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Research Article

Hybrid experimental investigation of MR damper controlled tuned mass damper used for structures under earthquakes

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ABSTRACT

This paper aims to investigate the performances of a semi-active tuned mass damper (STMD) used to reduce the vibrations of buildings under different seismic excitation by the real-time hybrid simulation (RTHS) method. In the STMD, the MR damper is used as a control element with a variable damping feature. The RTHS method is an alternative to experimentally studying the STMD system. MR damper is critically significant for the system and is experimentally installed. At the same time, the other parts are designed in numerical simulation and tested simultaneously. MR damper is a control element whose damping value can change according to the amount of voltage transmitted. Therefore, the groundhook control method determines the MR damper voltage variations. The results show that the control method applied to MR damper-controlled STMD effectively suppresses structural vibrations.

1. Introduction

Passive control applications have been implemented to improve the response of a structural system under the influence of earthquake excitations. In order to increase the performance of passive control applications, semi-active control studies[1]–[4] and active control studies [5]–[7] are performed. Tuned mass dampers (TMD) are commonly used in control applications in structural systems. TMDs applied to structural systems are used as passive control elements [8], [9]. Also, the performance of suppressing structural vibrations can be improved by applying active and semi-active control methods. Active control applications are successful in reducing structural vibrations.

Nevertheless, the cost and reliability of the equipment for this application are disadvantageous. The performance of TMDs with passive control is limited. Their performance decreases under variable conditions. Semi-active control methods applied to TMDs are safer than active control and perform better than passive control. In this study, STMD reduces the vibrations of a building with MDOF under seismic excitation.

Many simulation studies are related to STMDs using MR damper in the literature. Causal sub-optimal control [10], Clipped optimal control [11], LQR control [12], Sky-groundhook control with optimal fuzzy control [13], MIMO fuzzy logic control [14], Type 1 and 2 fuzzy logic control [15], Bang-Bang control [16]. Besides, many experimental studies have been made; Groundhook control [17], LQR control [18], and model-based feed-forward control [19]. Numerical simulations may not ultimately reflect reality. Experimental studies are of great importance in scientific research.

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However, the experimental setup and operation of structural systems are also significant problems.

In recent years, hybrid simulation methods have been applied for structural systems, including simulation and experimental studies. These methods combine the advantages of numerical simulation and experimental setups. The objective here is to experimentally construct system elements that are difficult to model mathematically and to use the measurement data obtained in this way in simulation in real-time. The responses of structures under harmonic excitation were investigated by the RTHS method [2]. However, the response of a building under earthquake reactions is an issue that needs to be investigated.

In this study, the performance analysis of the STMD, which is used to reduce the vibrations of MDOF building under seismic excitations by the RTHS method, is investigated. MR damper is a control element whose damping value can change according to the amount of voltage transmitted. For this reason, the groundhook control method is used for the voltage changes in the MR damper because it is simple and easy to implement.

2. Equation motion of system model

In this study, the semi-active control application of the 10-story building model, where only lateral vibrations are taken into account, is shown in Figure 1.

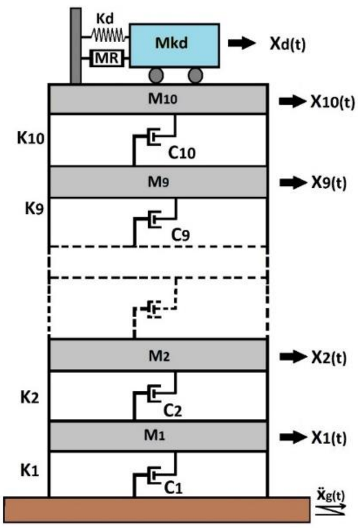


Figure 1. The building model with the STMD

The general equation of motion of the model is as follows.

$$M_s\ddot{x}(t) + C_s\dot{x}(t) + K_s x(t) = -T_s f(t) - M_s Z\ddot{x}_g \qquad (1)$$

The mass, damping, and stiffness matrices of the system are M_s, C_s ve $K_s \in R^{11x11}$ and the acceleration, velocity, and displacement vectors are $\ddot{x}(t),\ \dot{x}(t),\ x(t)\ \in R^{11x1}$ respectively. The damping force of the MR damper is f(t), and the earthquake ground acceleration is $\ddot{x}_g$. In Equation 2 and Equation 3, the displacement and seismic vectors of the system are given.

$$x = [x_1 \quad x_2 \quad x_3 \cdots x_9 \quad x_{10} \quad x_d]^T \qquad (2)$$

$$Z = [1 \quad 1 \quad 1 \cdots 1 \quad 1 \quad 1]^T \qquad (3)$$

The vector showing the location of the controller is shown below.

$$T_s = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1 \quad -1]^T \qquad (4)$$

3. Semi-Active Control Application

The groundhook configuration shown in Figure 2 cannot be practiced. Because the damper cannot be fixed to a stationary inertia frame, this semi-active control policy aims to mimic the ideal structural configuration of a passive damper between structure and ground [13] [20]. In Figure 2, the relative velocity is defined by subtracting the velocity of the structure from the velocity of the STMD, that is, $(dx_{10} - dx_d)$. Also, x_{10} is defined as displacement.

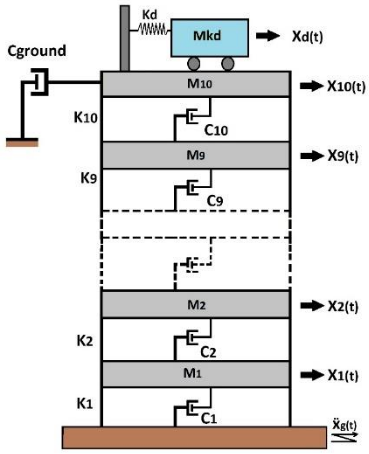


Figure 2. The groundhook control configuration

The groundhook control algorithm alternates between two different options for voltage determination, maximum and minimum. These are accomplished with a simple algorithm shown below.

$$V = \begin{Bmatrix} V_{max} & \text{if} & x_{10}(dx_{10} - dx_d) \geq 0 \\ V_{min} & \text{else} & x_{10}(dx_{10} - dx_d) < 0 \end{Bmatrix} \qquad (5)$$

Here, V_{min} and V_{max} represent the minimum and maximum voltages, respectively. As shown in Equation (5), the voltage transmitted to the MR damper can be determined by the command based on groundhook control. It has been effectively applied to real-time systems due to its simplicity and ease of application [13]. Therefore, the grounhook control is preferred for the hybrid system in this study.

4. Experimental System and Performance Analysis

4.1 Introduction of Experimental Setup

In this study, the implementation of the RTHS method takes place in two steps. Firstly, the relative speed data read from the building model in the computer simulation is transmitted to the experimental setup. Secondly, the MR damper force generated in the experiment set up by the effect of control methods is transmitted to computer simulation. The schematic view of the RTHS method is shown in Figure 3

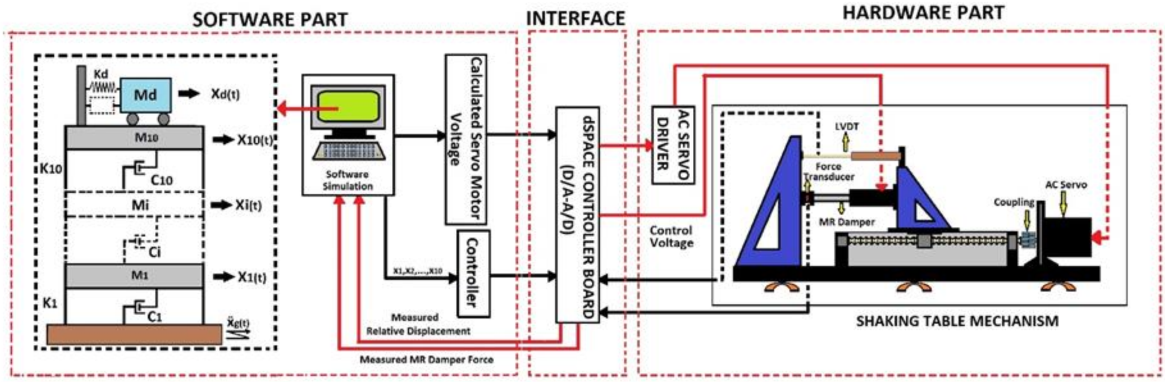


Figure 3. Application scheme of the RTHS method [21]

Structural control studies with the RTHS method are examined using the shaking table in Yıldız Technical University Vibration Research and Control Laboratory. In the experimental part, where force and relative displacement are measured, one force sensor and one linear variable position sensor are used. One RD-8041-1 type MR damper is used, which is the experimental part of the STMD control application. A computer communicates with the dSpace interface and is used to run the data processing, control, and shaking table.

4.2 Hysteresis properties of MR damper and system parameters

The characteristic features of the MR damper connected to the experiment setup are obtained with a sinusoidal input of 1 Hz and 5 mm amplitude. The determined force-displacement and force-velocity curves are shown in Figure 4.

The parameters of a ten-story building are used by scaling in STMD control application with the RTHS method [22], [23]. Parameters of the model in Figure 1; $m_{1...10} = 72\ \text{t}$, $k_{1...10} = 13x10^7\ \text{N/m}$, $c_{1...10} = 1.24x10^6\ \text{Ns/m}$ [2]. The mass ratio for the tuned mass damper is 0.03, and its parameters are determined as $m_d = 21.6\text{t ve } k_d = 81x10^4$ [8]. The system is excited by the accelerations of the El-Centro and Kocaeli earthquakes. Excitations are scaled due to the stroke limitation of the MR damper (El-Centro (0.04), Kocaeli (0.075)). The maximum and minimum voltages transmitted to the MR damper are $V_{max} = 10$ volts and $V_{min} = 0$.

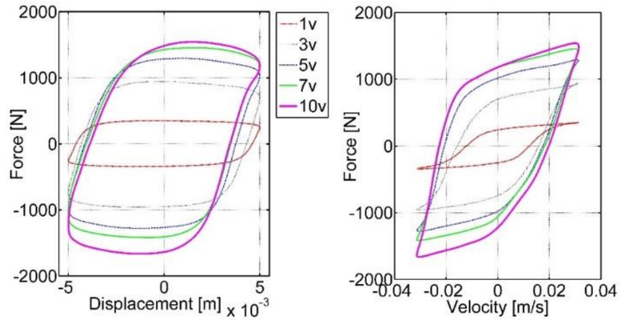
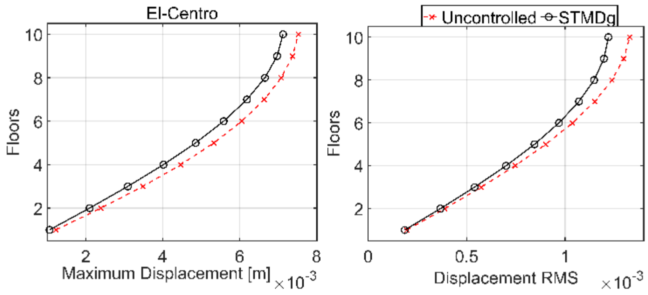


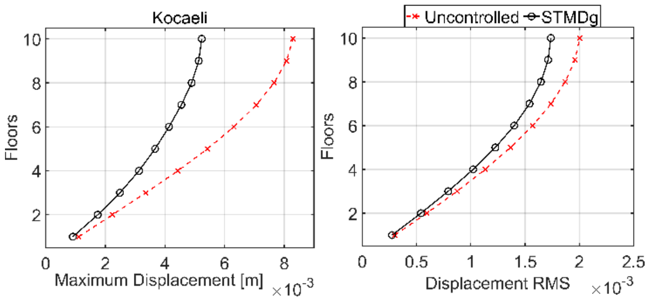
Figure 4. MR damper characteristics

4.3 Time responses

El-Centro and Kocaeli Earthquake excitations effect of the structural system of the maximum displacement and displacement RMS responses of all floors are researched. Figure 5 shows the displacement and displacement RMS values of all floors. The groundhook control method (STMDg) has successfully reduced the vibrations of the structural system in all excitation situations.

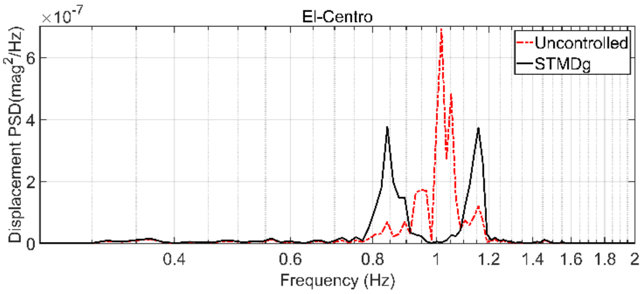


a)

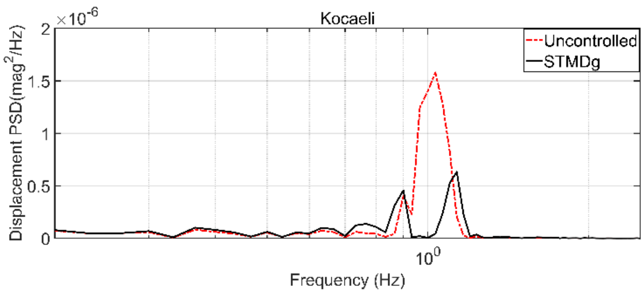


b)

Figure 5. Maximum displacement and displacement RMS responses of all floors of the STMD a) El-Centro earthquake b) Kocaeli earthquake



a)



b)

Figure 6. 10. Floors PSD responses of the STMD a) El-Centro earthquake b) Kocaeli earthquake

4.4 Frequency analysis and MR damper data

For the frequency-domain analysis, power spectrum density (PSD) responses of the frequency variations of the system are researched. The PSD curves of the displacements of the 10th floors for all excitation cases are shown in Figure 6. It is observed that the semi-active controllers successfully suppress the resonance peaks.

Table 1 shows the MR damper data read from the experimental setup and used in the computer simulation. It is seen that the maximum forces are almost equal in both earthquake excitations, and more force is produced in the Kocaeli earthquake in the force RMS values

Table 1. Experimental data of the MR damper

Earthquakes	Forces [N]		Voltages [V]	
	Maximum	RMS	Maximum	RMS
El-Centro	1959.64	490.8016	10	5.80
Kocaeli	1985.10	624.3378	10	5.94

4.5 Structural Vibration Performance Evaluations

Performance indices for the structural system are given as follows [24].

$$J_1 = \max\left\{\frac{\max_{t,i}\frac{|d_i(t)|}{h_i}}{\delta^{max}}\right\},\ J_2 = \max\left\{\frac{\max_{t,i}|\ddot{x}_{ai}(t)|}{\ddot{x}_a{}^{max}}\right\} \quad (6)$$

$$\delta^{max} = \frac{|d_i(t)|}{h_i} \quad (7)$$

Here δ^{max} , $\ddot{x}_a{}^{max}$, d_i and h_i the maximum inter-story drift ratio, absolute acceleration, the distance between floors, and relative displacement between floors, respectively. The performance indices in Table 2 compare the cases of no control application, and the cases of STMD are compared. Among the performance indices, J1 is calculated with the maximum displacement between floors, while J2 is calculated with the maximum acceleration value. Performance indices are expected to be smaller than one to improve system responses. It is seen that STMDg improves system responses in all performance indices in both seismic excitations affecting the structural system. In Kocaeli excitation, the performance index of j2 in all control cases is similar to the uncontrolled state. However, this is acceptable due to improvements in displacement performance indices.

Table 2. Performance Indices

Performance Indices	El-Centro	Kocaeli
	STMDg	STMDg
J_1	0,9126	0,8012
J_2	0,9932	1,0046

5. Conclusion

This paper investigates the structural vibration suppression performances of the STMDs with the RTHS method. The software part of the RTHS method consists of a building model computer and control algorithm, and the experimental part consists of an MR damper and sensors. The semi-active control element in STMD is the MR damper. The groundhook control algorithm determines the voltage transmitted to the MR damper. The system is excited with the El-Centro and Kocaeli earthquakes, and its displacement and PSDs are investigated. In all time responses, it has been found that the STMDg has improved system responses. PSD curves are analyzed for the frequency domain of system responses. Displacement PSD analysis shows that the STMDg is suppressing resonance peaks. The results show that the performances of STMDs used in structural vibration control can be effectively executed with RTHS, an alternative method to experimental setups.

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