



PERFORMANCE OF SEMI-ACTIVE CONTROLLERS FOR A LARGER-SCALE BASE-ISOLATION STRUCTURE WITH MR DAMPER

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Abstract

This paper will present a series of semi-active control strategies of a large-scale base-isolated building with a Magneto-Rheological (MR) fluid damper. The control strategies seek to reduce the displacement across the base isolation layer without an increase in acceleration. A MR damper is installed in the isolation layer of a large-scale base-isolated building structure tested on Japan's National Institute for Earth Science and Disaster Prevention (NIED) E-Defense shake table in Kobe, Japan. The MR damper is a Sanwa Tekki Company 10kN damper with a +/-300mm stroke. The force amplitude in the MR damper can be varied by proving the damper's electromagnetic coils varying levels of current, through a current driven power amplifier. The control logic, or controllers, used in identifying the appropriate level of current to provide the MR damper from available measurements of the structural system is the focus of this paper.

The isolated structure is a 15 metric ton steel frame supported on linear bearings and a rubber isolator. The isolated system is excited by a lateral ground acceleration of scaled historical earthquake excitations, as well as swept sine and random excitations. Uncertainty in the isolated structure is observed in the presence of friction in the linear bearings and the friction force is quantified from experimental test results. Shake table system identification tests allow for a numerical model of the system to be developed and validated. The steel frame is initially modeled as a rigid mass. To better capture the high frequency accelerations observed in initial controllers, the local vibration modes of the steel frame are modeled using measured data.

The controllers considered in this paper include two Skyhook-based controllers, two Fuzzy Logic controllers, a Modulated Homogeneous Friction controller, and two LQR Clipped Optimal controllers. The sensitivity of the controllers to friction and damping in the isolation layer are examined. The efficacy of the proposed control methods are verified using the E-Defense shake table tests and compared to the numerically predicted performance. The experimental tests demonstrate that an effectively controlled MR damper in the isolation layer is able to reduce the displacement across the isolation layer while also reducing the absolute accelerations of the structure. It is observed that the model-based controllers (e.g. the LQR Clipped Optimal controllers) were sensitive to the system models, while the non-model-based controllers (e.g. Skyhook, Fuzzy Logic and Modulated Homogeneous Friction) showed robustness to uncertainty in the system. The relative merit of the proposed controllers are further explored.

Keywords: E-Defense shake table experiment, magneto-rheological fluid damper, base-isolation



1. Introduction

Seismic protective systems have gained attention over the past decades since they have the potential to increase the resistance of structures while targeting higher performance objectives (Housner *et al.* 1997). Although they still have yet to be fully incorporated on the structural engineering community (Asai and Spencer 2015), a variety of promising systems have been developed, using passive, active, semiactive and hybrid control strategies (Soong *et al.* 1994; Housner *et al.* 1997). Base isolation systems remain within the most widely studied and implemented (Morgan and Mahin 2011; Warn and Ryan 2012). It is understood that base isolation is effective to reduce the response of buildings when the predominant frequencies of the ground motion are sufficiently higher than the fundamental natural frequency of the isolated structure. However, long-period excitations amplify the response of these lower-frequency isolated structures, causing large displacements across the isolation layer that can result in pounding and damage to the base isolators (Housner *et al.* 1997, Morgan and Mahin 2011, Masroor and Mosqueda 2013). These large displacements can be reduced by placing additional damping at the isolation layer. However, this has the counter effect of decreasing the isolation. As a result, higher frequencies accelerations can be increased such that nonstructural components and equipment become more vulnerable (Kelly 1993, Kelly 1999, Warn and Ryan 2012).

Semiactive damping devices placed at the isolation layer provide the promise of protection against large displacements while also maintaining isolation. Magneto-rheological (MR) fluid dampers have been suggested for this application, because they require low power, are stable in nature, and have a large dynamic range and a large temperature range and can produce large forces at low velocities. In addition, large-scale MR dampers are comparatively small and have few moving parts, which makes them more appealing for civil engineering applications (Yang, *et al.* 2002; Jiang and Christenson 2012). This paper will evaluate various semiactive control strategies for the large-scale seismic isolation.

2. Experimental Setup

The test specimen used for large-scale semi-active seismic isolation is shown in Fig. 1 as installed on the E-Defense shake table. The test specimen was 7.0 m by 5.5 m in plan and 2.3 m tall, weighing approximately 14.9 metric ton. The superstructure is constructed of H300 steel beam columns and V-shaped braces and is considered sufficient rigidity to be assumed a lumped mass. The seismic isolation system includes four linear guides and a single natural rubber bearing. An MR damper was installed in the isolation layer as well.



Fig. 1 – Base Isolated Test Specimen at E-Defense.



The MR fluid damper was a 10 kN controllable damper manufactured by the Sanwa Tekki Corporation. The MR damper had a stroke of ± 300 mm, maximum current of 5 amps, and a mass of 76.19 kg. A picture of the MR damper as tested subsequently at Kobe University, is shown in Fig. 2.

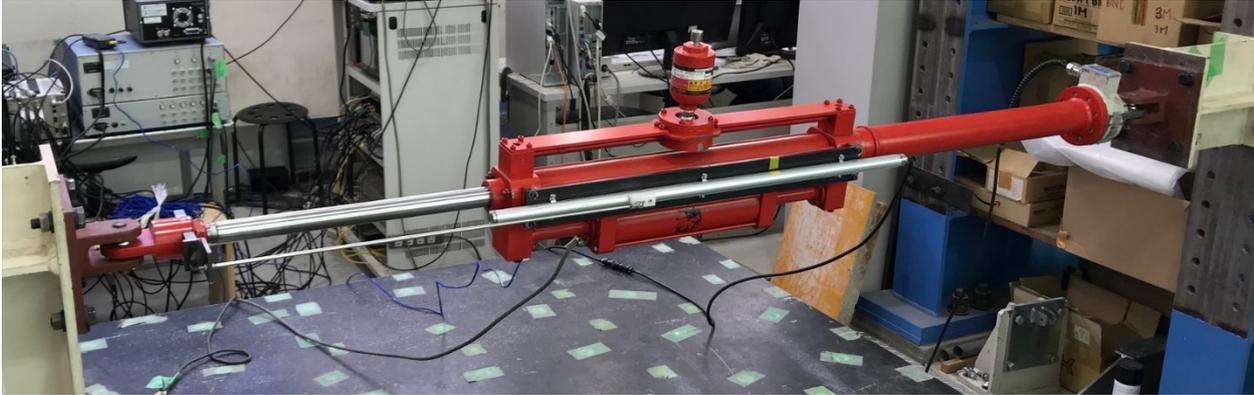


Fig. 2 – MR Fluid Damper used for Semi-Active Base-Isolation.

3. Semi-Active Control Strategies Considered

A set of specific controllers for the MR damper were considered by the authors, including fuzzy logic control, modulated homogenous friction control and skyhook control. The fuzzy logic control strategy is an adaptation of the work of Liu 2001. The modulated homogenous friction control strategy is an adaptation of the work of Inaudi 1997. The controllers considered are all non-model-based controllers, in that they do not require any model of the test structure or the MR damper. A more detailed description of these three controllers is provided.

3.1 Fuzzy logic control strategy

The fuzzy control strategy applies fuzzy logic to control the MR damper through the process of: first fuzzification of inputs; second logical operation of fuzzified inputs; and lastly defuzzification to output values. This process intends to simplify the controls in an intuitive and comprehensible manner. Both relative damper displacement (x_{rel}) and relative damper velocity (\dot{x}_{rel}) are used as inputs for this control strategy and the output is a command current (I_{cmd}) for the MR damper.

The fuzzification process of the control strategy first converts inputs into fuzzy variables. Eq. ($K_d=5x_{relmax}$ (1) and Eq. ($K_v=5\dot{x}_{relmax}$ (2) normalize the relative damper displacement and relative damper velocity about their maximum predicted values, respectively, and then scale the inputs bound on a range of ± 5 fuzzy variables integers.

$$K_d = \frac{5}{x_{rel}^{max}} \quad (1)$$

$$K_v = \frac{5}{\dot{x}_{rel}^{max}} \quad (2)$$

K_d was chosen to be 24 and K_v was chosen to be 12 for this application.

Lastly, these fuzzy variables are rounded to the nearest integer to intuitively represent the fuzzy variable in one of the following fuzzy categories: large, medium large, medium, medium small, small, or zero. This linguistic quantification membership function is shown in Fig. 3. The fuzzy input variables are related to fuzzy output using the output rule-base in Table 1 as a lookup table. Finally, a membership function presented in Fig. 4 is used for the defuzzification process. For a given linguistic fuzzy output, a numerical value of $U(t)$ is determined to be an integer between 0 and 5.

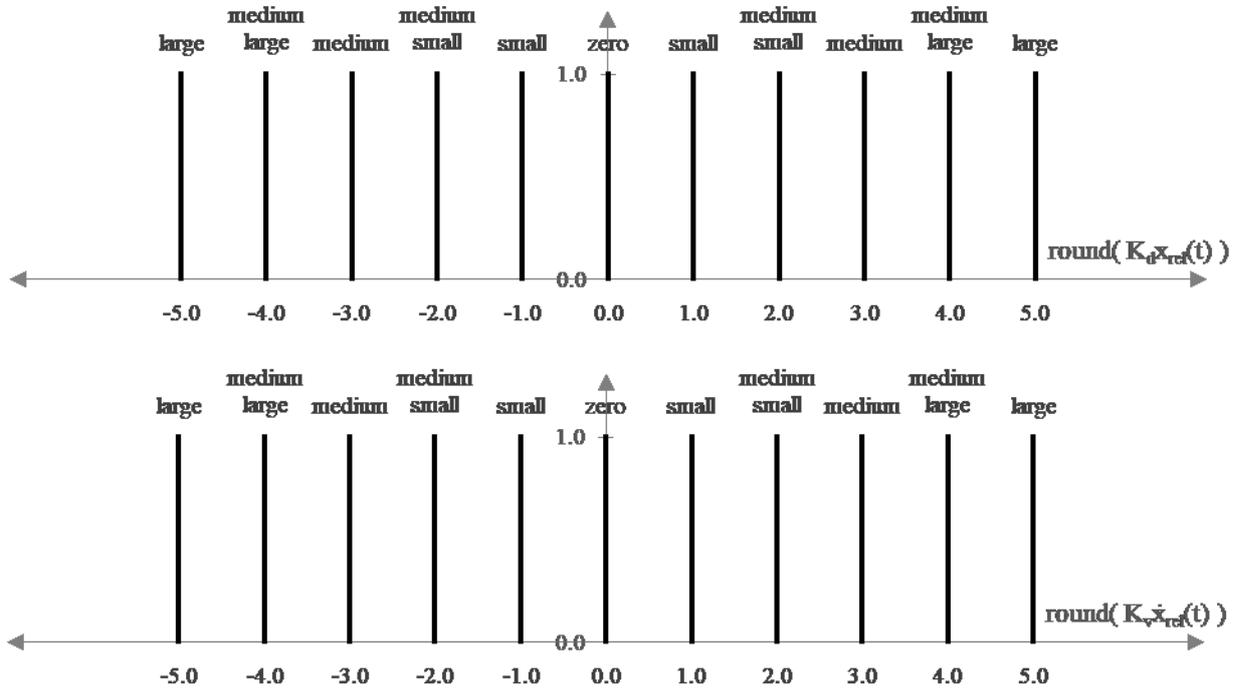


Fig. 3 – Input membership function

Table 1 – Fuzzy output rule-base

Output Rule-Base		round($K_v \dot{x}_{rel}(t)$)										
		(negative)					(positive)					
		large	medium large	medium	medium small	small	zero	small	medium small	medium	medium large	large
round($K_u x_{rel}(t)$)	(negative)	large	large	large	large	large	medium large	medium large	medium large	medium	small	zero
	medium large	large	large	large	large	medium large	medium large	medium	medium	small	zero	small
	medium	large	large	large	large	medium large	medium large	medium	small	zero	small	medium
	medium small	large	large	large	large	medium large	medium	small	zero	small	medium	medium large
	small	large	large	large	medium large	medium	small	zero	small	medium	medium	medium large
	zero	medium large	medium large	medium large	medium	small	zero	small	medium	medium large	medium large	medium large
	small	medium large	medium	medium	small	zero	small	medium	medium large	large	large	large
	medium small	medium large	medium	small	zero	small	medium	medium large	large	large	large	large
	medium	medium	small	zero	small	medium	medium large	large	large	large	large	large
	medium large	small	zero	small	medium	medium	medium large	large	large	large	large	large
(positive)	large	zero	small	medium	medium large	medium large	medium large	large	large	large	large	large

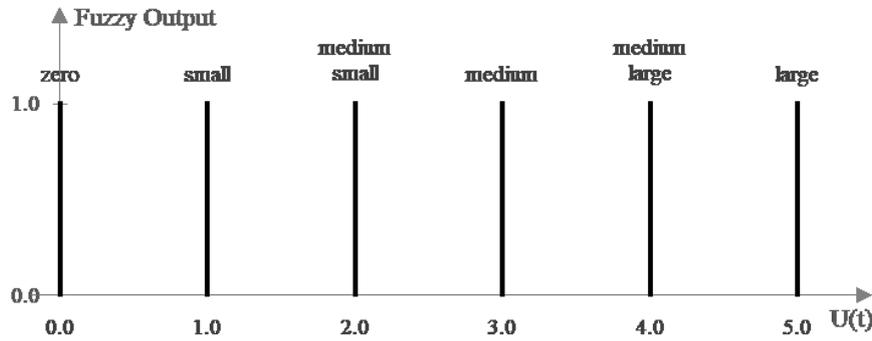


Fig. 4 – Output membership function

Using the numerical value of $U(t)$ determined from Fig. 4, the commanded current to the MR damper (i_{cmd}) is determined from the following equations:

$$i_{cmd} = i_{min} + K_u U(t) \quad (3)$$

$$K_u = \frac{i_{max} - i_{min}}{5} \quad (4)$$

For this test, the maximum current (i_{cmd}) value was 5, and the minimum current (i_{min}) was 0.

3.2 Modulated homogeneous friction control strategy

The modulated homogeneous friction control strategy is a relatively straightforward control, originally developed for use with variable friction devices (Inaudi 1997). The desired current applied to the damper is equal to a peak value of relative displacement across the damper (i.e., when the relative velocity across the damper is zero) multiplied by a gain constant. The control law is:

$$i_{cmd}(t) = g \times |P[x_{rel}(t)]| \quad (5)$$

$$g \cong \frac{i_{max}}{x_{rel}^{max}} \quad (6)$$

where g is a positive gain, based on a maximum applied current for a set relative displacement. For this test, a gain value of 45 was used, based on a value of maximum applied current of MR damper over maximum expected relative displacement, Eq. ($g \cong \frac{i_{max}}{x_{rel}^{max}}$) (6). Function $P[.]$ is the prior-local-peak (or prior-to-peak) operator; and x_{rel} is the damper relative displacement. The prior-to-peak operator finds the maximum (or minimum) relative damper displacement, and then holds that value until a new maximum (or minimum) is found. For implementation of this prior-to-peak operator, a peak value in relative damper displacement is taken when the relative damper velocity equals zero.

3.3 Skyhook control strategy

The philosophy of the skyhook control strategy intends to damp motions of a suspended mass relative to an absolute frame of reference. The principle is to mimic a theoretical situation where a suspended mass is “hooked” with a damper to the so-called “sky” in order to reduce suspended mass oscillations. This control strategy applied full current (i.e., maximum damper force) to the MR damper when the product of the absolute velocity of the suspended mass (\dot{x}) and the relative velocity of the across the damper (\dot{x}_{rel}) is positive. Otherwise no current is applied to the MR damper. The current for the skyhook damper is determined as:

$$i_{cmd}(t) = \begin{cases} i_{max}, & \text{\& if } \dot{x} \times \dot{x}_{rel} > 0 \\ 0, & \text{\& otherwise} \end{cases} \quad (7)$$



4. Results

In July 2019 a series of shake table tests were conducted at E-Defense. The large-scale semi-active seismic isolation system with 10 kN MR damper was tested for the three controllers identified, specifically: fuzzy logic; modulated homogeneous friction; and skyhook. Each controller is evaluated for three earthquake ground motions, specifically: the El Centro ground motion of the 1940 Imperial Valley Earthquake; the Takatori ground motion of the 1995 Southern Hyogo prefecture Earthquake; and the Sylmar ground motion of the 1994 Northridge Earthquake. The time history responses of the relative displacement across the isolation layer, the superstructure (floor) acceleration, and the MR damper force, are provided in Figs. 5-7. The peak (max) displacement across the isolation layer [disp], the superstructure (floor) acceleration [Accel], and the MR damper force [Force], are provided in Table 1.

Table 1: Peak Responses

Earthquake	El Centro 1940			Takatori 1995			Sylmar 1994		
	Disp. (mm)	Accel (m/s ²)	Force (N)	Disp. (mm)	Accel (m/s ²)	Force (N)	Disp. (mm)	Accel (m/s ²)	Force (N)
Fuzzy	131	3.72	10.27	192	5.48	9.56	143	4.99	9.38
Friction	128	1.79	7.31	167	1.25	6.99	182	1.90	7.36
Sykhook	106	2.16	7.88	173	1.82	7.05	131	1.89	7.14

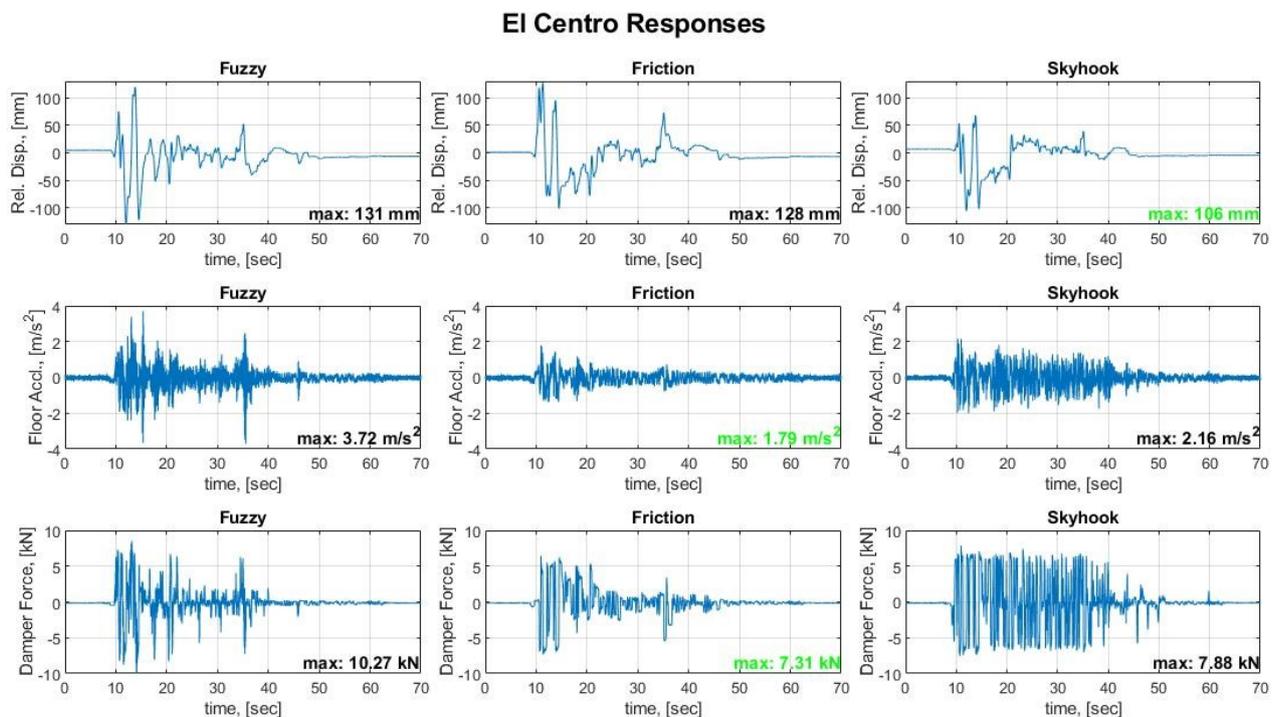


Fig. 5 – Controlled responses for El Centro earthquake excitation



Takatori Responses

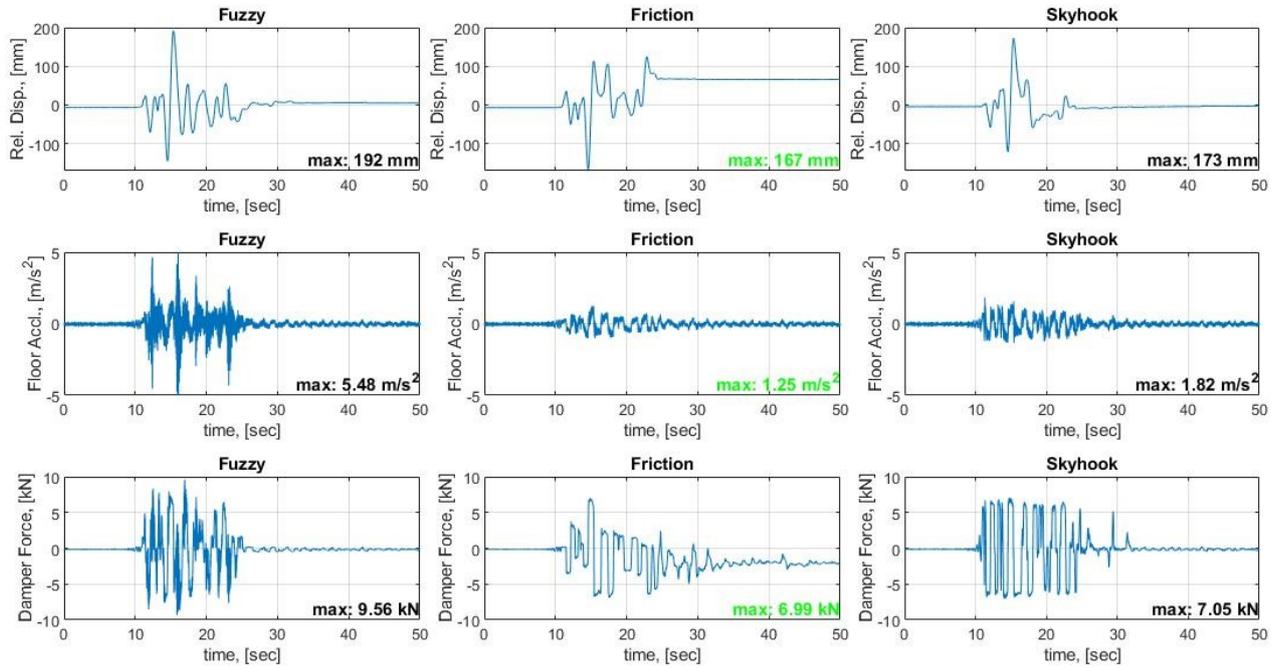


Fig. 6 – Controlled responses for Takatori earthquake excitation

Sylmar Responses

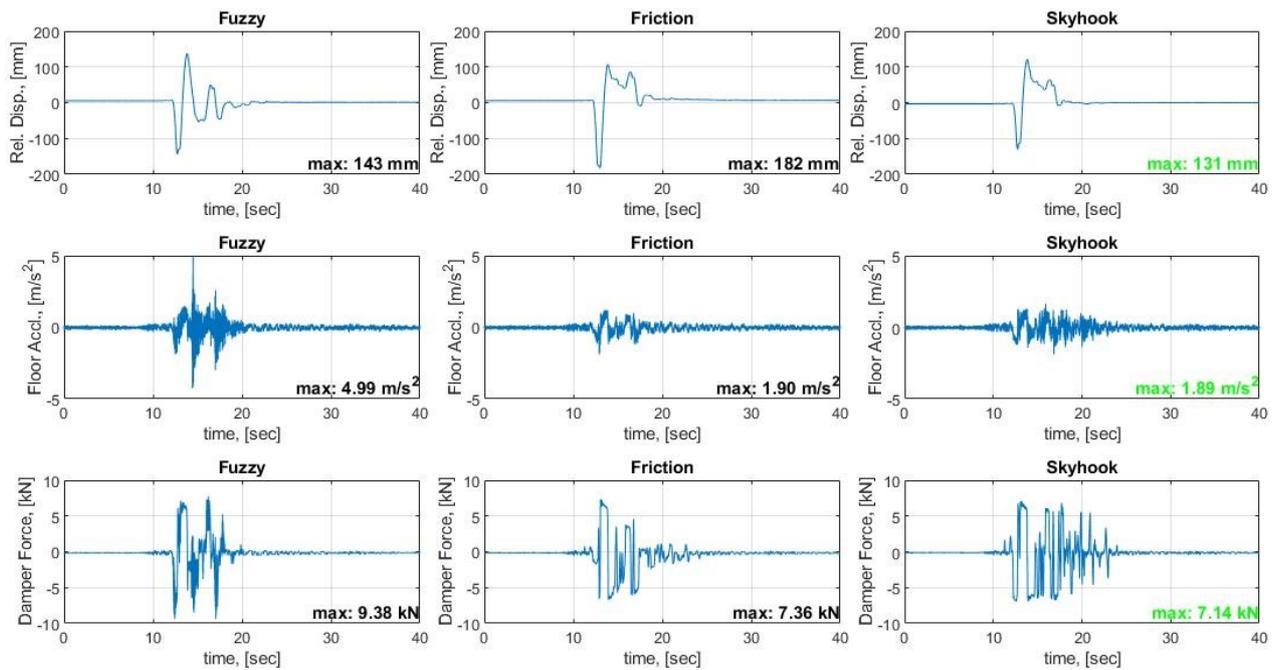


Fig. 7 – Controlled responses for Sylmar earthquake excitation



For the earthquake ground motions considered and the three non-model-based controllers considered, some observations can be made. The fuzzy logic controller resulted in larger peak relative displacement across the isolation layer, superstructure (floor) acceleration, and the MR damper force than the other two controllers considered. The modulated homogeneous friction controller was able to achieve similar performance to the skyhook controller with less aggressive MR damper control force. Additionally, the overall floor acceleration for the modulated homogeneous friction controller is less than the fuzzy logic and skyhook controller response.

5. Conclusion

This study presented results from large-scale shaking table tests of the semi-active control of a base isolation system with a 10 kN MR damper using the E-Defense shake table facility in Japan. Three semi-active control strategies are considered for controlling the displacement and acceleration response of the base isolated system. The controllers are non-model-based controllers, not requiring any information from the isolated structure or MR damper. These controllers included: fuzzy logic; modulated homogeneous friction; and skyhook. Each controller is evaluated for three earthquake ground motions: the El Centro ground motion of the 1940 Imperial Valley Earthquake; the Takatori ground motion of the 1995 Southern Hyogo prefecture Earthquake; and the Sylmar ground motion of the 1994 Northridge Earthquake. Time history responses and peak response values are examined. The fuzzy logic controller provided the best overall reduction of the relative displacement across the isolation layer along with a reduction in the superstructure (floor) acceleration. The fuzzy logic controller is able to reduce these responses with the less MR damper force than the fuzzy logic or skyhook controllers.

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