DESIGN AND IMPLEMENTATION OF A SLIDING MODE CONTROLLER FOR A SEISMIC SHAKE TABLE

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Abstract

Shake tablesare effective tools for simulating dynamic behavior of structures exposed to seismic loads. The main core of a shake table is its control system. The aim of the controllerin a shake table is to track the displacement, velocity, and acceleration profiles of a realor scaled version of a predefined earthquake. On the other hand, shake table control problem faces uncertainties arose from unknown model parameters and unmolded dynamics. Furthermore, the shake table is designed to test various test structures with different inertias. Therefore, the moving mass of the table is an uncertain parameter which should be concerned in the controller design in order to attain optimal control performance. In this paper, a supervisoryrobust sliding mode controlleris proposed for controlling motions of a laboratory-scale seismic shake table. For this purpose, a model is developed for the shake table and is validated against experimental data. Furthermore, the controller is implemented in the shake table and its performance is evaluatedvia test data. The shake table test results prove effectiveness of the proposed controller at tracking seismic profiles in the presence of the uncertainties. At the same time, the chattering frequency is confined to an applicable range.

Introduction

Earthquake is a natural hazardwhich can lead to a disaster if the structures are not fortified enough to withstand it. In order examine dynamic behavior of structures when subjected to seismic loads, simulation or shake table test may be employed. Although simulation is a fast and inexpensive approach for analyzing dynamic behavior of structures, it may not make real sense in the designer. However, shake table provides the capability of testing a full-scale or reduced model of a real structure in order to measure performance of the structure in confrontation with a real earthquake. In recent years, shake tables have been employed widely to analyze and control various(Kim et al., 2006, Baratta et al., 2012, Wu and Samali, 2002, Lu and Jiang, 2011).

Shake table is a system which simulates seismic disturbances via emulating earthquake motions in laboratory scale. Shake tables, depending on their pay load, may utilize hydraulic or electric driving system. The hydraulic shake tables can generate huge loads and therefore they are suitable for test of heavy structures. On the contrary, the electric shake table which benefits from an electric motor, as the driver, is suitable for test of light structures.Since 1890, when Millen and Emory built the first shake table, seismic shake tables have been evolved significantly(Severn, 2011, Xu et al., 2008, Sinha and Rai, 2009, Rakicevic et al.).

The kernel of a shake table is its control system whose duty is improvement of tracking performance. To do that, a feedback control system is employed. The aim of the feedback control system is minimizing the tracking errors. On the other words, a control system is evaluated as successful whenever a reference earthquake is tracked perfectly i.e. the achieved displacement, velocity and acceleration of the shake table coincides with the ones for the reference earthquake to be tracked.

Several works have been done on the control design of seismic shake tables in recent years.Maoult et.al employed a three loop controller to control a large scale shake table. In their controller, the inner loop, a PD controller, is responsible for servo valves control. The outer loop is also designated to minimize displacement, velocity, and acceleration errors. Finally, the third loop is used for correcting the control command in case of structural damage based on inversion of the initially measured system transfer function(LE MAOULT et al.).Kenta et.al proposed an adaptive controller for control of a seismic shake table(Seki et al., 2009).

In the other work, there is an electro hydraulic shake table which is used as adjustable hydraulic actuator .Last controller such as Proportional– integral – derivation (PID) control created a time delay between responses and desired order. So there is a global three loop controller in which the first loop contains a feedback controller for optimizing controller, second loop the Kalman filter estimates feedback value and third loop feed forward delays block to increase efficiency of controller(Jansen and Dyke, 2000).LARZA is an electric shake table developed at system simulation and control laboratory of Arak university. This shake table utilizes a two-loop supervisory fuzzy controller. In this shake table, a PI loop plays the main role in the motion control of the table. A supervisor fuzzy controller is also designated to enhance the tracking performance of the table.

Uncertainty modeling table’s parameters and physical parametric change in sight of structure’s parameters change which will be installed on the table. Due to the matter mentioned above, we have tried to design a robust controller.The purpose of this research is to design a sliding mode controller. Characteristic of this method is resistance against unmolding dynamics and additionally, this stable system against uncertainties and disturbance input. This controller is designed for controlling shake table velocity and used a nonlinear permanent magnet synchronous motor with ball-screw model for modeling dynamic shake table with a freedom degree behavior.

This paper is divided into several parts: in part 2 configuration of shake table is indicated, in part 3 we will discuss on the matter of shake table modeling, then in part 4 we would recommend a controller on the basis of SMC method which current motor is controlling input. In part 5 implementation and the results of this issue are explained under certain earthquake .And finally in part 6, there would be conclusion.

Modeling Larza shake table

We need a motor and ball-screw model for modeling a shake table. Mechanical and electrical components of motor separately are provided with a second order state space model. This equation shows axial motor system (d-q coordinate). All of the equations return to stator from axial rotor system(Tárník and Murgaš, 2011).

$$\frac{d}{dt}\mathrm{i_d} = \frac{1}{\mathrm{L_d}}\mathrm{v_d} - \frac{\mathrm{R}}{\mathrm{L_d}}\mathrm{i_d} + \frac{\mathrm{L_q}}{\mathrm{L_d}}\,\rho\omega\mathrm{i_q} \tag{1}$$

$$\frac{d}{dt}\mathrm{i_q} = \frac{1}{\mathrm{L_q}}\mathrm{v_q} - \frac{\mathrm{R}}{\mathrm{L_q}}\mathrm{i_q} + \frac{\mathrm{L_d}}{\mathrm{L_q}}\,\rho\omega\mathrm{i_d} - \frac{\lambda\rho\omega}{\mathrm{L_d}} \tag{2}$$

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

According to, this permanent magnet synchronous motor is Ld= Lq. Then to replace in equation (3) we have:

$$T_e = \frac{3}{2}\rho\lambda i_q \tag{4}$$

In the equations, Ld and Lq are inductances for the d and q axes respectively. R is the electrical resistance of the stator windings. id and iq are currents of d and q axes respectively. vd and vq are voltages of d and q axes respectively. ω is the 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. Te is electromagnetic torque(Tárník and Murgaš, 2011).

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

$$\frac{d\theta}{dt} = \omega \tag{6}$$

Where J is the equivalent rotational inertia at the motor shaft, β is the viscous damping coefficient at the motor bearings, and θ is the shaft rotation angle . The equations for ball-screw are as follows:

$$T = \frac{Fh}{2\pi\xi} \tag{7}$$

$$\omega = \frac{2\pi v}{h} \tag{8}$$

Where T is the motor output torque, F is transmitted linear force to the ball-screw, ξ is the ball-screw efficiency, and L is the lead of the ball screw. For a typical ball-screw the efficiency may be considered as a constant 90 percent value. Then we have from above equations:

$$\frac{d}{dt}\omega = \frac{1}{(j + \frac{Mh^2}{\xi})}(T_e - \beta\omega) \tag{9}$$

$$\frac{d}{dt}\omega = \frac{1}{j_{tot}}(T_e - \beta\omega) \tag{10}$$

View of the **Larza** shake table modeling show in figure.1:

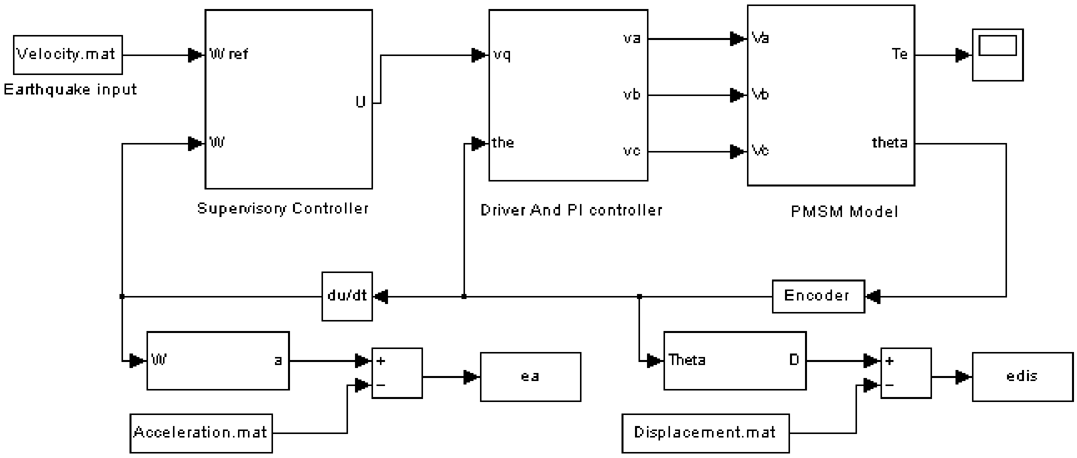
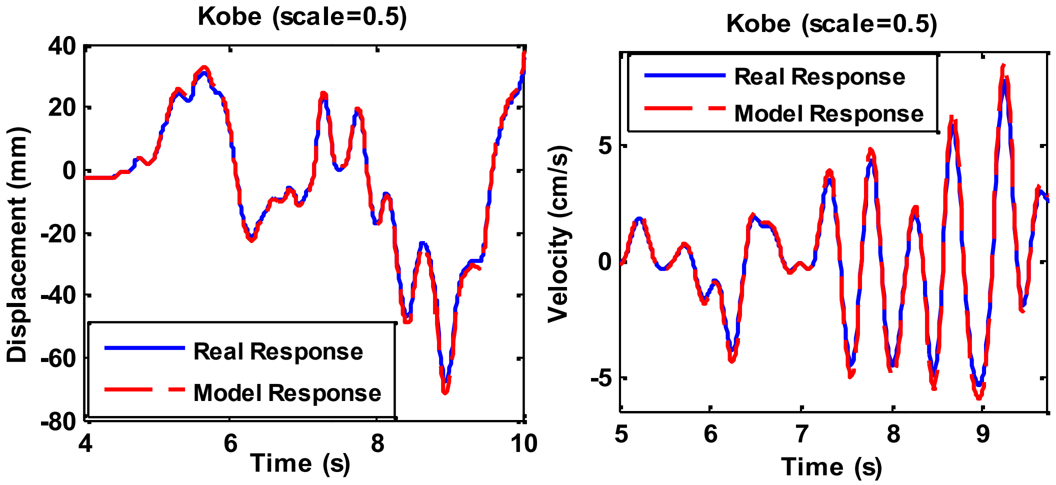


Figure 1.Modeling **Larza** shake table

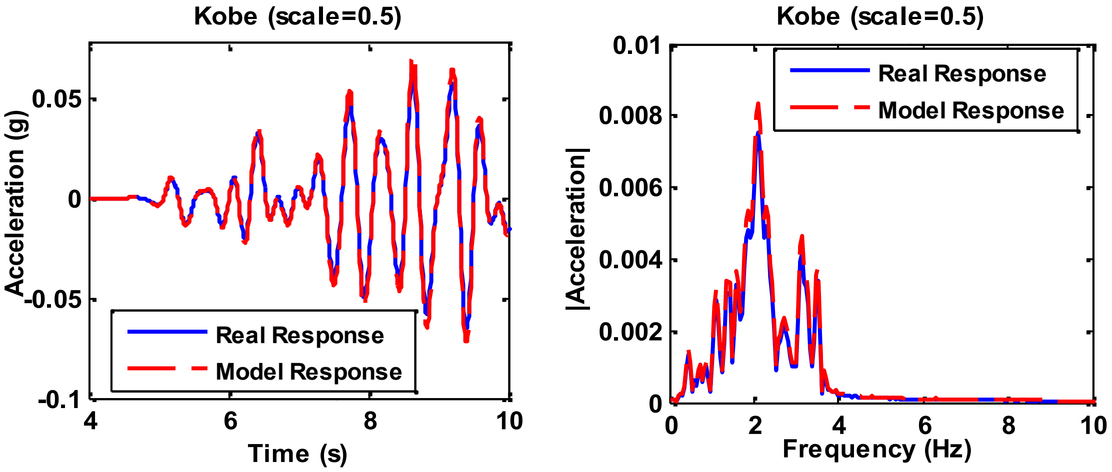
validation of **Larza** shake table model

For shake table modeling validation with shows in part (2), a default earthquake implements on Larza shake table with PI controller .Then results of this implementation would be compared with Larza shake table modeling results in this condition. Definition of validation is that we simulate a certain earthquake with correct scale for shake table model and its own and this configure is shown in Table (1). This result contains displacement, velocity and acceleration that are shown in figures 2,3. With attention to Kobe earthquake tracking error results, it can told that modeling for shaking table equal to reality with highest precision.



(a) (b)

Figure 2- Simulation displacement(a)and velocity(b)diagram for kobeearthquake and PI controller



(a) (b)

Figure 3- Simulation acceleration diagram in the timedomain(a) andfrequencydomain(b) for kobeearthquake and PI controller

sliding mode supervising controller design:

with regard to performance sliding mode controllers in different fields ,use of this controller is increases in last year .purpose of sliding mode controller is design a rule controlling which robust against parametrical uncertainty such as inaccuracy in the constant of electrical actuators torque.Sliding mode controller designing show rule method in stability problem when accrued with inaccuracy in modeling .also this method quantities a stasis between modeling and efficiency that mean, can clear hole of designing and experimental proses.Performance of shake table such that sending controlling commend for reducing error that proportional with error between reference earthquake profile and simulating profile which is simulated with Larza shake table. To continue, we are designing a sliding mode controller with equations in part 3.
We consider the sliding surface as shown in the bottom.

$$s(x,t) = \left(\frac{d}{dt} + \lambda\right)^{n-1} \tilde{x} \tag{10}$$

The $\tilde{x} = \omega - \omega_{des}$is tracking error between ω velocity and ω_{des} desierd velocity in reference earthquake. In attention to equation 1 to 6 we have that n=1, then sliding mode surface equal to:

$$s = \omega - \omega_{des} \tag{11}$$

Controlling input contains two $u_{eq}$and u_{reach}terms. u_{reach}Input term show that state of the system receive to s surface and uqe term’ s purpose is greeting states On s surface(Slotine and Li, 1991). Finally controlling input is achieved from two terms pluses.

$$u = u_{eq} - u_{reach} \tag{12}$$

with sliding condition:

$$s\dot{s} \leq -\eta|s| \tag{13}$$

will be result:

$$u_{\mathrm{reach}} = \mathrm{k\ sgn\ (s)} \tag{14}$$

that k and η are positive amount. foru_{eq} achieve should correct s□=0 condition.then we will have that:

$$\dot{s} = \dot{\omega} - \omega_{des} = 0 \tag{15}$$

With replace equation 11 in 17 will have:

$$\dot{s} = \frac{1}{j_{\mathrm{tot}}}\left(1.5\ \rho\lambda \mathrm{i}_{\mathrm{q}} - \beta\omega\right) - \dot{\omega}_{\mathrm{des}} = 0 \tag{16}$$

That result:

$$i_q = \frac{1}{6\hat{\lambda}}\left(\hat{\beta}\omega + \hat{j}_{tot}\dot{\omega}_{des}\right) \tag{17}$$

Here $\hat{\lambda}$, $\hat{\beta}$And $\hat{\mathrm{j}}_{\mathrm{tot}}$ are nominal values of λ , β and $\mathrm{j}_{\mathrm{tot}}$ Parameters with uncertainty in modeling.

$$\hat{\lambda} = \sqrt{\lambda_{min}\lambda_{\max}} \tag{18}$$

$$\hat{\beta} = \sqrt{\beta_{min}\beta_{\max}} \tag{19}$$

$$\hat{\mathrm{J}}_{\mathrm{tot}} = \sqrt{J_{totmin}\,\mathrm{J}_{\mathrm{totmax}}} \tag{20}$$

Controlling input, consider twou_{eq}, $\mathrm{u}_{\mathrm{reach}}$terms. $\mathrm{u}_{\mathrm{reach}}$input term show system state in s surface and u_{eq}The term's purpose is getting a state on s surface, so with replace relation:

$$i_q = \frac{1}{6\hat{\lambda}}\left(\hat{\beta}\omega + \hat{J}_{tot}\dot{\omega}_{des}\right) - ksgn(s) \tag{21}$$

Chatter reduce:

One of the disadvantages that there is in sliding mode controlling method, outbreak chatter which cause is discontinuous controlling law around surface s=0.for improving performance of the controller and its implement we have to remove This chatter which a current method for improving switching performance and thereby, removing the undesired chatter effect, is given a thin limit around the switch surface (Slotine and Li, 1991). in performance, for doing this performance is used sat(s/ø) replace sign(s) which in that sat is saturation function and ø is thickness of limiting layer and with adjust that can reduce chatter,So controller rule is:

$$i_q = \frac{1}{6\hat{\lambda}}\left(\hat{\beta}\omega + \hat{J}_{tot}\dot{\omega}_{des}\right) - ksat(\mathrm{s}/\emptyset) \tag{22}$$

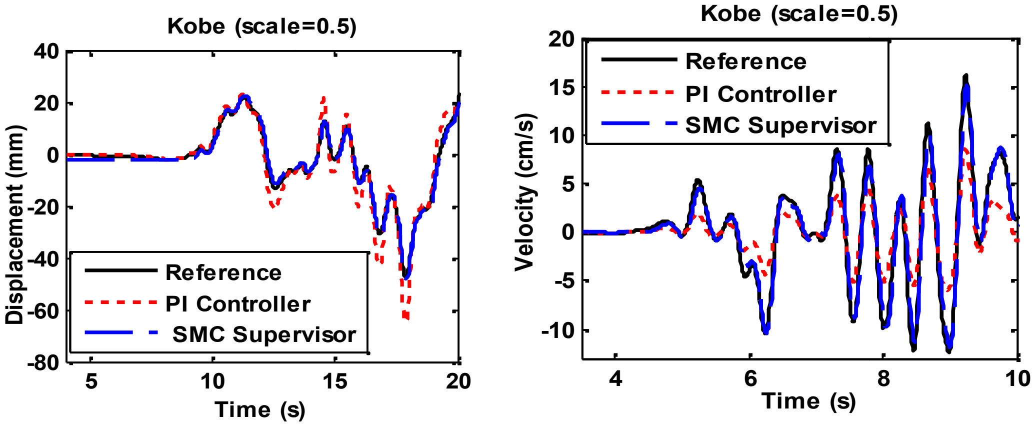
Impediment:

In this section, we survey impediment resets Larza shake table. There has been a comparison between the performance of sliding mode controller and PI controller in track specifications of simulated earthquake. For this purpose we used the kobeearthquake as reference. The specifications of the earthquake have been listed in table (1).

Table 1.Specifications for Kobe earthquake

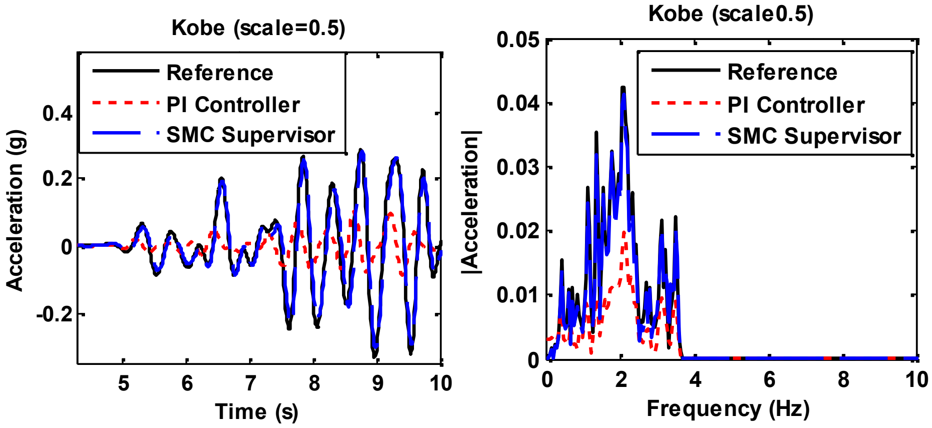
Specifications	Reference earthquake
Station: Nishi-Akashi Magnitude: M (6.9) Data Source: CUE	Kobe earthquakes

It has compared between and PI controller in the tracking of simulated earthquake configures. Figure.4 to Figure.5 are the results of displacement, Velocity and acceleration.



(a) (b)

Figure 4- Simulation displacement (a) andVelocity (b)diagram for kobeearthquake



(a) (b)

Figure 5- Simulation acceleration diagram in the timedomain(a) and frequencydomain (b) for kobeearthquake

As that is shown in the above, the sliding mode controller in comparing with the PI controller can good tracking profile of kobe earthquake.

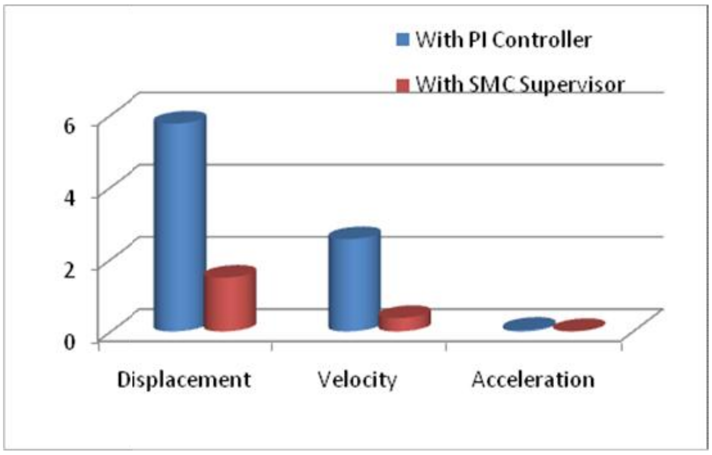


Figure 6– RMS diagram for kobeearthquake

Performance analysis controllers against parametric uncertainty

In this section,we analyze effect of parametrical uncertainty on the result of two controllers.For this section,we put a two freedom degree structures with 10kg on a shake table.Where the mass change effect on momentum of inertia of the follow relation(12), the moment of inertia is a parameter which considers uncertainty.After calculation of moment of inertia which result of put two freedom degree structure on table, uncertainty is equal to±23%.Here performance of sliding mode controller under condition of parametrical uncertainty which reviewed.As we can see in rms diagrams, error of sliding mode controller is less than PI controller

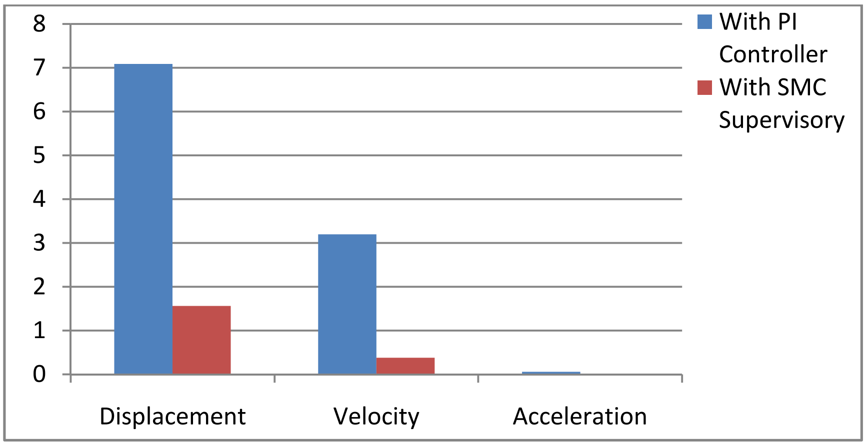


Figure.7–rms diagram error for kobe earthquake with structure

Conclusion

In this paper, a sliding mode controller presented for improving tracking performance configure earthquake. The effect of these controllers on Larza shake table performance, while we simulated behavior of the kobe earthquake, analysis on it.Results show that the sliding mode controller had a better performance than the PI controller and also it has a good resistant against parametrical uncertainty.

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