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Fuzzy supervisory control of a seismic shake table

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Abstract. This work addresses the design and implementation of a novel fuzzy supervisory control approach for the motion control of a seismic shake table. For this purpose, a single degree of freedom laboratory-scale electric shake table was developed. The control scheme comprises two loops: a PI inner loop and a fuzzy outer loop as the supervisor. Three separate supervisory controllers are proposed and implemented in the shake table, and their performance in tracking two real earthquakes is assessed via extensive shake table testing. The test results reveal the effectiveness of the fuzzy supervisory controller in reducing displacement and acceleration tracking errors.

1. Introduction

Earthquakes are natural disaster events that can cause damage and injury if structures are not sufficiently fortified to withstand them. In order to study the structural response variables of civil structures and evaluate their robustness against seismic loads, shake table tests may be employed. An earthquake shake table is a device that simulates strong ground motions. Depending on its size and payload, it can be employed to test full or laboratory-scale civil structures. Shake tables have been extensively used for structural dynamics testing in recent years [1-4].

Aside from their size and degrees of freedom, shake tables are classified as electric or hydraulic types. Hydraulic shake tables utilize hydraulic power and can produce huge forces. These are suitable for testing large structures. Electric shake tables, on the other hand, employ an electric motor as a deriving system and are usually designated for testing light structures. Since 1890, when the first laboratory shake table was built by Milne and Omori in Japan, several shake tables have been developed [5-8].

The main core of a shake table is its control system, whose principal function is to control the shake table motions based on feedback error signals in order to emulate the dynamic characteristics of an earthquake. In this study, the effectiveness of a shake table control system is evaluated by measuring the tracking error, i.e. the deviation in simulated motion achieved by the shake table from the reference motion acquired from a real or synthetic earthquake profile.

Tracking control of a seismic shake table is normally performed via a feedback control system, in which the reference and response signals are compared continuously and the control command is calculated based on the error signals. Several control approaches have been employed for this purpose. For example, Azalée [9], a six-degree of freedom shake table, utilizes a control strategy with three loops. Seki et al. [10] proposed an adaptive feedback compensator for a shake table and mounted structure control. Yang et al. [11] improved the tracking characteristics of a laboratory shake table using a three-state feedback and feedforward control algorithm based on the pole assignment principle. Time Delay Control (TDC)

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was used to improve the tracking performance of a shake table by Lee et al. [12]. Chase et al. [13] developed a controller to reduce acceleration spikes. Ji et al. [14] considered controlling an array of nine sub-tables with sixteen servo actuators. Airouche et al. [15] studied the application of a variety of controllers ranging from Amplitude Phase Control (APC) and Adaptive Harmonic Cancellation (AHC) to Adaptive Inverse Control (AIC) and online iteration (OLI) for shake table control. DE Canio et al. [16] considered applying 3-dimensional image processing to 3 variable controls on a hydraulic shake table.

Fuzzy Logic Control (FLC) as an effective control approach has attracted considerable interest in current years and has several advantages. First, it is possible to integrate the knowledge of an expert into the design procedure in terms of verbal statements. Besides, it does not require an exact model to function. This is a key advantage in the control of systems like shake tables, where the exact system model is not available. Finally, FLC is inherently robust and has great potential for adaptability, which makes it a good choice for controlling systems with uncertainties [17]. In order to enhance control performance, FLC may be combined with another control approach in a hierarchical control strategy. In this scenario, the system is controlled through a two-loop control system, where the inner loop is usually faster and sends control output directly to the system and the outer loop acts as a supervisor to improve the inner loop performance [18]. The fuzzy supervisory control approach has been successfully employed to control a base isolated benchmark building [19]. However, no work has addressed shake table motion control tables using this control approach. Application of fuzzy-supervisory controller to control seismic shake tables may be beneficial according to the following reasons:

1. Most of controllers provided by the motor-drive builders are of conventional PID type. In this case, performance of the controller is not optimal for all simulated earthquakes. Supervisory control can be added to these controllers as a modular outer loop to enhance tracking performance;
2. The designer knowledge can be simply translated to verbose statement for supervising purpose;
3. Fuzzy controller has an inherent robustness. It is very important that the shake table controller be robust in order to tackle systems uncertainties;
4. Fuzzy controller as the supervisor has a high potential of tunability, which makes it a good match for further optimizations.

The present study reports the application of a fuzzy supervisory control approach to control a laboratory-scale electric shake table. For this purpose, a single degree of freedom electric shake table is developed. The motion of the table is meant to be controlled primarily by a PI controller. A novel fuzzy logic controller is then designed and implemented in the shake table as the supervisor controller. The performance of the control system with and without a supervisor controller is subsequently evaluated via shake table tests.

This paper is structured as follows. The shake table configuration is initially introduced. The control design and implementation of the controller in the shake table is then described. Finally, the test results are presented and the control approach performance is discussed.

2. Shake table configuration

The developed shake table, LARZA, is depicted in Figure 1. LARZA is an electro-mechanical single degree of freedom seismic shake table that can simulate the horizontal motion of mild earthquakes of up to 100 mm/s velocity and 2 g acceleration. It utilizes a 1 kW permanent magnet synchronous AC servo motor in conjunction with a ball-screw mechanism as the drivetrain system. Moreover, the rotational motion of

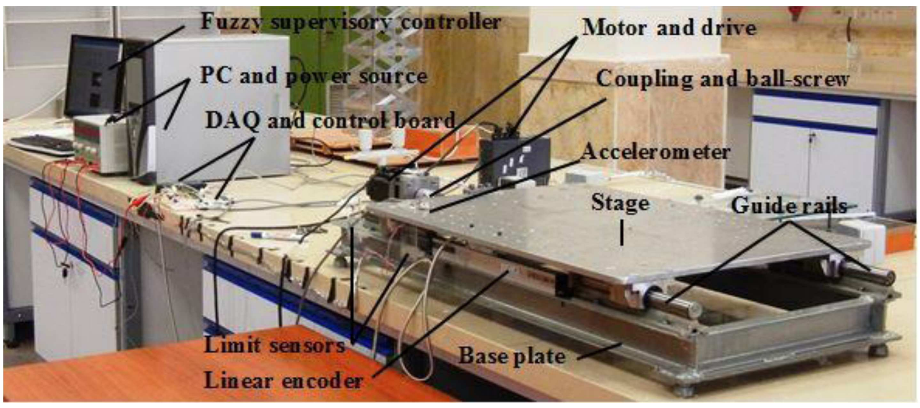

Figure 1. LARZA shake table.

Table 1. Specification of LARZA.

Component/characteristics	Value/description
Motor type	AC permanent magnet synchronous motor
Motor power	1 kW
Table dimensions ($B \times L$)	750 × 550 mm
Displacement (mm)	±90
Maximum velocity (mm/s)	1000
Maximum acceleration (g)	2
Maximum payload (kg)	35
Ball-screw lead (mm)	20
Acceleration sensor	dual-axis MEMS accelerometer with a measurement range of ±1.7 g
Displacement sensor sensitivity (μm)	5

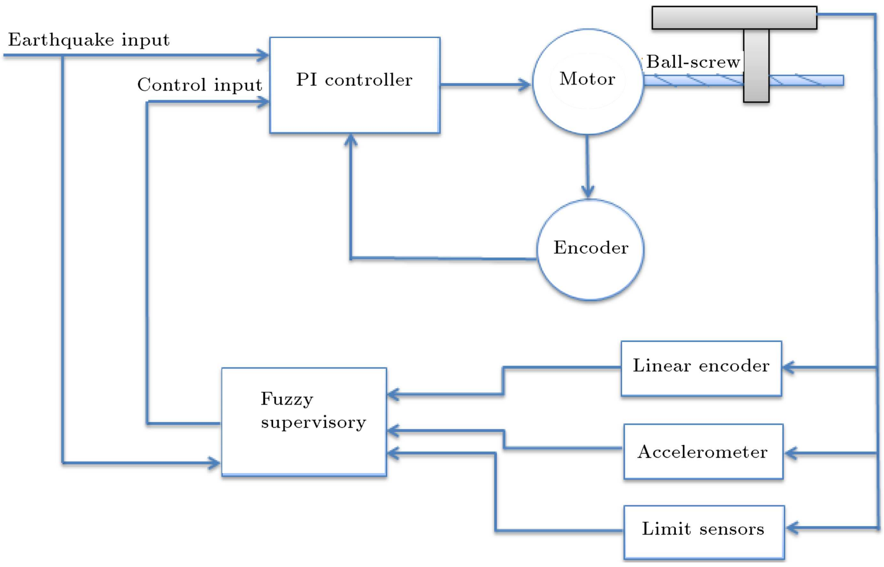

Figure 2. Schematic diagram of the control system.

the motor is translated into linear motion via a ball-screw mechanism. The table stage is 750 × 550 mm with stroke of ±80 mm.

The sensor system includes a 5 μm linear encoder that measures the stage displacement, a shaft encoder that measures the rotation angle of the electric motor shaft with 2500 pulses per revolution sampling frequency and an ADXL203 analog accelerometer that senses the horizontal acceleration of the stage. Moreover, the controller hardware includes a servo drive, a 200 kS/s 16-bit data acquisition (DAQ) card, an AT Mega 32 microcontroller, and a dual core Personal Computer (PC). Communication between these components takes place as follows. The linear encoder sends the acquired data to the microcontroller, which then calculates the shake table position and sends the information to the DAQ card as a 16-bit word. Meanwhile, acceleration data is acquired by the DAQ card, which is connected to the PC where the control program is implemented in Lab VIEW software. For safety reasons, two infrared CNY70 limit switches are used to shut down the system in case the stage travel exceeds the predefined stroke range of ±90 mm.

The specifications of LARZA are summarized in Table 1.

3. Controller design and implementation

The control scheme shown in Figure 2 comprises two loops, including an inner PI loop as the core controller and a fuzzy controller as the supervisor. In this scenario, the PI controller in the inner loop is the main component in the table's motion control, and it controls the motor speed based on the feedback error signals. The outer loop, i.e. fuzzy supervisory controller modifies the inner loop's performance. Basically, in this application, the supervisor controller is meant to enhance the tracking performance of the PI controller by compensating for the tracking errors. In

Table 2. Fuzzy rule base for FLC_1.

$\dot{\text{Err}}_{\text{displacement}}$ / $\text{Err}_{\text{displacement}}$	**PB**	**PM**	**PS**	**Z**	**NS**	**NM**	**NB**
NB	PM	PM	PB	PB	PB	PB	PB
NM	PSS	PS	PS	PM	PM	PM	PB
NS	PSS	PSS	PS	PS	PS	PS	PS
Z	NSS	NSS	Z	Z	Z	PSS	PSS
PS	NS	NS	NS	NS	NS	NSS	NSS
PM	NB	NS	NM	NM	NS	NS	NS
PB	NB	NB	NB	NB	NB	NM	NM

this case, perfect tracking is achieved when the desired displacement, velocity, and acceleration adopted from a real or synthetic earthquake profile coincide with the corresponding values achieved by the shake table.

The reference signal for motor speed control is calculated by transforming the desired stage velocity to the required motor shaft speed using Eq. (1):

$$\omega = \frac{v}{L}, \tag{1}$$

where ω is the electric motor rotational speed (reference signal), v is the desired stage velocity corresponding to the earthquake horizontal velocity, and L is the lead screw.

Three separate fuzzy supervisory controllers are proposed using various feedback error signals. In the first FLC, i.e. FLC_1, displacement error and velocity error are considered error signals fed to the FLC. In the second FLC, i.e. FLC_2, displacement error and acceleration error form the FLC inputs and finally, in the third, FLC_3, velocity error and acceleration error are selected as the FLC control inputs. In all mentioned FLCs, the control command is the input voltage to the electric motor. Table 2 depicts the fuzzy rules developed for FLC_1.

In this table, $\text{Err}_{\text{displacement}}$ is the displacement error and $\dot{\text{Err}}_{\text{displacement}}$ is the displacement error rate (velocity error); NB, NM, NS, NSS, Z, PSS, PS, PM, and PB represent negative big, negative medium, negative small, very negative small, zero, very positive small, positive small, positive medium, and positive big, respectively. Consider a rule, for instance, a rule for which both displacement and velocity errors are 'negative big' implying a large error and a strong tendency toward a larger error. In this case, a big reverse control command like PB would be required to counteract this large error. The other rules are written in the same manner. Furthermore, according to Figure 3, each input is described by seven membership functions. Similarly, the FLC output is described by nine membership functions, as shown in Figure 4.

The fuzzy rule bases for FLC_2 and FLC_3 are shown in Tables 3 and 4, respectively.

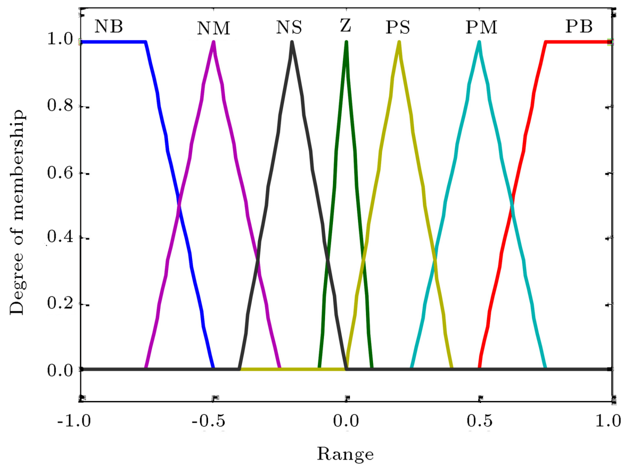

Figure 3. Input membership functions.

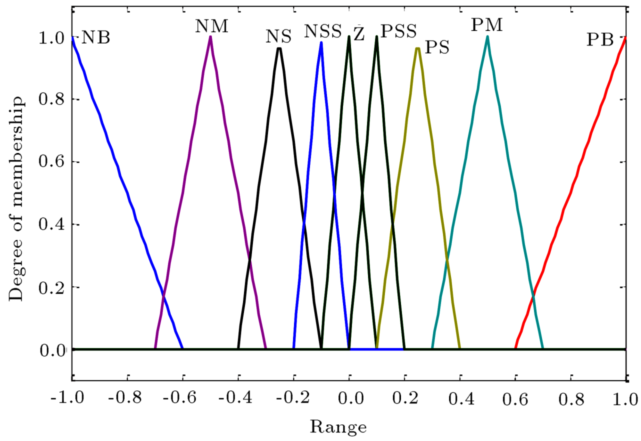

Figure 4. Output membership functions.

Table 3. Fuzzy rule base for FLC_2.

$\text{Err}_{\text{acceleration}}$ / $\text{Err}_{\text{displacement}}$	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	PB	PM	PM	PM	PS	PS	PSS
NM	PM	PM	PM	PS	PS	PSS	PSS
NS	PS	PS	PS	PSS	PSS	Z	Z
Z	PSS	Z	Z	Z	Z	Z	NSS
PS	NSS	NSS	NS	NS	NS	NS	NS
PM	NS	NS	NM	NM	NM	NM	NB
PB	NM	NM	NB	NB	NB	NB	NB

4. Test results and analysis

The shake table test results are presented and discussed in this section. Four controls including a PI controller without a supervisor and the aforementioned fuzzy supervisory controllers were implemented in the shake table. Subsequently, the controllers' performance in tracking earthquake profiles was compared. A scaled version of the Kobe and Chalfant earthquakes [20]

Table 4. Fuzzy rule base for FLC_3.

$\mathbf{Err_{velocity}}$ / $\mathbf{Err_{acceleration}}$	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	PB	PB	PS	PSS	Z	NS	NS
NM	PB	PB	PS	PSS	Z	NS	NS
NS	PB	PM	PS	PSS	NS	NS	NM
Z	PM	PM	PSS	Z	NSS	NS	NM
PS	PM	PM	PSS	Z	NS	NM	NM
PM	PM	PS	PS	NSS	NS	NM	NB
PB	PS	PS	Z	NSS	NS	NB	NB

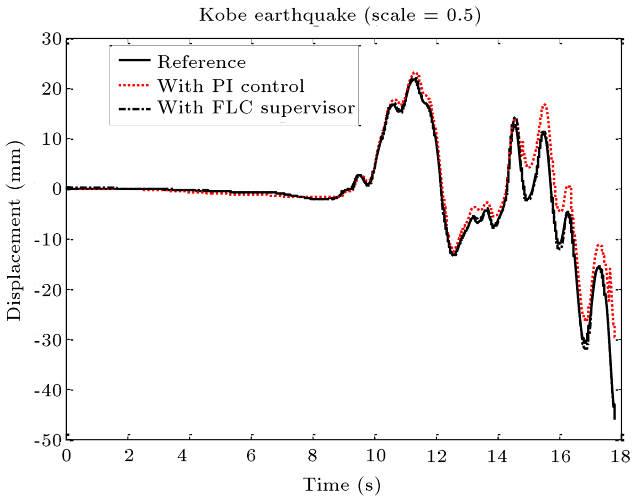

Figure 5. Stage displacement response with FLC_1.

was employed for this purpose. Specifications of the mentioned earthquakes are given in Table 5.

Figure 5 compares the displacement response histories for the shake table with PI and FLC_1 controllers. As seen in this figure, employing a PI controller with no supervisor results in considerable tracking error, whereas applying the fuzzy supervisory controller in conjunction with the PI controller causes a drastic drop in tracking error.

Figures 6 and 7, respectively, depict the tracking performance of the FLC_2 and FLC_3 supervisory controllers, respectively. These figures indicate that FLC_3 performs much better than FLC_2. Nevertheless, FLC_3 performs more poorly than FLC_1, implying the superior performance of FLC_1 in displacement tracking.

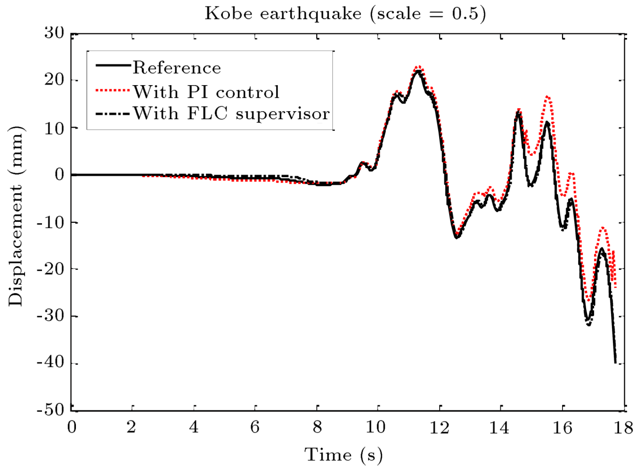

Figure 6. Stage displacement response with FLC_2.

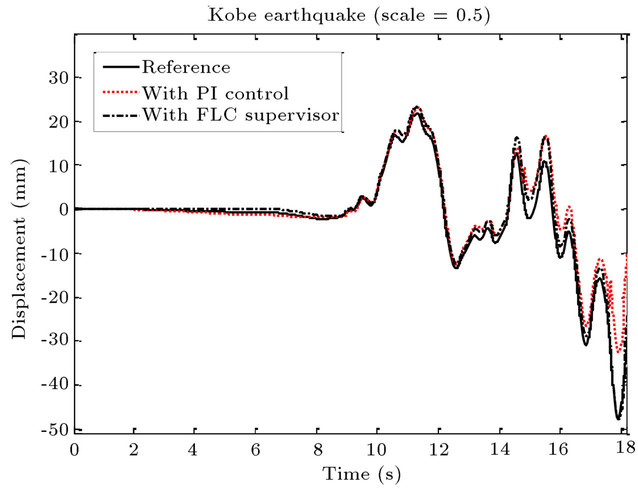

Figure 7. Stage displacement response with FLC_3.

In order to measure and compare tracking errors objectively, the RMS criterion (Eq. (2)) may be employed:

$$Err_{\mathrm{RMS}} = \sqrt{\frac{\sum_{i=1}^{N}(X[i] - X_{\mathrm{ref}}[i])^2}{N}}, \qquad (2)$$

where N is the number of samples, X is the achieved response, and X_{ref} is the reference signal.

Figure 8 compares the controllers' performance in displacement tracking based on the mentioned criterion. This figure signifies that the fuzzy supervi-

Table 5. Specification of reference earthquakes.

Reference earthquake	Specifications
Kobe earthquake	Station: Nishi-Akashi Magnitude: M (6.9); Data source: CUE
Chalfant valley earthquake	Station: 54428 Zack Brothers Ranch Magnitude: Ml (5.9); Data source: CDMG

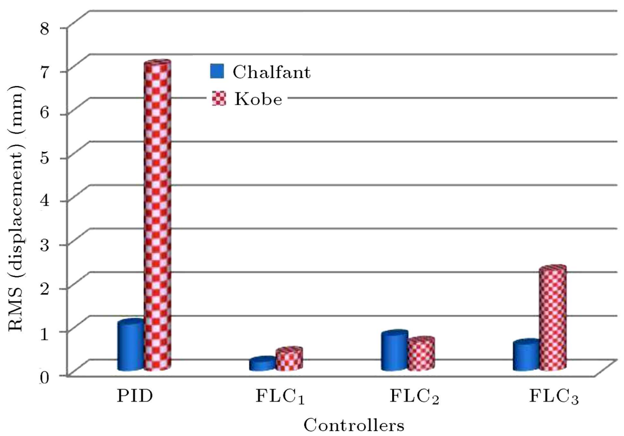

Figure 8. RMS of displacement error with various controllers.

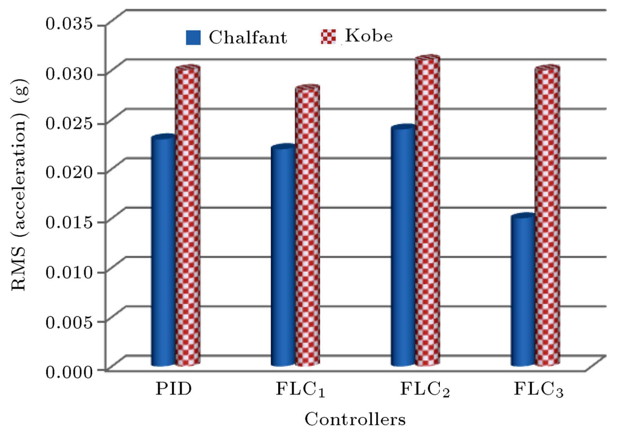

Figure 9. RMS of acceleration error with various controllers.

sory controllers successfully improved the displacement tracking errors for both earthquake types. Moreover, among the fuzzy supervisory controllers, FLC_1 performed the best.

Figure 9 illustrates the acceleration tracking errors. According to the obtained results, applying FLC_1 yields a slight decrease in acceleration tracking error for both earthquakes. In contrast, FLC_2 causes higher acceleration tracking error. However, applying FLC_3 results in virtually the same level of tracking error for the Kobe earthquake and considerable tracking error for the Chalfant earthquake. Furthermore, although the calculated RMS values for the tracking error are dissimilar to the considered earthquakes using the primary PI controller, according to Figures 8 and 9, fuzzy supervisory could successfully decrease displacement and acceleration errors substantially. Moreover, after employing the fuzzy-supervisory controller, the displacement and acceleration reduction indicated by RMS criterion are nearly at the same level for both earthquakes, indicating robustness of the supervisory controller in comparison with the PID one.

5. Conclusion

A novel fuzzy supervisory controller was designed and implemented for motion control of a seismic shake table in this work. Three different fuzzy supervisory controllers were proposed and implemented in the shake table. The impact of the fuzzy supervisory controller on the shake table's tracking performance was evaluated through testing while emulating the behavior of two predefined earthquakes. It was shown that the fuzzy supervisory controller can drastically improve the displacement tracking performance of the PI controller. Moreover, using the fuzzy supervisory controller attained a slight improvement in acceleration tracking performance.

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