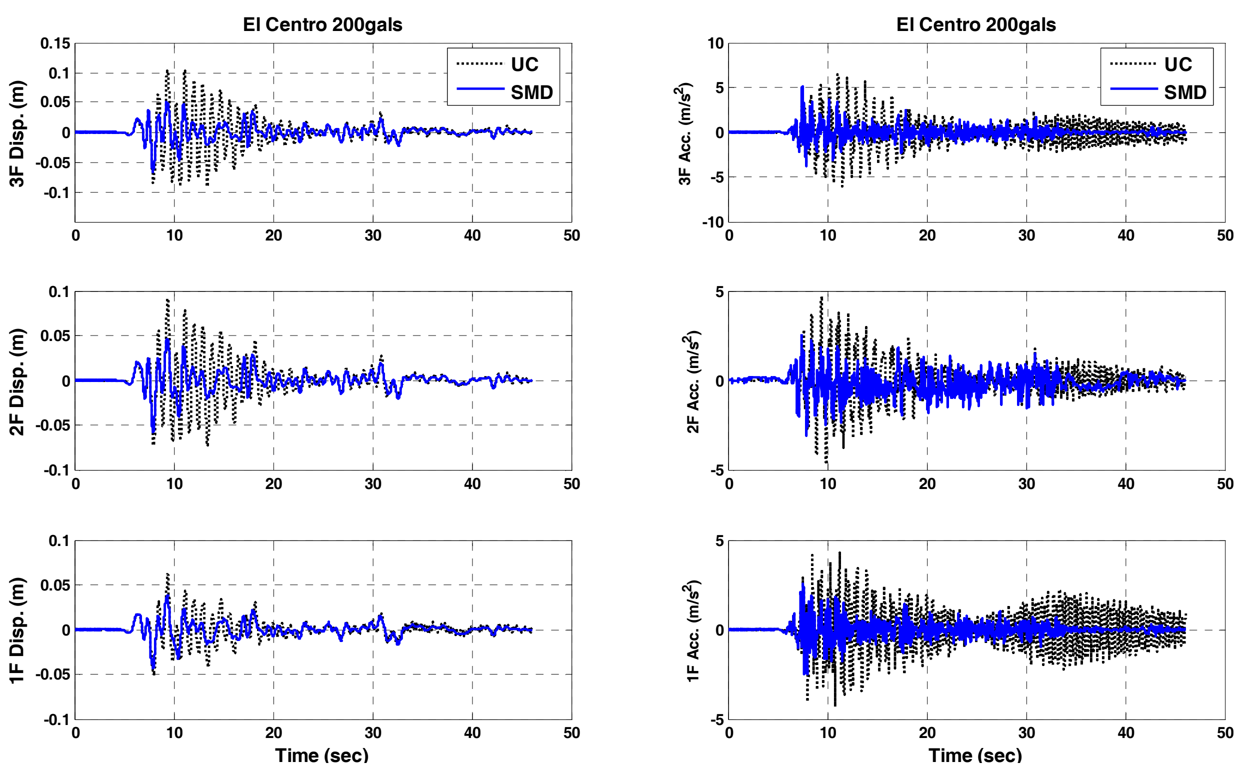

Figure 7. Comparison of the displacement and acceleration time history responses of the

uncontrolled structure and structure with SMD under El Centro earthquake (normalized to 200gals)

Summary and Conclusion

A smart SMD system using MR dampers is proposed in this research. To integrate the robustness of the traditional TMD and the superb control performance of the AMD systems, the frictionless RPS and the MR damper were used to compose the smart system while using a full-scale three-story building as the benchmark structure.

To accurately predict the behavior of the designated large-stroke MR damper, a numerical representation combining the modified Bouc-Wen model and interpolation technique was established. Seven sets of the parameters describing the relationship between the velocity and the damping force under fixed voltages were used to form the database. The damping force with arbitrary velocity and voltage was then calculated by the interpolated coefficients. The MR damper model was verified by the performance test of the MR2005 damper in NCREE. The result has shown that both the time history and the hysteresis loop of the MR damper can be estimated correctly by the numerical model.

A smart control algorithm combining the LQR method and the continuous–optimal control concept was developed with the success of the MR damper model. To offer an objective-oriented control outcome, all floor responses including relative displacement, relative velocity, and absolute acceleration of the benchmark structure were considered in the performance index of the LQR method. The command voltage was then calculated by the continuous–optimal control concept by interpolating between the best two voltage levels. The proposed smart SMD theory was verified by two typical earthquakes. The numerical simulation demonstrated that the structural response can be alleviated satisfactorily by the smart SMD system.

The practical performance of the smart SMD system was carried out by a series of shaking table tests at NCREE with four diverse earthquakes. The experimental results has proved that the MR damper can be manipulated smartly by the proposed control algorithm with on average an improvement of 40-50% from the uncontrolled state. The control efficiency can be upgraded between 20-30% by this robust control system compared to that of a TMD system. In addition, different from the TMD and the AMD methods, compared to the alternative solution of deploying dense seismic dampers throughout the structure, the proposed SMD system on the roof can be implemented much easier and with a similar reduction percentage.

This study proposes a new smart SMD system including such novel techniques as the modified Bouc-Wen model, the interpolation process, and the continuous–optimal control concept to enhance the practicality and reliability of the SMD system. The theoretical results and the experimental verification all demonstrate that the new system can successfully mitigate the response of the main structure. The proposed smart SMD system can be easily implemented in practice

References

[1]. Frahm H. Device for damping of bodies. U.S. Patent No. 989, 958, 1911.
[2]. Ormondroyd J, Den Hartog JP. The theory of the dynamic vibration absorber. Transactions of the ASME 1928; APM-50-7: 9–22.
[3]. Brock JE. A note on the damped vibration absorber. Journal of Applied Mechanics, ASME 1946; 13: A-284.
[4]. Mackriell, L.E.; Kwok, K.C.S.; Samali, B. Critical mode control of a wind-loaded tall building using an active tuned mass damper Engineering Structures, v 19, n 10, Oct, 1997, p 834-842
[5]. Qu, Z.-Q.; Shi, Y.; Hua, H. A reduced-order modeling technique for tall buildings with active tuned mass damper Earthquake Engineering and Structural Dynamics, v 30, n 3, March, 2001, p 360-362
[6]. Chang, C.C.; Yang, Henry T.Y. Control of buildings using active tuned mass dampers Journal of Engineering Mechanics, v 121, n 3, Mar, 1995, p 355-366
[7]. Loh, Chin-Hsiung; Chern, Wen-Yung Seismic effectiveness of active tuned mass dampers for the control of flexible structures Probabilistic Engineering Mechanics, v 9, n 4, 1994, p 225-234
[8]. M.Sakamoto, T.Kobori, T.Yamada, M.Takahashi, Practical applications of active and hybrid response control systems and their verifications by earthquake and strong wind observations, Proceedings of First World Conference on Structural Control, Los Angeles, CA,USA,1996.
[9]. Pinkaew, T.; Fujino, Y. Effectiveness of semi-active tuned mass dampers under harmonic excitation Engineering Structures, v 23, n 7, July, 2001, p 850-856
[10]. Den Hartog JP. Mechanical Vibrations (3rd edition). McGraw-Hill: New York, 1947.
[11]. Ricciardelli, Francesco; Occhiuzzi, Antonio; Clemente, Paolo Semi-active Tuned Mass Damper control strategy for wind-excited structures
Journal of Wind Engineering and Industrial Aerodynamics, v 88, n 1, Nov, 2000, p 57-74
[12]. Yang, Runlin; Zhou, Xiyuan; Liu, Xihui Seismic structural control using semi-active tuned mass dampers Earthquake Engineering and Engineering Vibration, v 1, n 1, June, 2002, p 111-118
[13]. Setareh, M. Use of semi-active tuned mass dampers for vibration control of force-excited structures Structural Engineering and Mechanics, v 11, n 4, April, 2001, p 341-356
[14]. Hyun-Su Kim, Paul N Roschke, Pei-Yang Lin, Chin-Hsiung Loh, "Neuro-fuzzy model of hybrid semi-active base isolation system with FPS bearing and MR damper", Engineering structures 28, 2006, PP947-958,
[15]. Yang, J. N., Bobrow, J., Jabbari, F., Leavitt, J., Cheng, C. P., and Lin, P. Y., " Full-Scale Experimental Verification of Resetable Semi-Active Stiffness Dampers ", Journal of Earthquake Engineering and Structural Dynamics, 36, PP1255-1273, 2007
[16]. Spencer B F, Dyke S J, Sain M K, Carlson J D, "Phenomenological model for magnetorheological dampers", J. of Engr. Mech. Am. Soc. Civil Eng. 123, 230-252, (1997).
[17]. MATLAB, User's Guide, The MathWorks, Inc.: Natick, MA 01760, 1992.
[18]. dSPACE Release 4.2, Solution for control, 2005 dSPACE GmBH, Germany