

Fuzzy-sliding mode supervisory control of an electric seismic shake table

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ABSTRACT

Precise tracking of the earthquake acceleration profile in the presence of uncertainties is a challenge for the shake table control design. Design and implementation of a fuzzy-sliding mode supervisory controller for an electric seismic shake table with variable payload is addressed in this paper. The proposed controller contains two layers including a PI loop and a fuzzy-sliding mode supervisory controller. The controller is then implemented in the shake table and its performance is evaluated via extensive experiments. The test results reveal successful performance of the proposed controller at robust tracking of two sample earthquakes in the presence of parametric uncertainties.

Keywords: *Shake table, earthquake, acceleration tracking, fuzzy-sliding mode, variable payload*

1 INTRODUCTION

Seismic shake tables are effective tools employed to assess robustness of civil structures, power facilities, transportation systems etc. against seismic loads [1, 4, 7]. Depending on its payload, a seismic shake table may utilize an electric or a hydraulic power train system. Hydraulic shake tables are usually designed for full-scale or very large structures and can produce huge forces which resemble real earthquake disturbance. On the other hand, electric shake tables are usually designed for small or laboratory-scale structures and employ an electric motor to produce the driving force.

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One of the main concerns in tracking control of shake tables is variation of system parameters as a result of mounting various structures. In this case, the controller should compensate impact of the parametric uncertainties initiated from the load variations. Some works have been done on robust control design of shake table in the presence of uncertainties. Seki et. al proposed a compensation algorithm in order to increase tracking accuracy of a shake table with a mounted structure [9].

However, no work has been reported on fuzzy-sliding mode control of shake table in the presence of uncertainty arisen from the variable payload. Moreover, in the previous works, despite

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proper tracking of displacement and velocity signals, acceleration tracking is accompanied with a considerable error. Design and implementation of a fuzzy-sliding mode controller for a laboratory-scale seismic shake table is addressed in this work. The main goal of this work is to devise an effective control strategy for robust tracking of scaled earthquakes in the presence of parametric uncertainties and unmodeled dynamics. Especial attention is paid to the acceleration tracking performance and it is aimed to decrease acceleration tracking errors in both time and frequency domains.

Structure of this paper is as follows: first the shake table configuration is introduced. Mathematical modelling of the shake table and validation procedure is described afterward. Finally, control design and implementation are presented and the test results are discussed.

2 MATHEMATICAL MODEL AND MODEL VALIDATION

LARZA (Fig. 1) is a laboratory-scale uniaxial shake table developed at Arak University in 2012. The shake table utilizes a permanent magnet synchronous AC motor in conjunction with a ball screw mechanism as its powertrain system. This shake table is capable of simulating scaled version of moderate earthquakes with maximum 100 mm/s velocity and 2g acceleration.

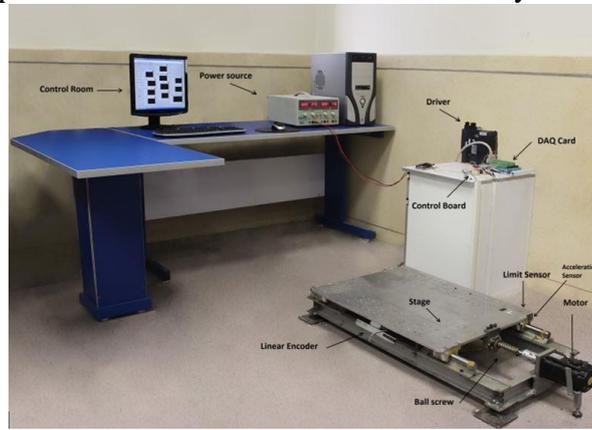


Figure 1 – Larza shake table.

The sensor system includes a 5 μm linear encoder which measures the stage displacement, a shaft encoder which measures the rotation angle of the electric motor shaft with 2500 pulses per revolution sampling frequency, and an ADXL203 analog accelerometer which senses the stage horizontal acceleration. 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).

Mathematical model of the system and the model validation are described as follows. (1)-(3) depicts the governing dynamic equations for the electric motor in d-q coordinate system using Park transformation [11].

$$\frac{d}{dt} i_d = \frac{1}{L_d} v_d - \frac{R}{L_d} i_d + \frac{L_q}{L_d} \rho \omega i_q \quad (1)$$

$$\frac{d}{dt} i_q = \frac{1}{L_q} v_q - \frac{R}{L_q} i_q + \frac{L_d}{L_q} \rho \omega i_d - \frac{\lambda \rho \omega}{L_d} \quad (2)$$

$$T_e = \frac{3}{2} \rho [\lambda i_q + (L_d - L_q) i_d i_q] \quad (3)$$

In the equations above, L_d and L_q are inductances of d and q axis respectively, R is the electric resistance of the stator windings, i_d and i_q are currents of d and q axis respectively, v_d and v_q are voltages of d and q axis respectively, ω is angular velocity of the rotor, λ is the flux amplitude induced by the rotor permanent magnets at the stator phases. ρ is number of pole pairs,

and T_e is the electromagnetic torque. As for the permanent magnet synchronous electric motor, $L_d = L_q$, (3) can be rewritten as (4).

$$T_e = \frac{3}{2} \rho \lambda i_q \quad (4)$$

The governing dynamic equations of motor shaft motion are also as follows.

$$\frac{d}{dt} \omega = \frac{1}{J} (T_e - \beta \omega - T_l) \quad (5)$$

$$\frac{d\theta}{dt} = \omega \quad (6)$$

where J is the effective inertia at motor shaft, β is the viscous damping coefficient at motor bearings, and θ is shaft rotation angle [3]. The ball screw mechanism is also modelled as (7).

$$T = \frac{FL}{\xi} \quad (7)$$

where T is the motor output torque, F is the transmitted linear force to the ball-screw, 2 is the ball-screw efficiency, and 1 is lead of the ball screw. The efficiency of the ball screw mechanism is assumed 90 percent [11]. (8) and (9) depict governing dynamic equations for the table stage. (10) and (11) also show governing dynamic equations of motion for electric motor shaft considering the stage load.

$$F = mh\ddot{\theta} \quad (8)$$

$$T = \frac{mh^2\ddot{\theta}}{\xi} \quad (9)$$

$$j \frac{d\omega}{dt} = T_e - \beta\omega - \frac{mh^2\ddot{\theta}}{\xi} \quad (10)$$

$$(j + \frac{mh^2}{\xi}) \frac{d\omega}{dt} = T_e - \beta\omega \quad (11)$$

where m is the stage mass. The total mass of the stage including mass of the mounted structure is also defined as (12). Where m_1 is the mass of the mounted structure.

$$M = m + m_1 \quad (12)$$

Rearranging (11) and (12), dynamic equations of motion for the electric motor shaft can be written as (13)-(15).

$$(j + \frac{Mh^2}{\xi}) \frac{d\omega}{dt} = T_e - \beta\omega \quad (13)$$

$$\frac{d}{dt} \omega = \frac{1}{j_{tot}} (T_e - \beta\omega) \quad (14)$$

$$j_{tot} = j + \frac{mh^2}{\xi} \quad (15)$$

2.1 Model validation

In order to measure accuracy of the model, the model responses are compared with those of the shake table for two reference earthquakes. Table 1 depicts the specifications of the employed earthquakes. The implemented controller for the model validation study is a primary PI one.

Table 1: EARTHQUAKES SPECIFICATIONS

Reference earthquake	Specifications
Kobe earthquakes	Station: Nishi-Akashi
halfant earthquakes	Station: Zack Brothers

Figure 2 compares the displacement responses in the model and test. As is seen in this figure, there is a good agreement between the model and test response variables for both employed earthquakes.

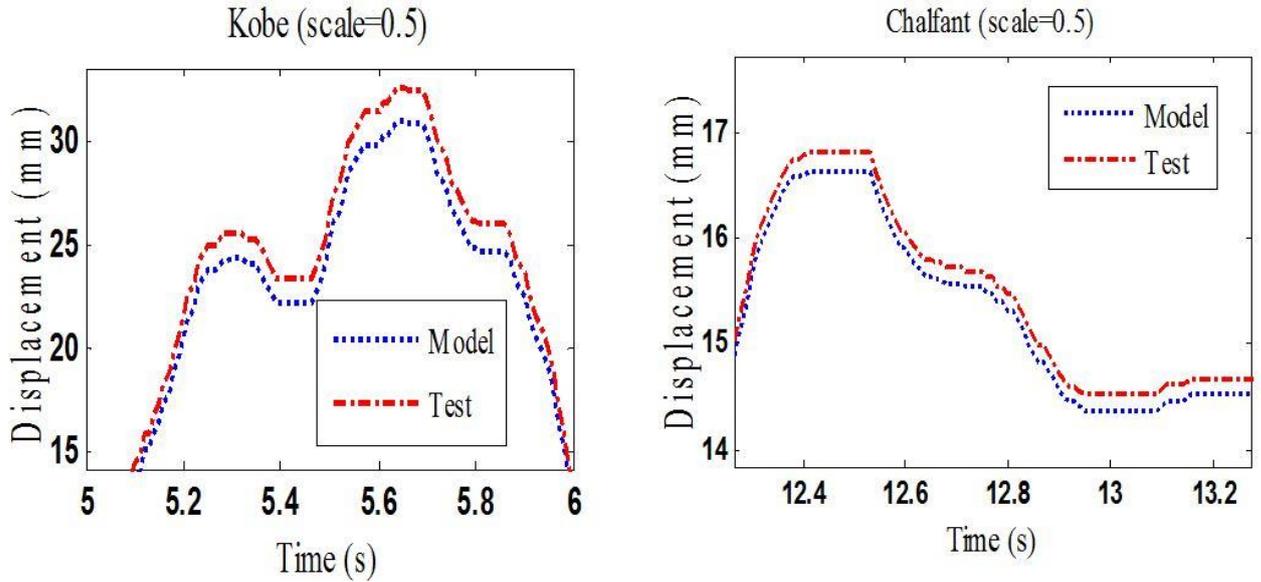


Fig.2. Comparison of displacement tracking performance for model and table with the primary controller

3. CONTROLLER DESIGN

Controller design is described in this section. The aim of control design is robust tracking of predefined earthquakes in the presence of uncertainties. Two sources of uncertainties have been considered in this work. The first is model uncertainties due to unmolded dynamics. This source of uncertainty is evident from the results obtained in the validation section where the model response variables show a small deviation from those in the test. Another inevitable source of uncertainty in the shake table tests is payload variations due to mounting various structures on the shake table. In order to tackle the mentioned uncertainties, a robust controller can be a good match. The driving force of the shake table, as mentioned in section II, is generated by a permanent magnet synchronous motor (PMSM). Some works have been conducted on robust control of this kind of electric motor. Su et al. proposed a highly robust automatic disturbances rejection controller for high-precision motion control of PMSM [10]. Chiu-Keng et al. proposed a new sliding-mode controller for position control of PMSM [5]. Faa-Jeng et al. presented a robust fuzzy neural network sliding-mode controller supported by computing torque control to control the PMSM. It was reported that by using the proposed method, tracking performance was substantially improved [6]. El-Sousy proposed a novel robust control system by combining hybrid H_∞ -based wavelet neural network controller for PMSM to enhance position tracking. The new method could estimate the uncertain system dynamics via online tuning [2]. The proposed controller in this work is a new supervisory fuzzy-sliding mode described in the following section. Fig.3 shows the schematic diagram for the proposed fuzzy sliding mode supervisory controller.

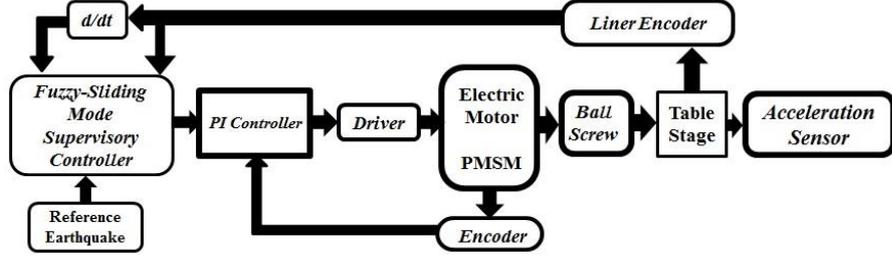


Fig.3. Schematic diagram of the fuzzy-supervisory controller

The control strategy comprises two control loops. In the first one, a PI controller is primarily responsible for motion control of the PMSM motor. Moreover, a supervisory fuzzy sliding mode controller is devised to improve tracking performance. The sliding surface is defined as (16).

$$s(x, t) = \left(\frac{d}{dt} + \lambda \right)^{n-1} \tilde{x} \quad (16)$$

where $\tilde{x} = \omega - \omega_{des}$ is the error signal calculated via translating the linear velocity error signal to that of the electric motor rotational speed. Furthermore, n is the order of governing dynamic equations, here 2, and λ is a strictly positive constant. The sliding surface therefore can be rewritten in the following form.

$$s = \omega - \omega_{des} \quad (17)$$

The control input is also defined as (18) where u_{eq} is the equivalent control and is obtained from (19). u_{reach} is also calculated from the sliding condition as (20)[3].

$$u = u_{eq} - u_{reach} \quad (18)$$

$$\dot{s} = \dot{\omega} - \dot{\omega}_{des} = 0 \quad (19)$$

$$u_{reach} = k \operatorname{sgn}(s) \quad (20)$$

Substituting (16) in (19):

$$\dot{s} = \frac{1}{J_{tot}} (1.5 \rho \lambda i_q - \beta \omega) - \dot{\omega}_{des} = 0 \quad (21)$$

$$i_q = \frac{1}{6\hat{\lambda}} (\hat{\beta} \omega + \hat{J}_{tot} \dot{\omega}_{des}) \quad (22)$$

Where $\hat{\lambda}$, $\hat{\beta}$ And \hat{J}_{tot} are estimated values of λ , β and J_{tot} parameters respectively.

$$\hat{\lambda} = \sqrt{\lambda_{min} \lambda_{max}} \quad (23)$$

$$\hat{\beta} = \sqrt{\beta_{min} \beta_{max}} \quad (24)$$

$$\hat{J}_{tot} = \sqrt{J_{totmin} J_{totmax}} \quad (25)$$

The sliding control law is calculated as (26).

$$i_q = \frac{1}{6\hat{\lambda}} (\hat{\beta} \omega + \hat{J}_{tot} \dot{\omega}_{des}) - k \operatorname{sgn}(s) \quad (26)$$

In order to reduce the control input chattering, introducing a boundary layer \emptyset , u_{reach} is replaced with (27).

$$i_q = \frac{1}{6\hat{\lambda}} (\hat{\beta} \omega + \hat{J}_{tot} \dot{\omega}_{des}) - k \operatorname{sat}(s/\emptyset) \quad (27)$$

The sliding control gain k , a strictly positive constant, is also determined based on a fuzzy inference mechanism based on the deviation from the sliding surface and its time derivative. Table III depicts the fuzzy rule base.

Table 3: FLC rule base

S	N	Z	P
\dot{s}			
N	PH	PB	PM
Z	PS	Z	PS
P	PM	PB	PH

In this table, N is negative, Z is zero, P is positive, PH is positive very big, PB is positive big, PM is positive medium, and PS is positive small. Let's consider a rule e.g. the case which both deviation and its derivative are negative implying a negative deviation from the sliding surface and a tendency to further deviation. In this case, the sliding gain is determined as positive very big in order to push the error state towards sliding surface.

4. CONTROLLER IMPLEMENTATION AND RESULTS ANALYSIS

The proposed controller has been implemented in the shake table using LAB VIEW software. Kobe and Chalfant earthquakes have been considered as the reference earthquakes to be tracked.

Figs. 4-6 compare the tracking performance of the primary and supervisory controllers. As is seen in Fig. 4, the primary controller cannot track the displacement signal properly. Application of FSMC controller on the other hand, caused a considerable drop in the displacement tracking error for both earthquakes. Similar results are seen for velocity and acceleration tracking performance as shown in Fig. 5. and Fig .6. implying successful performance of the FSMC in precise tracking of the mentioned earthquake profiles.

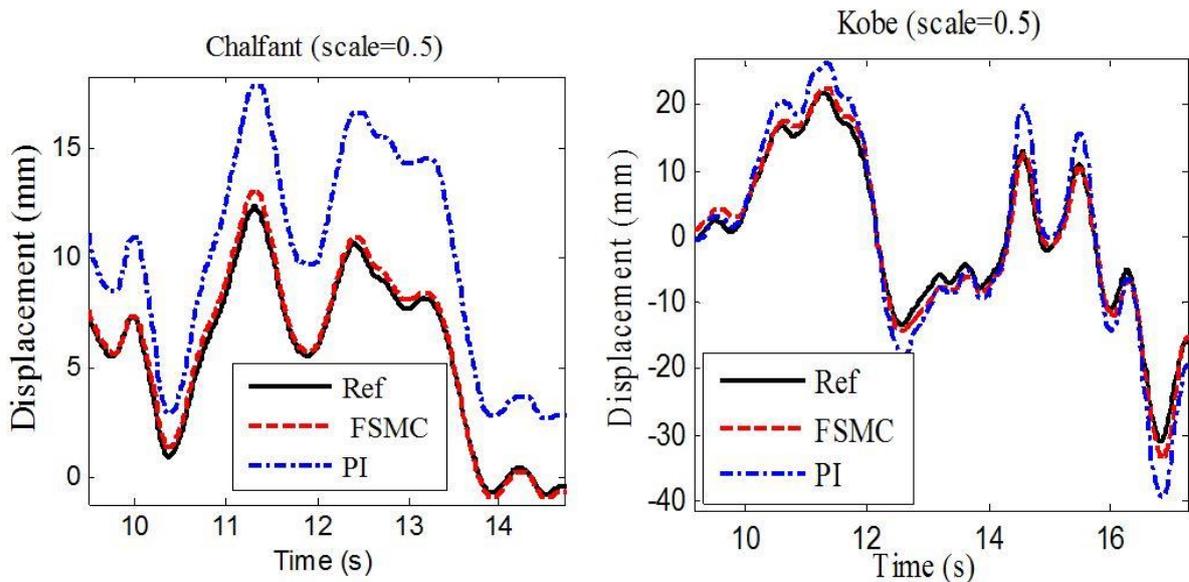


Fig.4. Displacement tracking performance with the primary and supervisory controllers

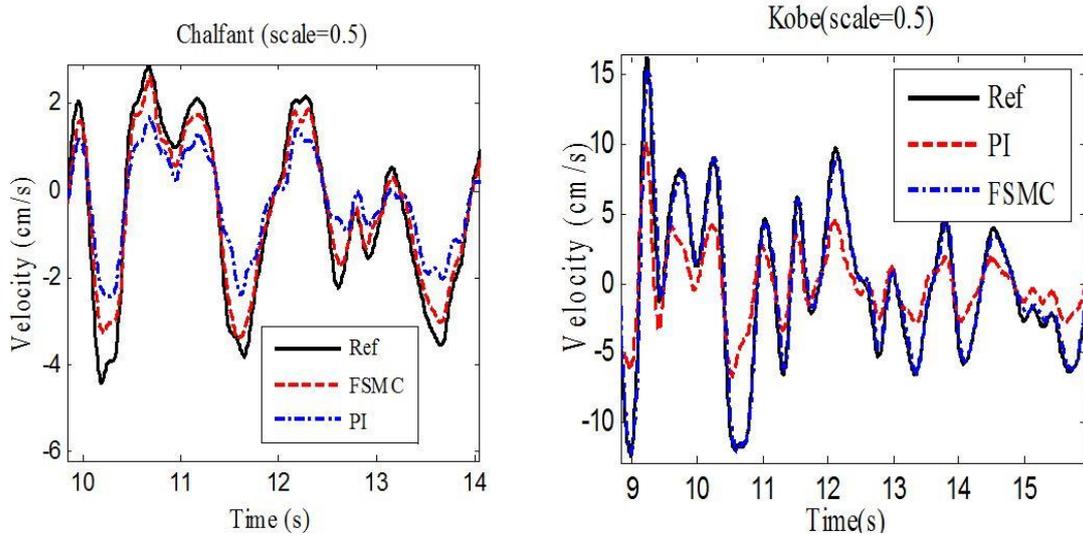


Fig. 5. Velocity tracking performance with the primary and supervisory controllers

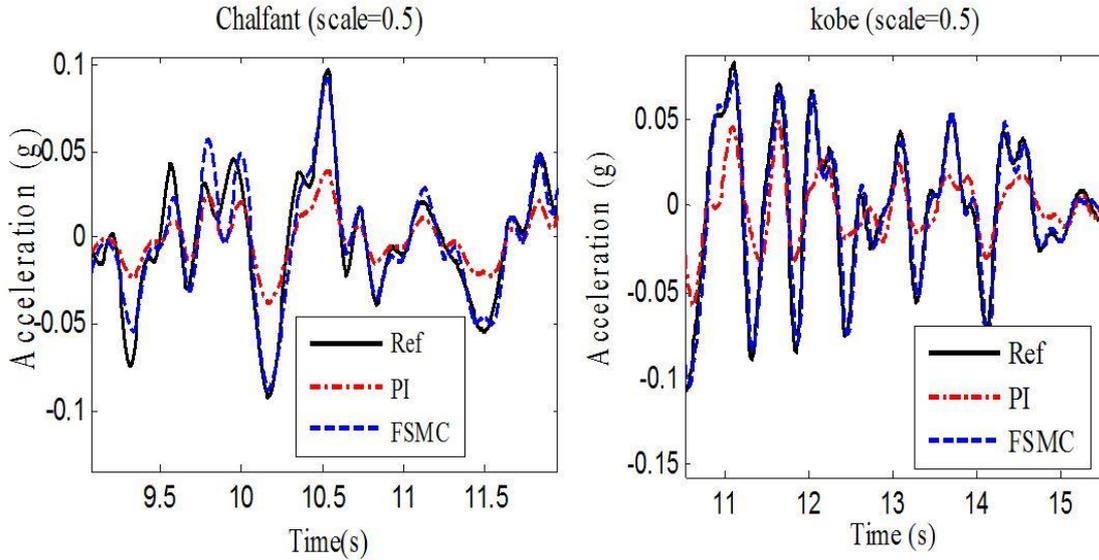


Fig. 6. Acceleration tracking performance in time domain with the primary and supervisory controllers

According to the reported results, application of FSMC controller in the shake table yielded a substantial drop in tracking errors. Moreover, tracking performance in frequency domain is acceptable, especially at low frequencies. These results are in agreement with the tracking error reported for the Chalfant and Kobe earthquakes in the frequency domain. In this case, the tracking error in the frequency domain is higher for Chalfant earthquake. This can be due to different nature of the mentioned earthquakes, as Kobe is a narrow band earthquake, but Chalfant is a wide band one. In order to evaluate robustness of the proposed controller, the shake table test is repeated with a 10 kg structure mounted on the table. This added mass is equivalent to 23% uncertainty in the effective inertia according to (15).

Fig. 7 to Fig. 9 compare tracking performance of the FSMC with and without mounted structure.

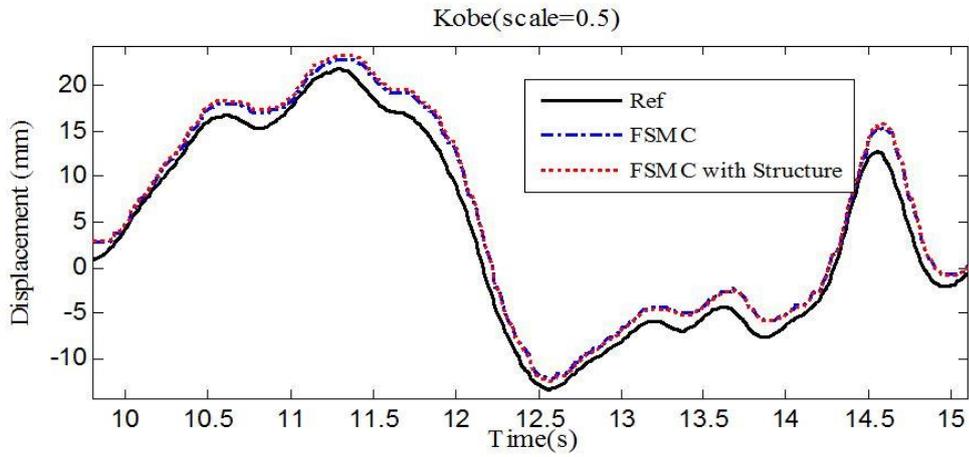


Fig.7. Displacement tracking performance in time domain with and without mounted structure

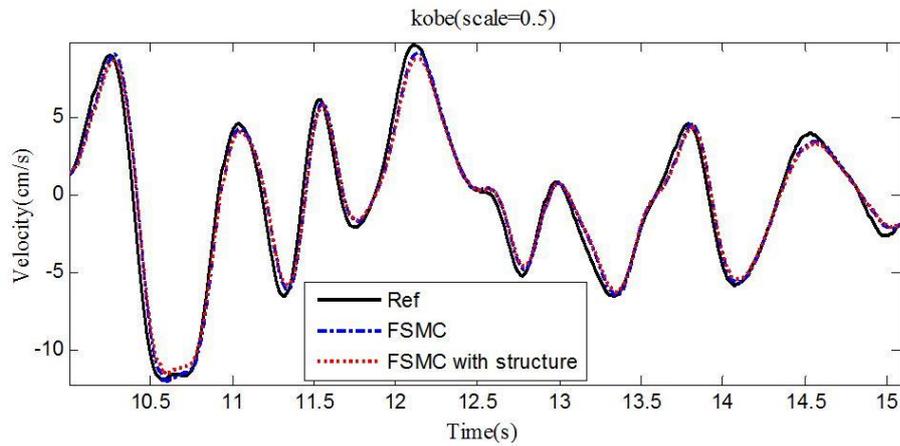


Fig.8. Velocity tracking performance in time domain with and without mounted structure

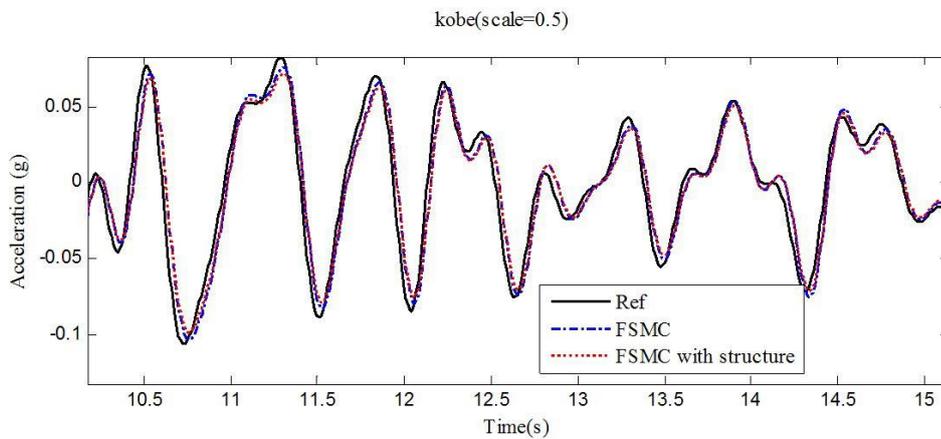


Fig.9. Acceleration tracking performance in time domain with and without mounted structure

According to the obtained results, the FSMC controller can successfully track the displacement, velocity, and acceleration signals despite parametric uncertainty arisen from the added structure.

5. CONCLUSION

Design and implementation of a new fuzzy-sliding supervisory controller for motion control of a laboratory-scale shake table was addressed in this paper. For this purpose, a mathematical model was developed for an electric seismic shake table named LARZA. The model was then validated against experimental data available for two sample earthquakes. A two-loop controller with a PI inner loop and a fuzzy supervisory outer one was devised and implemented in the shake table and its effectiveness was investigated via test. The experimental results indicate superior performance of the proposed controller at tracking the scaled earthquakes. Furthermore, robustness of the supervisory controller was examined through applying the controller to the shake table with a mounted structure equivalent to 23% parametric uncertainty. The test results prove robustness of the proposed controller in tracking the earthquakes trajectories.

REFERENCES

- [1] Nichols, J., Todd, M., Seaver, M. & Virgin, L. Use of chaotic excitation and attractor property analysis in structural health monitoring, *Physical Review E, APS*, 2003; **67**:016209.
- [2] Preumont, A. & Seto, K. *Active Control of Structures*. Wiley Blackwell, 2008.
- [3] Clark, A. *Dynamic characteristics of large multiple degree of freedom shaking tables*, Paper presented at the Proceedings of the 10th World Conference on Earthquake Engineering, 1992.
- [4] El-Sousy, F. F. Hybrid-based wavelet-neural-network tracking control for permanent-magnet synchronous motor servo drives, ” *Industrial Electronics, IEEE Transactions on*, 57(9), 2010; 3157-3166.
- [5] Gang, S., Zhen-Cai, Z., Lei, Z., Yu, T., Chi-fu, Y., Jin-song, Z., Jun-Wei, H. Adaptive feed-forward compensation for hybrid control with acceleration time waveform replication on electro-hydraulic shaking table, *Control Engineering Practice*, 2013; 21(8), 1128-1142.
- [6] Kim, H.-S., Roschke, P. N., Lin, P.-Y., & Loh, C.-H. Neuro-fuzzy model of hybrid semi-active base isolation system with FPS bearings and an MR damper, *Engineering structures*, 2006; 28(7), 947-958.
- [7] Lai, C.-K., & Shyu, K.-K. A novel motor drive design for incremental motion system via sliding-mode control method, *Industrial Electronics, IEEE Transactions on*, 2005; 52(2), 499-507.
- [8] Ogawa, N., Ohtani, K., Katayama, T., & Shibata, H. Construction of a three-dimensional, large-scale shaking table and development of core technology, ” *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 2001; 359(1786), 1725-1751.

- [9] Seki, K., Iwasaki, M., Kawafuku, M., Hirai, H., & Kishida, K. Practical controller design of hybrid experimental system for seismic tests, ” *Industrial Electronics, IEEE Transactions on*, 2009; 56(3), 628-634.
- [10] Stehman, M., & Nakata, N. Direct acceleration feedback control of shake tables with force stabilization, *Journal of Earthquake Engineering*, 2013; 17(5), 736-749.
- [11] Strano, S., & Terzo, M. *A non-linear robust control of a multi-purpose earthquake simulator*, Paper presented at the Proceedings of the World Congress on Engineering, 2013.