Investigations of Shaking Table Test of Randomly Base-Excited Building Structures with MR Dampers

Jie Li, Zhen Mei, and Yong-Bo Peng

Abstract Structural vibration control has demonstrated its value for mitigating earthquake hazards and enhancing the safety and serviceability of structural systems in recent years. However, in most existing investigations of numerical simulations and experimental verifications on seismic control of structures, only several ground motions at different levels are considered. The experimental investigations of seismic performance of controlled structures accounting for the randomness inherent in the earthquake ground motions did not receive sufficient attentions. In this chapter, a complete shaking table test on a multistory shear frame structure with MR dampers is carried out. The representative time histories of ground accelerations, as the base excitation, are generated employing the stochastic ground motion model. The stochastic response analyses of the experimental structures with and without control are conducted, respectively. Experimental and analytical results indicate that the seismic performance of the test structure is significantly improved compared with that of the uncontrolled structure.

Keywords Shaking table test • Stochastic ground motions • Structural control • Probability density evolution method • MR dampers

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1 Introduction

In the last four decades or so, the application of modern control techniques to mitigate the effects of seismic loads on civil engineering structures offers an appealing alternative to the traditional earthquake resistant design method, and considerable researches have been conducted to advance structural control as a direct means of vibration attenuation [4, 11].

It is noted, however, that in the experimental research and numerical simulation on structural vibration control under earthquake actions, only several ground motions at different levels, like El Centro earthquake and so on, are considered as excitations [3, 8]. The experimental investigations of seismic performance of controlled structures accounting for the randomness inherent in the earthquake ground motions did not receive sufficient attentions. Moreover, the efficacy of vibration mitigation is usually given by the reduction of dynamic responses (particularly peak displacements or peak accelerations) under control compared to those without control [9, 10]. The statistical values, such as the standard deviation, as well as the probability distributions of responses of the controlled and uncontrolled structures cannot be obtained in most cases. The guaranty of requirement of safety or serviceability of controlled structures is still a challenging task. Therefore, stochastic vibration control of structures subjected to the random earthquake ground motion should be studied [6, 7].

The focus of this chapter is to experimentally investigate the efficacy of seismic response control considering the randomness involved in earthquake excitations. A complete shaking table test on a multistory shear frame structure with MR dampers is carried out. The representative time histories of ground acceleration, using for the base excitation of the shaking table test, are generated based on a physical stochastic ground motion model [5]. Following that, the experimental setup and experimental program are both described in detail. Some experimental and analytical results of stochastic vibration control tests are included.

2 Simulation of Earthquake Ground Motions

2.1 Brief Introduction of Physical Stochastic Ground Motion Model

Based on a physical background, seismic ground motions are mainly affected by the properties of the sources, propagation paths, and the properties of the site soil. The uncertainty of the three factors is the cause of the randomness of seismic ground motions. For a certain engineering site, the ground motion parameters at the bedrock could be provided by the seismic hazard assessment considering the properties of the sources and the propagation process [2]. Therefore, taking into

Table 1 Statistical values of peak accelerations of the sampled ground motions

Statistic quantity	Min	Max	Mean	Std.d
Value (m/s^2)	0.78	4.61	2.18	0.56

Annotation: *Min* minimum, *Max* maximum, *Std.d* standard deviation

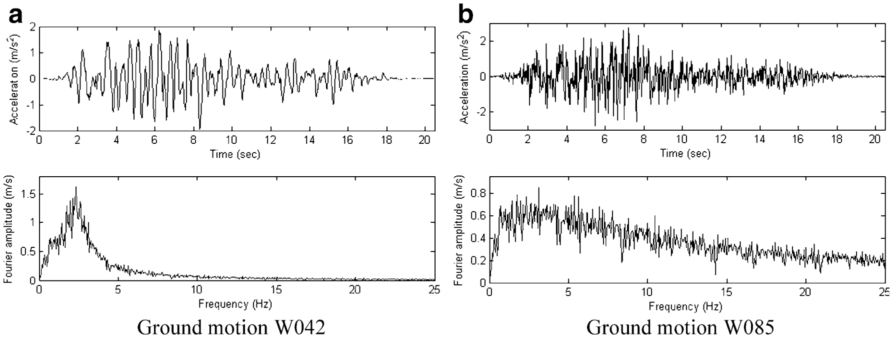

Fig. 1 Two typical time histories and Fourier amplitude spectra of ground accelerations. (**a**) Ground motion W042, (**b**) Ground motion W085

account the properties of the site soil and combining with the ground motion at the bedrock will lead to the so-called physical stochastic ground motion model [5].

The effects of engineering site could be regarded as a multilayer filtering operator. For the sake of clarity, it is modeled as a single-degree-of-freedom (SDOF) system. Using the ground motion at the bedrock as the input process, the absolute response of the SDOF system is, namely, the process of the ground motion at the surface of the engineering site. More details on the physical stochastic ground motion model proposed by Li and Ai could be found in the two references just mentioned.

2.2 Simulation of Representative Time Histories of Ground Acceleration

In conjunction with the strategy of tangent spheres for selecting representative points [1], time histories of ground acceleration at the engineering site considered can be generated employing the physical stochastic ground motion model outlined in the preceding section. In this investigation, 120 representative ground accelerations are generated. Meanwhile, the ground acceleration valued by mean of parameters of the model is obtained, and its peak acceleration is 2.00 m/s^2.

It should be noted that the peak accelerations as well as the frequency spectrum characteristics of the representative ground accelerations differ from each other. The statistical properties of peak accelerations of these ground motions are given in Table 1. In Fig. 1, two typical ground accelerations, labeled W042 and W085, and

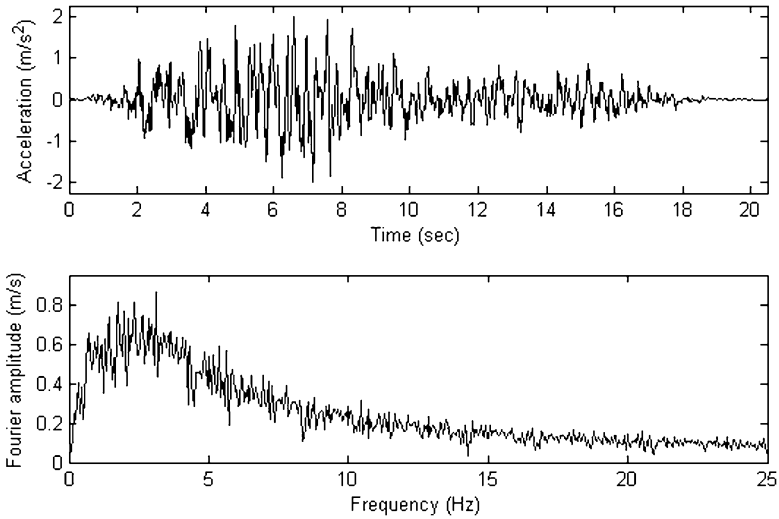

Fig. 2 Ground acceleration valued by mean of parameters and its Fourier amplitude spectrum

the corresponding Fourier amplitude spectra are illustrated, respectively. Additionally, the ground acceleration generated using the mean parameters, labeled W000, and its Fourier amplitude spectrum are presented in Fig. 2.

3 Design of Experiments

3.1 Experimental Setup

Experimental investigations were performed in the State Key Laboratory of Disaster Reduction in Civil Engineering in Tongji University, China. The test structure used in this experiment is a six-story, single-bay, model steel structure (Fig. 3). It is designed to be a scale model of a part of a prototype building. This steel model structure is of 5 m high. The total mass of the model is about 2.8 ton, excluding additional artificial quality (total of 7.2 ton, distributed evenly among the six floors). The ratio of model quantities to those corresponding to the prototype structure is employed as follows: time = 0.4472, force = 0.04, mass = 0.04, displacement = 0.2, and acceleration = 1.

The MR dampers (marked as MRD-A and MRD-B, respectively) employed in the experiment are shown in Fig. 4. The two dampers have the same design parameters. Forces of up to 10 kN can be generated by the damper. It is of 72.5 cm long in its extended position, and the main cylinder is of 10.0 cm in diameter. The damper has a ±5.5-cm stroke, and its input current is in the range

Fig. 3 Photograph of the test structure with MR dampers

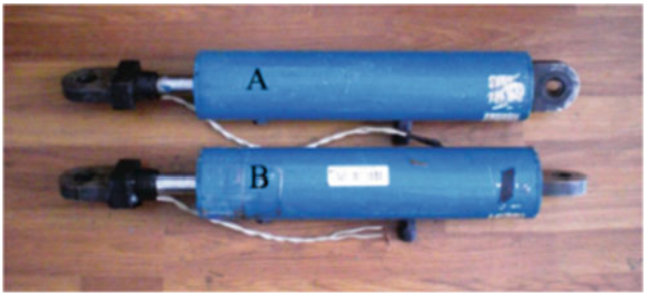

Fig. 4 MRD-100-10-type MR dampers

of 0–2 A. The force generated by this device is stable in the range of –40 to 60 °C. Additionally, the total weight of the damper is approximately 20 kg.

In the shaking table test, the data are recorded by an automatic data acquisition system. An accelerometer as well as a displacement transducer is used to measure the shaking table's actual motion. Simultaneously, six accelerometers and six displacement transducers are installed to measure the dynamic responses of each floor. The setup of transducers is given in Fig. 5.

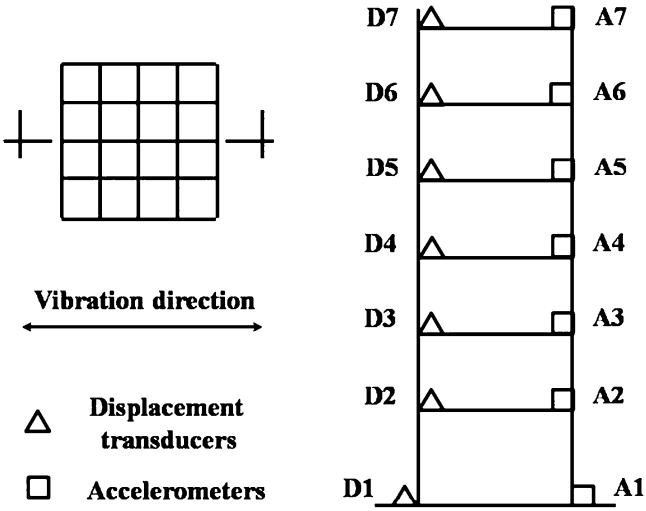

Fig. 5 Setup of transducers

Table 2 Experimental program

Case number	Seismic input	Amplitude (m/s^2)	Remark
1	W000	1.00	Without control
2–121	W001–W120	Statistical values as shown in Table 1	Passive-on control (two MR dampers installed)
122–241	W001–W120	Half of the amplitudes in cases 2–121, respectively	Without control
242	W000	1.00	Without control

3.2 Experimental Program

In the stochastic control tests, the time histories of ground acceleration generated in Section "Simulation of Earthquake Ground Motions" are used as the one-dimensional inputs. There are total 242 cases as shown in Table 2. In the uncontrolled cases (case nos. 1, 242), the ground acceleration W000 is considered as the seismic inputs, and experimentally measured frequency response functions (FRFs) are used in the identification of the test structure. In the passive-on control cases (case nos. 2–121), the two MR dampers pictured in Fig. 4 are installed as the control devices. The MRD-A is placed between the ground and first floor, and the MRD-B is placed between the second and third floors of the model structure, as shown in Fig. 3. Additionally, the currents applied to the two dampers are held fixed at 1.5 A in the controlled cases.

4 Results of Stochastic Control Experiments

4.1 Identification of Dynamic Characteristics of Test Structure Without Control

In the experiments, dynamic characteristics of the test structure without control can be obtained from the experimentally measured FRFs. The first six natural frequencies of the test structure without control are identified, and the results are listed in Table 3. According to the results, it is seen that the first six natural frequencies of the model structure is only slightly changed through the whole experiment. For instance, the first natural frequency is changed from 1.460 to 1.453 Hz, only decreases by about 0.48%. Moreover, the first three identified mode shapes of the test structure without control are presented in Fig. 6. It is clear that the first three modes remain almost unchanged.

In view of the identification results, it can be assumed that the test structure itself still remains within the range of linear state in the whole tests. It is noted that the amplitudes of seismic inputs in cases nos. 122–241 are only half of those in case nos. 2–121, respectively. As such, the experimentally measured data of the test structure without control should be doubled based on the assumption that the model remains in the linear state.

Table 3 The first six natural frequencies of the test structure without control.

	First six natural frequencies (Hz)					
Case number	1	2	3	4	5	6
1	1.460	4.624	8.365	12.452	16.803	20.277
242	1.453	4.605	8.338	12.385	16.745	20.184

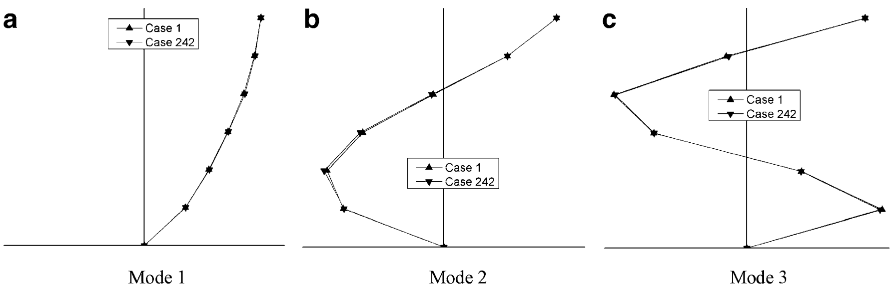

Fig. 6 The first three mode shapes of the test structure without control. (**a**) Mode 1, (**b**) Mode 2, (**c**) Mode 3

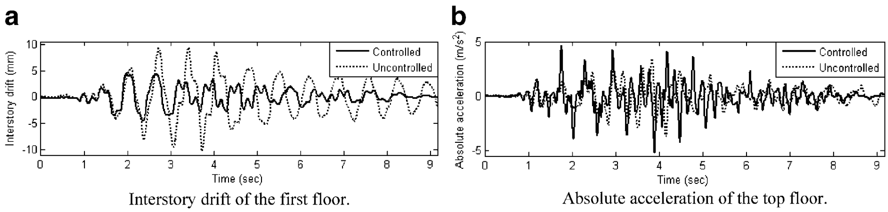

Fig. 7 Comparison of structural responses subject to ground acceleration W042. (**a**) Interstory drift of the first floor. (**b**) Absolute acceleration of the top floor

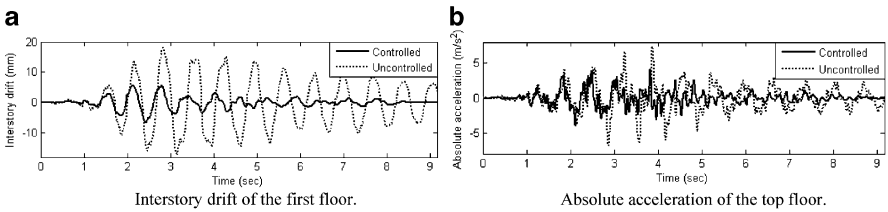

Fig. 8 Comparison of structural responses subject to ground acceleration W085. (**a**) Interstory drift of the first floor, (**b**) Absolute acceleration of the top floor

4.2 Structural Responses Subject to Representative Ground Motions

The comparative studies of structural responses with and without control subject to the two representative ground motions pictured in Fig. 1 are carried out. The time histories of responses of the controlled (Con.) and uncontrolled (Unc.) structures are shown, respectively, in Figs. 7 and 8. It is easily seen that the control effectiveness is of difference in case that the test structure is subject to various ground motions. The passive-on control is relatively more capable in mitigating both interstory drifts and absolute accelerations when the ground motion time history, labeled W085, is used as the seismic input. In Fig. 7b, the absolute acceleration with control, however, is even amplified compared to that without control during the time interval from 1.5 to 5.0 s. Therefore, the randomness involved in earthquake excitations should not be ignored.

4.3 RMS Responses of Test Structure

The root mean square (RMS) responses of the test structure along with the structural height with and without control are shown in Fig. 9. It is quite evident that RMS responses in the controlled cases are evidently smaller than those in the uncontrolled cases. As shown in Fig. 9a, the values of mean and standard deviation

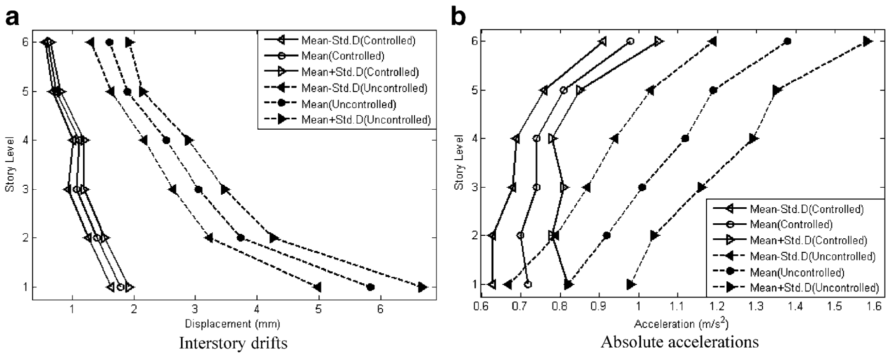

Fig. 9 RMS responses of test structure with and without control. (**a**) Interstory drifts, (**b**) Absolute accelerations

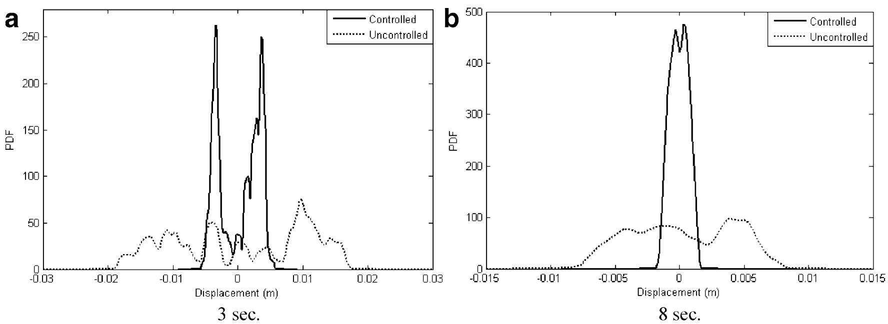

Fig. 10 Typical PDFs of interstory drifts of the first floor at different instants of time. (**a**) 3 s, (**b**) 8 s

of RMS interstory drifts are averagely reduced by 62.7 and 77.5%, respectively. As pictured in Fig. 9b, similar capacity toward the mitigation of RMS absolute accelerations is clearly exposed. The passive-on control system is able to reduce the mean values of RMS absolute accelerations of each story by 12.6–34.0% and the standard deviations by 38.7–75.1%.

4.4 PDFs of Responses of Test Structure

In this section, stochastic response analysis of the controlled and uncontrolled structures is carried out employing the probability density evolution method [6]. Typical PDFs of structural responses with and without control at instants of time (3 and 8 s) are shown in Figs. 10 and 11. One can readily see that the PDFs are mostly irregular, quite different from widely used regular probability distributions.

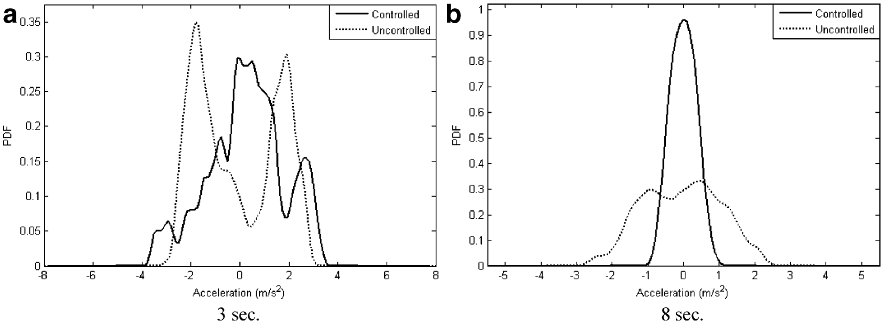

Fig. 11 Typical PDFs of story acceleration of the top floor at different instants of time. (**a**) 3 s, (**b**) 8 s

Moreover, the PDFs vary greatly against time. One might realize, for instance, from Fig. 10 that the distribution width of PDFs of the first interstory drifts at 3 s is larger than that at 8 s in the controlled cases. It is also seen that the fluctuation (characterized by the distribution width of the PDF) is significantly reduced with control. That is to say, the variation of interstory drifts of the first floor is obviously decreased. Similarly, the distribution ranges of the PDFs of the top story acceleration become narrower with the control. Moreover, the shape of the PDFs of responses arises to be more regular in the controlled cases, compared with that in the uncontrolled cases. In brief, the seismic performance of the primary structure has been greatly enhanced after the passive-on control applied.

5 Concluding Remarks

In this chapter, stochastic control of structures subject to random earthquake ground motions is experimentally investigated. Experimental results indicate that the seismic performance of the test structure with MR dampers is significantly improved compared with that in the uncontrolled cases. It is seen that control effectiveness of the test structure is different in case of different ground motions. The RMS responses of the controlled structure are obviously smaller than those in the uncontrolled cases. In the controlled cases, the distribution range of PDFs of typical responses becomes narrower, and the shape of the PDFs arises to be more regular. Therefore, more attentions should be paid to the randomness involved in seismic excitations.

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