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Investigation on the performance of the six DOF C.G.S., Algeria, shaking table

Hassan AKNOUCHE[∗,1,2], Hakim BECHTOULA[1b], Abdelhalim AIROUCHE[1, 2a] and Djillali BENOUAR[2c]

[1]National Earthquake Engineering Research Center, CGS, Rue Kaddour Rahim Prolongée Bp 252 H-Dey Alger, Algeria
[2]University of Bab Ezzouar (USTHB), FGC/ Built Environment Res. Lab. (LBE) BP 32 El Alia, Bab Ezzouar, Alger 16111, Algeria

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Abstract. Shaking tables are devices for testing structures or structural components models with a wide range of synthetic ground motions or real recorded earthquakes. They are essential tools in earthquake engineering research since they simulate the effects of the true inertial forces on the test specimens. The destructive earthquakes that occurred at the north part of Algeria during the period of 1954-2003 resulted in an initiative from the Algerian authorities for the construction of a shaking simulator at the National Earthquake Engineering Research Center, CGS. The acceleration tracking performance and specifically the inability of the earthquake simulator to accurately replicate the input signal can be considered as the main challenge during shaking table test. The objective of this study is to validate the uni-axial sinusoidal performances curves and to assess the accuracy and fidelity in signal reproduction using the advanced adaptive control techniques incorporated into the MTS Digital controller and software of the CGS shaking table. A set of shake table tests using harmonic and earthquake acceleration records as reference/commanded signals were performed for four test configurations: bare table, 60 t rigid mass and two 20 t elastic specimens with natural frequencies of 5 Hz and 10 Hz.

Keywords: servohydraulic shaking table; MTS 469D controller; stex3.0 controller; adaptive control

1. Introduction

It is well known that Algeria suffers from destructive earthquakes. Obviously, the best way to mitigate the effects of earthquakes is to improve knowledge on the structural behaviour and to compile the necessary regulations for earthquake design. The destructive earthquakes that occurred at the north part of Algeria during the period of 1981-2003 resulted in an initiative for the construction of a shaking simulator at the National Earthquake Engineering Research Center, CGS. The shaking table has become an important tool for conducting experimental research in the

∗Corresponding author, PhD Candidate, E-mail: haknouche_70@yahoo.fr, haknouche@cgs-dz.org
[a]PhD Candidate, E-mail: airouche@yahoo.fr
[b]Associate Professor, E-mail: bechhakim@gmail.com
[c]Professor Director, Built Environment Res. Lab. (USTHB), Email : dbenouar@usthb.dz

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emerging areas of structures identification assessment, and control. Shaking table is the only means to properly simulate inertia force on distributed mass systems in a laboratory. This is a major advantage of the earthquake simulator. The purpose of a shaking table is to evaluate the response of scaled model structures subjected to base excitation. Most shaking tables are used as earthquake simulators. For example, the university of California at Berkley (Bertero *et al*. 1980, Rinawi and Clough 1991), and the university of California San diego (Ozcelik *et al*. 2008c) and the university at buffalo (Maddaloni and Reinhorn 2011) are used to simulate both historical earthquake ground motions and artificial acceleration in order to study their effects on reduced scale structural models such as buildings, towers and vibration sensitive mechanical equipment. Specimen size limitation can be viewed as a disadvantage and typically earthquake simulations are conducted on scaled specimen. Scaled structures can range from large scale to small scale of the prototype. The exception is the E-Defense shake table in Japan where operates the world's largest and most advanced 3-D, full scale, earthquake testing facility, which can carry large size soil and structures models and reproduce the processes of structural failure (Keiichi *et al*. 2004). Another issue related to shake table testing is associated with acceleration tracking performance and specifically the inability of the earthquake simulator to accurately replicate the input signal. It is well known that in general the shaking table reproduction of commanded signals, displacement or acceleration time histories such as earthquake accelerograms are imperfect. The degree of distortion in signal reproduction depends on different factors, but key influences identified in the literature are related to: 1) the configuration and characteristics of control loops (type of control algorithm, feedback signals, data acquisition system,…), 2) physical system parameters (foundation, oil column frequency, platen, servovalves…), 3) characteristic of the payload under test (linear and nonlinear specimen) (Conte and Trombetti 2000).

From point of view of control, the shaking table and test specimen must be viewed as one complete system whose frequency response will change with each specimen (Adam 1997). The complex dynamics of the shaking table systems arises from multiples linear and nonlinear dynamic interactions between the various components of the shaking table (mechanical, hydraulic and electronic) and the test specimen (Ozcelik *et al*. 2008a).

In the literature, we find a limited number of studies focusing on modelling of complete shaking table systems and acceleration tracking performance of servo-hydraulic shaking tables (Rinawi and Clough 1991, Clark 1992, Matthew 1997, Williams *et al*. 2001, Shortreed *et al*. 2001, Crewe and Severn 2001, Trombetti and Conte 2002, Twitchell *et al*. 2003, Thoen and Laplace 2004, Ozcelik *et al*. 2008a, 2008b, Plummer 2010, Shen *et al*. 2011, Gu and Ozcelik 2011, Ceresa *et al*. 2012).

Bertero *et al.* (1980) reported errors as high as 22% between the shaking table simulated signal and the input signal when testing a 5 story 1/7th scale reinforced concrete structure on the Berkeley shaking table. The error was reported based on differences in amplitude. To measure the adequacy of ground motion reproduction capability of the shaking table, a number of comparisons and measures in both time and frequency domain were used in the literature which included direct comparison between peak accelerations, response spectrum, constant ductility response spectra, root mean square error and relative root mean square error for the achieved and intended response signal (Ozcelik *et al*. 2008c). Based on theses comparisons, it was concluded by Luco *et al*. (2010), that a signal fidelity achieved for specific amplitude cannot be maintained at different amplitudes. It was also found that a large relative RMS error (60% for El-Centro earthquake acceleration records) is achieved for both harmonic and earthquake inputs records when the calibration, PGA, is significantly smaller than the test PGA. At sufficiently high calibration amplitude, the associated error decreases (10%-20% relative RMS error).

The capability of the shaking table system to reproduce the frequency content of a prescribed signal input is another measure of the performance of the table. To investigate the effects of the frequency content, Luco *et al*. (2010), found a significant distortions in the achieved signal when the predominant frequency of the excitation, or its odd multiples, approaches the oil column frequency. For sinusoidal vibration test, Jian-Jun Yao *et al*. (2011), has analyzed the impact of the excitation signal on harmonic distortion and harmonics distribution. It was found that odds harmonics of the fundamental frequency cause this distortion (THD reach 36%) in the feedback signal and that the mechanical source of this distortion is the system nonlinearity of the electro-hydraulic shaking table. Measurement errors, electrical noise, and thermal effect were explicitly modelled, and their effects on the displacement, velocity and acceleration response of the actuator were quantitatively investigated by Nakata (2011) for various input signals.

Some authors have been working on a development of acceleration control strategies to improve reproducibly of reference acceleration in shaking table tests. Adaptive and Iterative Control techniques were used by Thoen (2004), to improve the capabilities of the controller to force the table to track a prescribed (command/target) motion and to compensate for linear and nonlinear sources of distortions signals. To eliminate harmonic distortion in feedback signal, a proposed control scheme basis on adaptive notch filter was used by Yao *et al*. (2012) as a basis for the development of an acceleration harmonic cancellation algorithm. Nakata (2012) has proposed a method incorporate an acceleration feed forward and a command shaping that is based on the inverse of the system dynamics. More details about the acceleration trajectory control including theoretical back ground and experimental performance was resumed by Nakata (2010). A nonlinear control algorithm, the sliding mode control strategy, was proposed to control a shaking table test of a nonlinear single degrees-of-freedom system with the goal to account for nonlinear response, model uncertainties and other disturbance affecting the test as the test is being performed (Yang and Schenllenberg 2008). After the upgrade of the existing seismic shaking table system in the dynamic testing laboratory at IZIIS, Skopje, Republic of Macedonia with the newest real time three variables digital control system a series of test for bare table and rigid mass (14 t) was done to evaluate the acceleration tracking performance. A minimum value of 10% of relative RMS error was obtained for Petrovac earthquake input record (Rakicevic *et al*. 2012).

The objective of this study is to validate the uni-axial sinusoidal performances curves and to assess the accuracy and fidelity in signal reproduction using advanced adaptive control techniques incorporated into the MTS Digital controller and software of the CGS shaking table. A set of shaking table tests using harmonic and earthquake acceleration records as reference/commanded signals were performed for four test configurations that an: bare table, 60 t rigid mass and two 20 t elastic specimens with natural frequencies of 5 Hz and 10 Hz.

2. Description of the facility

The CGS servo hydraulic shaking table has six degrees of freedom with an operational range of 0-100 Hz, giving control on the three orthogonal translational degrees of freedom and the associated rotational degrees of freedom. The steel platform, as illustrates in Fig. 1, measures 6.1 m × 6.1 m and weights 40t. It can carry a maximum payload of 60 t. The platform is in the form of an inverted pyramid, with a depth of 2.2 m. It is stiffened internally by steel plates having the shape of honeycomb which gives the platform a very high bending stiffness. The platform surface

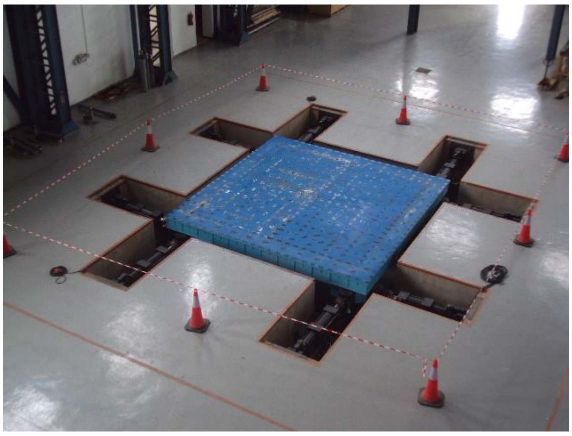
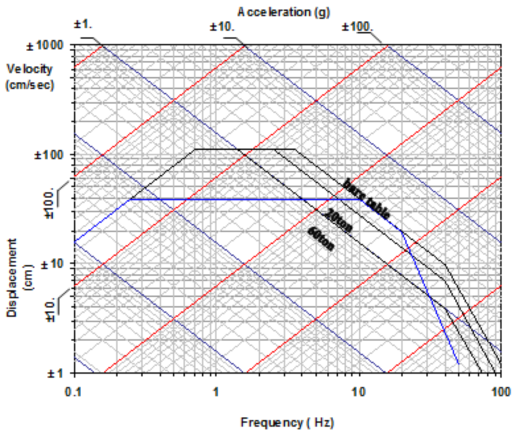
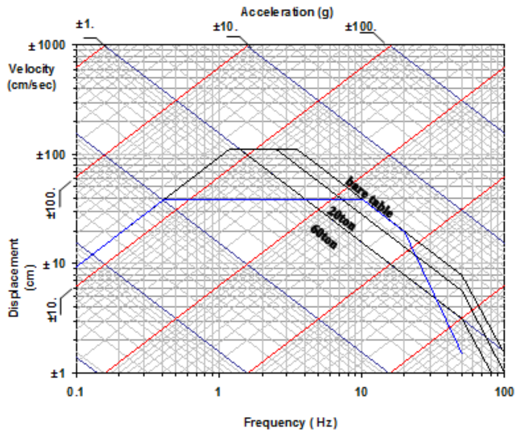


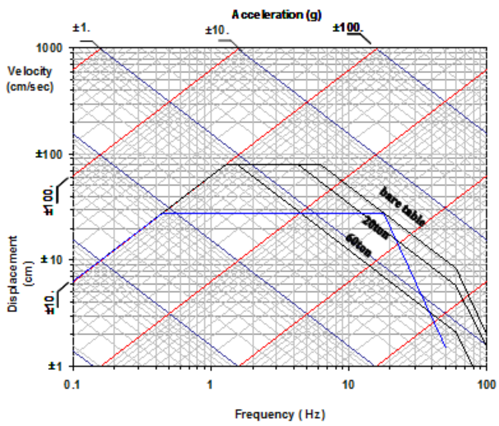
Fig. 1 CGS shaking table



(a) Longitudinal direction



(b) Lateral direction



(c) Vertical direction

(━) Uniaxial performance limit, (━) Tri-axial performance limit

Fig. 2 Uniaxial and tri-axial performance curves

Table 1 Major specification of CGS shaking table

Three-dimensional full-scale earthquake testing facility			
Table size	6.1 m × 6.1 m		
Table mass	40 t		
Maximum specimen mass	60 t		
Controlled degrees of freedom	6		
Transitional	X,Y, Z		
Rotational	θ_X, θ_Y, θ_Z		
Shaking direction	X	Y	Z
Maximum Acceleration *	±1.0 g	±1.0 g	±0.8 g
Maximum Velocity	±1.1 m/s	±1.1 m/s	±0.8 m/s
Maximum displacement	±0.25 m	±0.15 m	±0.1 m
Maximum allowable moment	Overturning moment		Yawing moment
	180 tm		90 tm

*Maximum acceleration is at maximum loading.

has a total of 169 M30 and 300 M20 bolt holes in a 50 cm × 50 cm grid for mounting specimens. A base excitation is applied to the structure by means of 12 servo hydraulic actuators controlled by a MTS256 three stages servo-valve having a full flow rate of 1600 lpm and maintains this to nearly 50 Hz. The capacity of each of the four vertical actuators is 440 KN and 330 KN for each of the eight horizontal actuators. The actuators are attached to a fixed concrete foundation weighting more than 7000 t designed to withstand the dynamic vibration of the actuators whilst the transmitting vibration up to 0.01 g at 10 m from the foundation.

The gravity load due to the table and the model mass is sustained by a special system with four pneumatic static supports. The total bearing capacity for static loads is 1400 KN. This system is located in the lower part of the steel platform. The stroke of the horizontal actuator is ± 250 mm in X direction, and ± 150 mm in Y direction. In the vertical direction the maximum displacement is ± 100mm. The peak velocity is ± 1.1m/sec in the horizontal direction and 0.8 m/sec in the vertical direction for the bare table condition with a maximum acceleration of 2.5 g and 3.2 g in the horizontal and vertical directions respectively. For the case of 60 t rigid mass these values are respectively 1.0g and 0.8g. The capacity of the table is 180 tm for the overturning moment. The hydraulic units used to power the table can supply a peak flow rate of 3600 lpm at 210 bars. In order to increase the working flow of the system, twelve additional pressured accumulators with capacity of 45 litres of hydraulic fluid are used. Table 1, summarizes the performances characteristics of the CGS shaking table. This performance data is based on uniaxial sinusoidal motion of the shaking table with a rigid 60 t payload.

The plot in Fig. 2(a) trough Fig. 2(c), shows the tripartite uniaxial performance envelopes of the CGS shaking table. It can be seen the relationships between the frequency and the maximum displacement, velocity, and acceleration for harmonic condition. At frequencies lower than 1 Hz, the table motion is limited by the maximum actuator stroke of 250 mm, at intermediate frequencies from 1-4, the servo-valves can accommodate table velocities in excess of 1.1 m/sec, at higher frequencies the force capabilities of the actuators limit table acceleration to 2.5 g (all specifications for longitudinal axis and bare table). Each curve has three load cases: Bare table, 20 t elastic specimen and the maximum specified specimen of 60 t. The specimen is assumed to be rigid and firmly attached to the table.

The earthquake simulator is serviced by 10 t and 32 t overhead cranes and the vertical clearance between the test platform and the crane hook is 16.5 m. The large overturning moment capacity and test height clearance of this facility represent very suitable conditions of testing tall structural systems.

3. Control system and tuning of shaking table

The MTS digital controller 469D, which is installed for the CGS seismic testing system, is real time, digital controller that provides: three variable closed loop controls along with adaptive control, differential pressure stabilization and force balance compensation. It also provides an operator interface to the real-time hardware and permits faster set up and tuning of new specimen configurations. The control hardware architecture is based on digital signal processing technology that optimizes the performance of the embedded control system, and allows for the implementation of advanced control and data filtering operations (Thoen 2004).

3.1 Three variable controllers

The digital control software MTS 496D includes a basic form of compensation; know as Three-Variable Control (TVC). The TVC concept provides simultaneous control of displacement, velocity, and acceleration variables. The controller can be set to run under displacement, velocity or acceleration control mode. Depending on the control mode (displacement at low-range frequencies, velocity at middle-range frequencies, and acceleration at high-range frequencies), only one state variable becomes the primary control variable with the others serving only as compensation signals to improve damping and stability of the system (Thoen and Laplace 2004).

Before the start of the tests, the TVC system of the shaking table was tuned to reach, as close as possible, a wide band unit response. The tuning is performed under band limited white noise (0-50 Hz) input acceleration with RMS amplitude sufficiently high to obtain a good signal to noise ratio in the feedback acceleration and reliable total transfer function estimation between command and feedback accelerations, but not enough to avoid damage to the shaking table or to the specimen. The parameter adjustment process continues until the table transfer function is deemed satisfactory. This tuning process involves adjusting the various displacement, velocity, and acceleration lead terms of the control system, as well as implementing some user-defined resonance canceling notch filters (Thoen and Laplace 2004). Mechanical resonances associated with the oil column of the hydraulic system were identified and compensated by the notch filters for the three directions: longitudinal, lateral and vertical. It was nothing that during the tuning process, the specimen is constantly being excited. This may have the undesired effect of low-level damage or fatiguing, even if the specimen is tuned while in the elastic range (Thoen and Laplace 2004).

3.2 Advanced MTS adaptive control techniques

The MTS 469D Digital seismic table controller provides four adaptive and iterative control techniques to improve the system performance and to compensate for linear and/or nonlinear sources of signal distortion: Amplitude Phase Control (APC), Adaptive Harmonic Cancellation

(AHC), Adaptive Inverse Control (AIC) and Online Iteration (OLI) (Thoen 2004). Two of these adaptive techniques namely APC and AHC were used in the tracking capabilities of the CGS shaking table system and presented hereafter.

3.2.1 Amplitude phase control (APC)

Amplitude Phase Control (APC) is used for the automatic correction amplitude and phase errors in sine waveforms. It is a control compensation technique that augments a fixed-gain controller to correct amplitude and phase irregularities, in order to improve control fidelity. It measures the control system dynamics directly and modifies the control compensation accordingly in real-time. APC is characterized by its fast convergence to the optimum correction because the correction is updated at every point on the sine wave, not just at the peaks.

3.2.2 Adaptive harmonic cancellation (AHC)

A non-linear system like servo hydraulic seismic systems will often produce harmonics in its feedback signals even when the command signal is a clean sinusoid; AHC is a compensation algorithm designed to remove these unwanted harmonics from a sinusoidal feedback signal. It uses a technique developed in the “adaptive noise control” field that adds harmonics to the controller command signal with the right phase and amplitude to completely cancel the unwanted harmonics at the system output.

4. MTS Seismic test executive (Stex3.0)

MTS seismic test execution software version 3, Stex3.0, supplements the real time MTS 469D digital controller by providing much functionality: Table programming, data analysis in time and frequency domains, off line iterative test compensation method for reducing the non linear distortion during earthquake time history and random wave form testing, post test data processing, data acquisition and data management (MTS system corporation 1991).

5. Data acquisition

Data acquisition system includes 128 channels of conditioned inputs (DC conditioners), expandable, maximum sampling rate per channel simultaneously is 2000 data samples per second. The shaking table is permanently instrumented with linear variable differential transformers LVDTs and differential pressure cells mounted on each actuator and 11 Setra 141A Setra ® - Model 141A accelerometers with a range of ± 8 g and a flat frequency response from DC to 300 Hz. However, the signal conditioners used for the accelerometers included a built-in analog low-pass filter with cut-off frequency set at 100 Hz.

6. Shaking table seismic performances test program

A series of tests were carried out in order to establish the performance limits of the shaking table system. The testing program was used for four conditions: bare table condition, 60 t rigid mass and two 20 t elastic specimens with natural frequencies of 5 Hz and 10 Hz.

Fig. 3 View of the 60 t rigid mass

6.1 Rigid mass - 60 t

This mass is made of 12 concrete blocks tied together by 12 high strength M20 bars to form a 60 t rigid body measuring 5 m × 5 m × 0.9 m, shown in Fig. 3. The concrete body was clamped to the platform by post-tensioned 32 high strength steel M30 bars. The total mass to be moved was 110 t including the weight of the platform and actuators. This test was selected to determine the effect of a rigid test specimen with relatively low overturning moment on the table performance. The centre of gravity of the mass was 0.45 cm above the surface table.

6.2 Elastic specimen of 20 t

Two elastic model specimens were designed to be used to assess the performance of the CGS shaking table. The elastic specimen is a single-story braced steel moment resisting frame shown in Figs. 5 and 6. The members of the frame were selected to achieve a fundamental frequency of 5 Hz frequency for the first specimen and 10 Hz for the second specimen. The two elastic steel frame specimens were 2500 × 2000 mm, and the height was 2000 mm and 3500 mm for the 10 Hz and 5 Hz specimens, respectively. The columns were made of HEA280 and beams with IPE270 steel sections. While the mounting diagonal for fixing the damper and the X braces were made of UPN160 and UPN 80 sections, respectively. A 20 t mass made of four concrete blocks was anchored to a steel beams that acted as horizontal diaphragm. Additional damping was provided using the two viscous dampers type ALGA-FD100. The damping system was installed in the tested direction of the specimen. The damping device was linear with a damping constant equal to 100 N.Sec/m. Each damper was designed for a maximum stroke of ±50 mm, a peak force of 100 KN and a peak velocity of 800 mm/sec. Details of the damper are shown in Fig. 4.

For a given structural system, the main dynamics properties are: the natural frequencies/periods and the equivalent viscous damping ratios. In an experimental program, a wide band (0 to 50 Hz) white noise base acceleration was applied by shaking table separately in longitudinal, lateral and vertical directions to determine the dynamic characteristic (natural period and damping ratio) of the two elastic specimens. The peak acceleration was scaled to 10%-g RMS to provide enough excitation such that the modes of vibration could be identified. The specimen responses were measured by three Setra ® -Model 141A accelerometers fixed at the top of the specimen in the three directions, two horizontal and one vertical. The data was collected by seismic test executive (Stex3.0). Fig. 7 shows the amplitude and phase transfer functions (roof acc/base acc) of the two elastic specimens with the linear viscous damper in the three directions. The equivalent viscous damping factors of the two elastic specimens were calculated at frequency domain analysis using the well knows half power (bandwith) method.

The clear peak in the transfer functions which correspond to the natural frequencies are well seen in the figures. The phase transfer functions have an inversion of phase exactly at the frequencies corresponding to those of the natural frequencies. The extracted natural frequencies from these figures and the corresponding damping ratios of the 10 Hz elastic specimen are: (11 Hz, 7.23%), (12 Hz, 6.12%) and (30 Hz, 1.80%) in the three directions, respectively. Concerning the 5 Hz elastic specimen theses values are respectively: (5.5 Hz, 5.1%), (8 Hz, 6.28%) and (18 Hz, 5.27%).

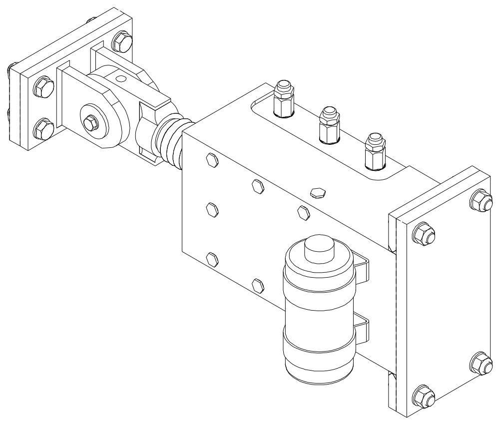


Fig. 4 Fluid damper type ALGA-FD100

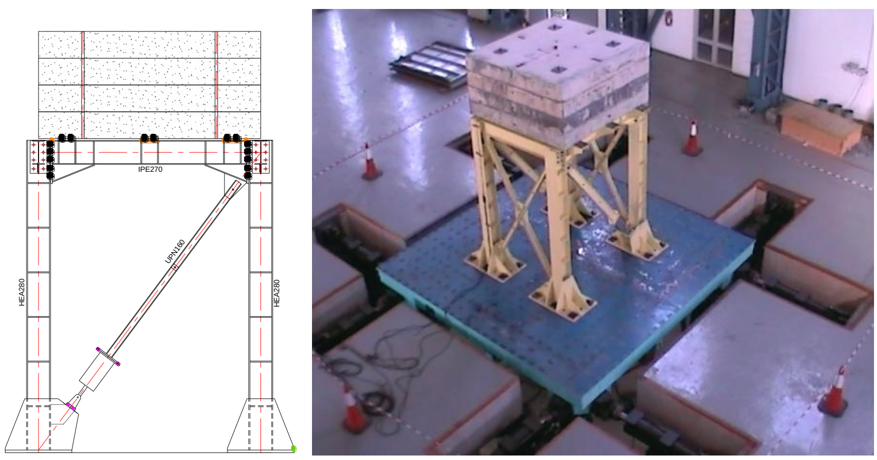


Fig. 5 View of the 20 t elastic specimen with fundamental frequency of 5 Hz

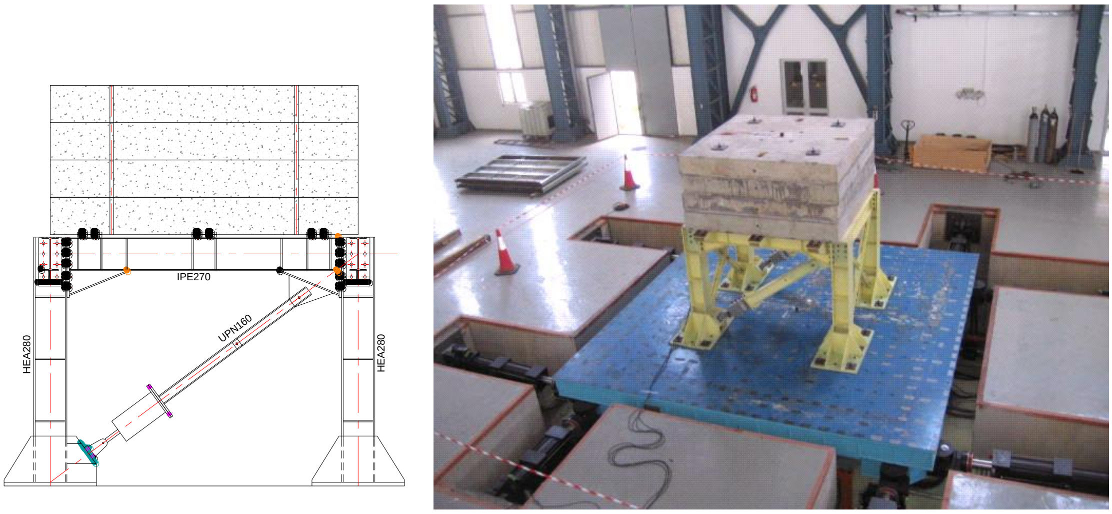
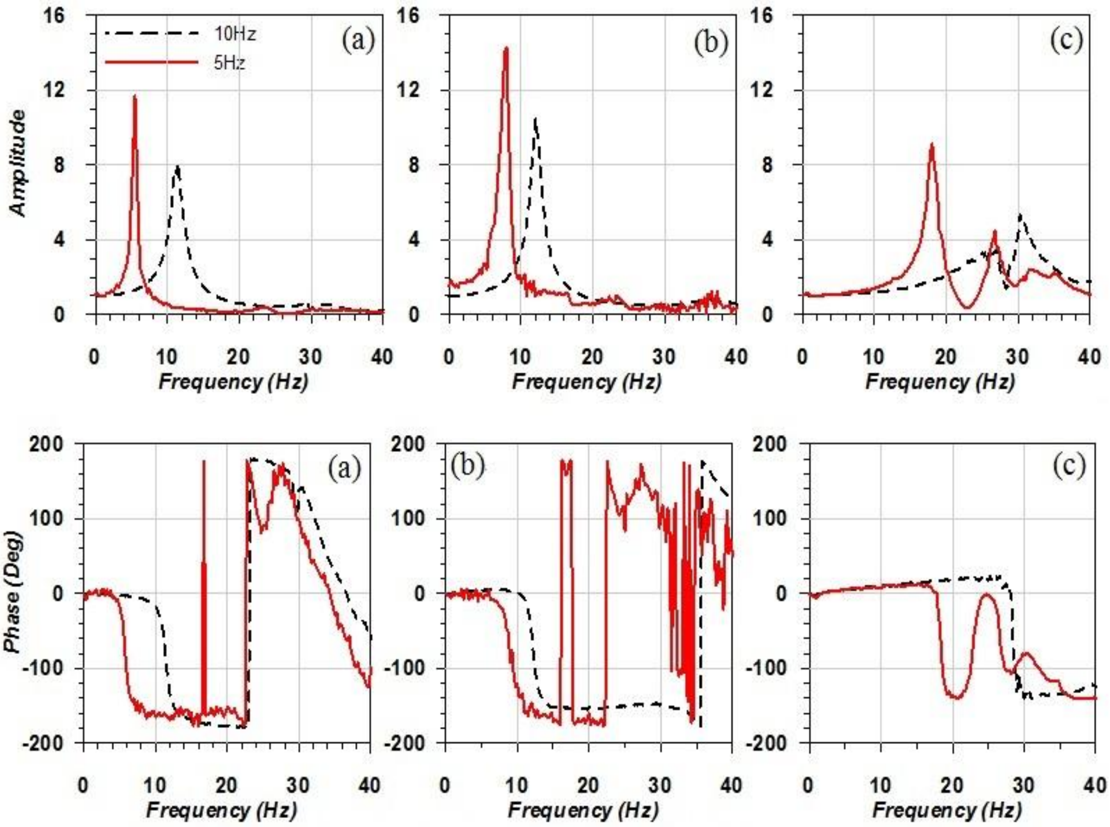


Fig. 6 View of the 20 t elastic specimen with fundamental frequency of 10 Hz



(a) Long direction (b) Lateral direction (c) Vertical direction

Fig. 7 Transfer functions of the two elastic specimens

7. Performance criteria

In order to assess the performance of the CGS shaking table, a performance criteria was established. The criteria included the RMS error (*RMSError*), the relative RMS error (*RRMSError*) and the Total Harmonic Distortion (*THD*).

7.1 The RMS error

The acceleration time histories obtained from the acceleration feedback signals measured during the tests were compared to those of the reference signals. The error (in percentage) between the feedback and the reference is presented in a tabular form, using the following equation

$$RMSError = \sqrt{\frac{1}{N}\sum\left(\ddot{x}_{fbk}(i) - \ddot{x}_{ref}(i)\right)^2}\,x100 \quad (1)$$

Where N denotes the total number of data samples within the time window chosen to calculate the error $\ddot{x}_{ref}(t)$ is the reference-command acceleration and $\ddot{x}_{fbk}(t)$ is feedback-achieved acceleration.

For the earthquake records, this time window was chosen to be the time interval between the 5% and 95% contributions of the reference acceleration time histories to the arias intensity. The achieved table acceleration time history was shifted in time to correct for any delay introduced by the plant (Luco *et al.* 2010).

7.2 The relative RMS error

For the cumulative measure of the error in signal reproduction, the relative RMS error measure is used and defined as (Luco *et al*. 2010)

$$RRMSError = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\ddot{x}_{fbk}(i) - \ddot{x}_{ref}(i)\right)^2}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\ddot{x}_{fbk}(i)\right)^2}}\,x100 \quad (2)$$

7.3 The total hrmonic distortion

For sinusoidal shaking tests, harmonic distortion is an important criterion. Total harmonic distortion is always used to measure the level of distortion of the shaking table response to harmonic command signal. The *THD* is computed using Eq. (3) as follow (Kusner *et al.*1992)

$$THD = \frac{\sqrt{A_2^2 + A_3^2 + A_4^2 + ...}}{A_1}\,x100 \quad (3)$$

where A_1 is the fundamental amplitude, A_2 is the amplitude of second harmonic, A_3 is the amplitude of the third harmonic, and so on. The *THD* was calculated using acceleration control for high frequency, and displacement control for low frequency.

8. Testing program (test protocol)

The testing program was set for four cases: bare table, 60 t rigid mass and two 20 t elastic specimens with natural frequencies of 5 Hz and 10 Hz. The loading input signals, were of three types: white noise, sinusoidal and earthquake. The series of tests are intended to validate the uni-axial sinusoidal performances curves and to evaluate the accuracy and fidelity in signal reproduction in order to check the performance of the shaking table.

8.1 Uniaxial sinusoidal performance

Uni-axial sinusoidal performance tests for the longitudinal, lateral and vertical axes were measured for various frequencies (0.1, 0.2, 0.5, 1.0, 2.0, 5.0, 10.0, 20.0, and 50.0 Hz) and loadings conditions and compared with the theoretical performances curves. Advanced MTS adaptive control techniques APC and AHC were used. From the obtained data the different performance criteria defined previously were calculated. During the tests, the digitized data were recorded by the MTS 496D seismic controller software. The sampling rate of this software can be set at a different rate. During the tests, the sampling rate of the recorder was set at 2048 Hz.

The tuning of the table in preparation for the uni-axial harmonics excitations tests was performed independently for the six degrees of freedom and two load conditions (bare table and 60 t rigid mass) under acceleration control as follows:

First, a flat shape random signal of root mean square (RMS) amplitude of about 10%-g was applied to adjust the multiples control variables, such as gains, notch filters and various displacement, velocity and acceleration lead terms required by the TVC (Three Variables Control) controller. These terms are incrementally changed and the results determined from the Frequency Response Function (FRF) between the desired and the achieved signals, since any error or incorrect choice of term can result in damage to shaking table or to the specimen. This iterative procedure is continued until the acceptable level of FRF matching is achieved.

Second, the AHC forward plant model was constructed under the same condition of excitation and loaded to further improve the response of the system.

It is worth noting that, the delicate tuning operation of a shaking table is very dependant on the experience of the operator and has a great effect on the achieved test motion. Also, great caution should be taken especially when using AHC in order to prevent instability that could destroy the testing specimen.

As an example, in Fig. 8 are presented the waveform comparison curves of the acceleration time histories of the reference and feedback signals due to harmonic excitation in the longitudinal direction with f = 5 Hz and PGA = 1.2 g for the case of bare table. It can be observed that, when APC and AHC are set to tracking *ON* the match is almost perfect.

It can be seen clearly from Fig. 8(a) that, the achieved acceleration response is seriously distorted due to the presence of odd harmonics in the feedback signal mainly due to the nonlinearity of the servovalves, which excite the oil column frequency in the direction of excitation (Kusner *et al.* 1992). The corresponding *RMSError*, *RRMSError* and *THD* are 23.54%, 27.75% and 20%, respectively.

Fig. 8(d) shows the ideal case, in which APC and AHC are correctly used, where the feedback is a perfect replicate of the reference and the corresponding RMS error, relative RMS error and *THD* tend to smaller values of 0.55%, 0.65% and 0.48%, respectively. When performing sine wave testing; both AHC and APC are simultaneously used. APC and AHC complement each other:

APC enhances the fundamental frequency component of the system response, see Fig. 8(b), while AHC cancels the odd harmonics as illustrated in Fig. 8(c).

Tables 2, 3 and 4 show the frequencies, the control mode, the adaptive control and the target amplitudes of single-frequency sine wave motion used for the tests for bare table and 60 t loaded table condition in the three directions. The adequacy of performance by comparing amplitudes of input and response at various frequencies of sine wave motion, which yields an amplitude spectra envelope of the shaking table response are also shown. This comparison helps in defining the accuracy of the shaking table control settings and shaking table frequency performances limitations. The frequencies and amplitudes of waveform were controlled using the MTS 469D digital controller in acceleration, velocity or displacement control. The adaptive control techniques APC and AHC were used for the control of these motions. The results of these experiments are displayed in Fig. 9.

Figs. 9(a) and (b) illustrate the expected and theoretical performance curves for the two conditions, bare table and 60 t rigid mass, in the three directions. The triangle shapes represent the achieved performance corresponding to the frequencies listed in Table 2, 3 and 4. It can be observed from Fig. 9 that, the achieved and the theoretical performance curves are in good agreement for all frequencies of operation.

In Tables 2, 3 and 4 are also presented the errors in percentage between the feedback and the reference in terms of *RMSError*, *RRMSError* and *THD*.

It can be clearly seen that the obtained results of the *THD*, for all cases, shown in Tables 2, 3 and 4 are less than (<10%), regardless of the frequency and the amplitude excitation. This demonstrates the effectiveness of these adaptive control techniques, mainly AHC, in compensating the response of the shaking table. When the shaking table was controlled in acceleration mode, the errors (RMS and Relative RMS error) in the reproduction of the required harmonic acceleration were highly satisfactory, and in the worst case it was only 6.44%. When the table was controlled in displacement mode, the errors of the obtained displacements were as low as 2.9%. The presented results, Fig. 9 and Tables 2, 3 and 4, confirm in most cases and for all investigated waveform records, the excellent tracking performance of the MTS 469D controller.

Table 2 Comparison of feedback and reference signals-sinusoidal excitation in the longitudinal direction

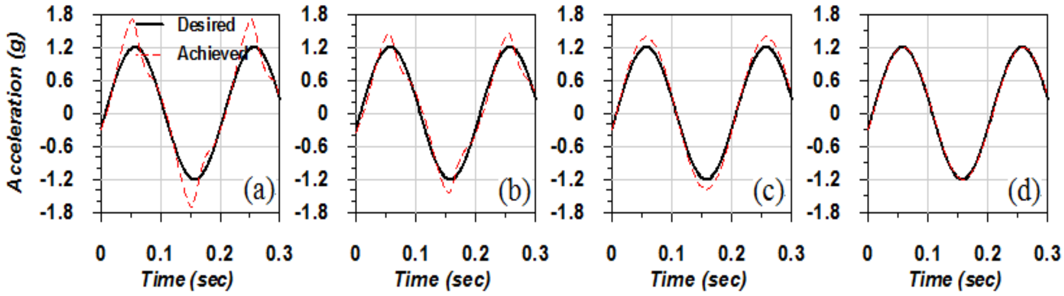
Freq (Hz)	Adaptive control	Bare table				60 t rigid mass			
		Test amplitude	*RMS error* (%)	*RRMS error* (%)	*THD* (%)	Test amplitude	*RMS error* (%)	*RRMS error* (%)	*THD* (%)
0.1	APC	±250 mm	0.09	0.48	0.14	±250 mm	0.28	0.16	0.15
0.2	APC	±250 mm	0.11	0.65	0.23	±250 mm	0.50	0.28	0.27
0.5	APC	±250 mm	0.37	2.10	0.25	±250 mm	0.12	0.64	0.63
1	APC-AHC	±1.10 m/s	1.74	2.20	3.48	±1.10 m/s	0.61	1.22	1.07
2	APC-AHC	±1.10 m/s	1.92	1.89	1.70	±1.00 g	0.79	1.11	0.83
5	APC-AHC	±2.50 g	2.59	1.46	1.24	±1.00 g	0.37	0.52	0.21
10	APC-AHC	±2.50 g	0.51	0.58	0.22	±1.00 g	0.27	0.38	0.22
20	APC-AHC	±2.50 g	0.37	0.42	0.23	±1.00 g	0.48	0.69	0.32
49	APC-AHC	±2.50 g	1.43	1.68	1.17	±1.00 g	0.47	0.68	0.47
50	APC-AHC	±2.50 g	1.73	2.02	2.60	±1.00 g	0.53	1.54	0.71

Table 3 Comparison of feedback and reference signals-sinusoidal excitation in the Lateral direction

Freq (Hz)	Adaptive control	Bare table				60 t rigid mass			
		Test amplitude	*RMS error* (%)	*RRMS error* (%)	*THD* (%)	Test amplitude	*RMS error* (%)	*RRMS error* (%)	*THD* (%)
0.1	APC	±150 mm	0.10	0.95	0.14	±150 mm	0.15	0.14	0.14
0.2	APC	±150 mm	0.15	1.46	0.18	±150 mm	0.20	0.19	0.19
0.5	APC	±150 mm	0.30	2.90	0.29	±150 mm	0.40	0.38	0.36
1	APC-AHC	±150 mm	0.62	5.90	0.86	±150 mm	0.27	2.58	2.57
2	APC-AHC	±1.10 m/s	1.37	1.35	0.91	±1.00 g	0.37	0.52	0.36
5	APC-AHC	±2.50 g	1.44	1.62	10.98	±1.00 g	0.33	0.47	0.26
10	APC-AHC	±2.50 g	0.64	0.73	0.29	±1.00 g	0.21	0.30	0.23
20	APC-AHC	±2.50 g	0.3	0.34	1.33	±1.00 g	0.42	0.59	0.25
49	APC-AHC	±2.50 g	1.05	1.23	2.43	±1.00 g	0.87	1.27	0.49
50	APC-AHC	±2.50 g	1.38	1.61	0.14	±1.00 g	0.85	1.25	0.59

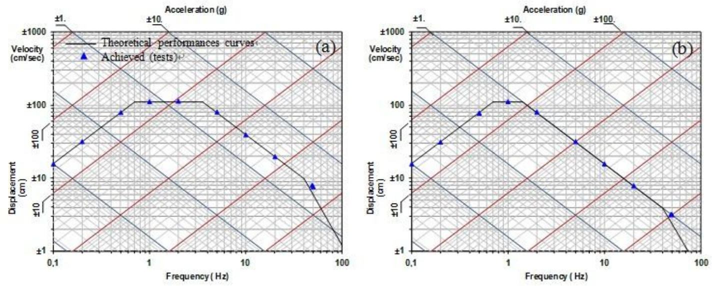
Table 4 Comparison of feedback and reference signals-sinusoidal excitation in the vertical direction

Freq (Hz)	Adaptive control	Bare table				60 t rigid mass			
		Test amplitude	*RMS error* (%)	*RRMS error* (%)	*THD* (%)	Test amplitude	*RMS error* (%)	*RRMS error* (%)	*THD* (%)
0.1	APC	±100 mm	0.04	0.65	0.14	±100 mm	0.33	0.46	0.35
0.2	APC	±100 mm	0.06	0.93	0.15	±100 mm	0.49	0.70	0.70
0.5	APC	±100 mm	0.12	1.79	0.39	±100 mm	0.74	1.04	1.03
1	APC-AHC	±100 mm	0.25	3.55	0.22	±100 mm	0.71	9.99	4.78
2	APC-AHC	±0.80 m/s	1.07	2.97	3.12	±0.8 g	0.73	1.29	1.03
5	APC-AHC	±0.80 m/s	2.15	2.37	2.18	±0.8 g	1.38	2.44	0.36
10	APC-AHC	±3.2 g	1.85	1.64	1.62	±0.8 g	0.43	0.77	0.28
20	APC-AHC	±3.2 g	0.68	0.61	0.49	±0.8 g	0.26	0.46	0.18
49	APC-AHC	±3.2 g	1.38	1.26	1.62	±0.8 g	2.82	5.13	3.59
50	APC-AHC	±3.2 g	6.44	5.90	9.66	±0.8 g	1.87	3.41	2.30

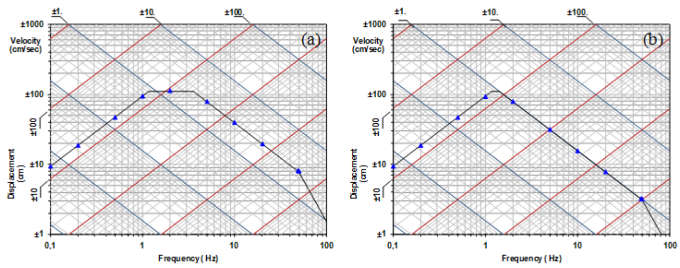


(a) APC and AHC OFF (b) APC ON (c) AHC ON (d) Ideal case (APC and AHC ON)

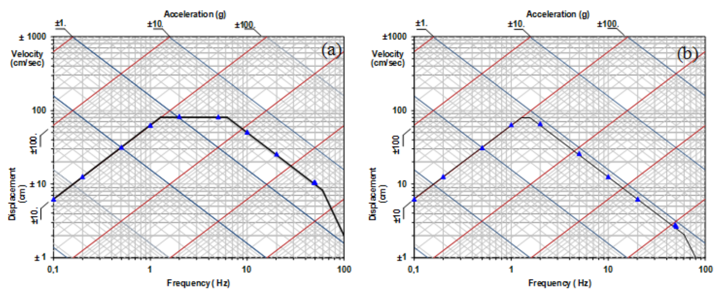
Fig. 8 Type of discrepancies in the shaking table feedbacks



(1) Longitudinal direction



(2) Lateral direction



(3) Vertical direction

(a) Bare table (b) 60 t rigid mass

Fig. 9 Expected and theoretical performances curves

8.2 Earthquake simulation test

Earthquake simulation test were also carried out for loaded conditions of the bare table, 60 t rigid mass and the two 20 t elastic specimens to investigate the efficiency of the control system in reproducing accurate shaking table motion. Off line iterative test compensation with Stex3.0 software were used to reduce the nonlinear distortion during earthquake time history loading.

Prior to conducting the earthquake simulation tests, a random white noise test was conducted to determine the system transfer function (table/specimen), and subsequently the system model. The white noise used to drive the shaking table consisted of a randomly generated acceleration time history with a flat frequency spectrum between 0.5 to 50 Hz and 10%-g RMS amplitude. The white noise signal was generated using the MTS Systems corporation Seismic Testing Execution (Stex3.0) software. Independently generated signals, each with a duration of approximately 100 seconds, were applied to each axis. The six DOFs were tested sequentially for a total duration of approximately 300 seconds. The acceleration level must be low enough to prevent damage to specimen but sufficient to produce a reasonable system response. Shaking table motion data was acquired using Stex3.0 Software. Frequency analysis was performed on the data acquired during the white noise test in order to determine the system transfer function. Data was processing using frequency analysis built into Stex3.0, and the system transfer function was determined. The transfer function consists of a matrix of achieved versus desired for each active degree of freedom. The resulting matrix contains elements representing the response of each degree of freedom measured simultaneously with the sequential excitation of each axis. The system transfer function is essentially a function of the nonlinearities and cross-coupling present in the system response due to the dynamic interaction between the specimen and the shaking table. A system model was created by mathematically inverting the transfer function, applying a smoothing function one or more times. The resulting system model was later applied to compensate the initial drive signals. The modified drive signals files were executed and signal error was computed for each degree of freedom from achieved and desired motion. A percentage of signal error is applied to drive signals for the next run. The run was repeated until the require level of matching between desired and achieved motions is attained.

The quality of the estimated system model depends on the noise level, the input amplitude level and the nonlinearities in the system. System model estimation with Stex3.0 is done in the case of 60 t rigid mass under white noise acceleration with 10%-g RMS amplitude applied in the three translational degrees of freedoms only. In the case of the 20 t elastic specimens and the bare table, system model estimation was estimated with white noise signal driven in six degrees of freedom with 7%-g and 15%-g amplitude, respectively, applied in the translational directions and 20 deg/sec^2 applied in rotational directions.

To get an overview of the performance of the CGS shaking table in terms of fidelity in signal reproduction, it was convenient to compare the achieved and the reference acceleration time histories. The tracking performance of the seismic simulator was evaluated for the time history acceleration corresponding to the three components of the 1940 Imperial Valley Earthquake records at El Centro station applied simultaneously. For the case of a 60 t rigid mass the input records were scaled to 50% for the three directions.

The achieved shaking table motions of earthquake test, obtained from the last iteration, are shown over section of the time domain plot in Figs. 10-11 for the two conditions of load in the longitudinal, Lateral and vertical degrees of freedom. Fig. 10 corresponds to the case of bare table whereas; Fig. 11 presents the case of the 60 t rigid mass. The time history plots, illustrated in Figs. 10-11, show that a good signals reproduction fidelity is obtained.

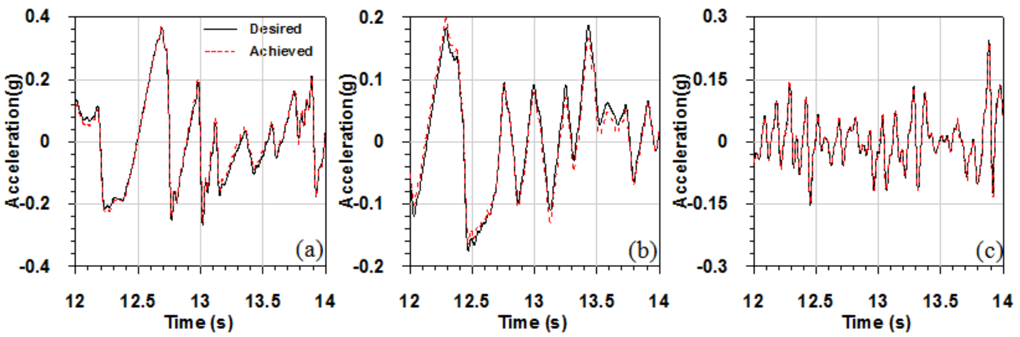
The capability of the shaking table, to reproduce the response spectrum of the prescribed acceleration time history, is another measure of the performance of the shaking table calculated from reproduced acceleration time histories and compared with the response spectrum of the desired acceleration record. The response spectrums were computed in the three directions. Graphical representations of the response spectrum achieved for the earthquake test in bare table and the 60 t rigid mass are shown in Figs. 12 and 13, respectively. The plots display the Response spectrum results achieved for the 3 degree of freedoms computed for a frequency range of 0.5-50 Hz and for a damping ratio of 5%. A good response spectrum match was also achieved, demonstrating the ability of the CGS control system to match multi-component shakes.

The general trend of the relative RMS error versus the iteration number, during the bare table and the 60 t rigid mass earthquake process, is shown in Fig. 14 which indicates that the relative RMS error decreases with the iteration number. It can be seen from Fig. 14(a) that, for the case of bare table, the relative RMS error for the first iteration is 21% for longitudinal and lateral direction and 24% for vertical direction. The relative RMS error tends to reach a minimum value of the order of 8-16% for the three directions at the 8th iteration. Results given in Fig. 14(b), for the case of the 60 t rigid mass, show also the same trends as seen for bare table. The relative RMS error ranged between 26-42% at the first iteration and between 8-14% at the 12th iteration for the three degrees of freedom.

The relative RMS error response trends clearly show that, higher fidelity in signal reproduction requires a higher iteration number which in turns brings the problem of higher risk of premature damage to the specimen during earthquake test.

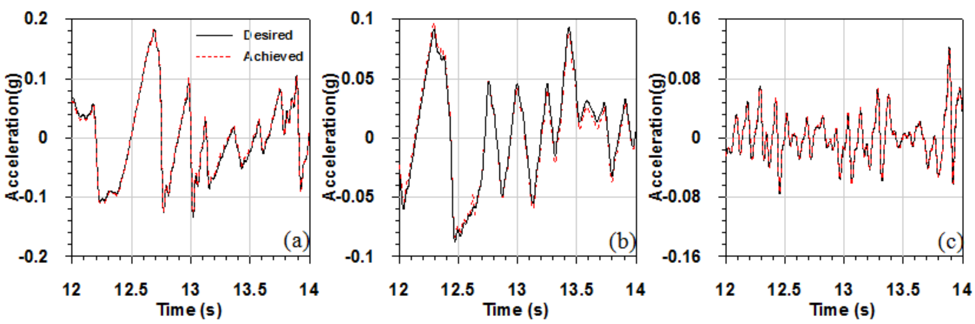
For the two 20 t elastic specimens with natural frequencies of 10 Hz and 5 Hz, a comparison of the desired (input) and achieved (output) of El-Centro time histories obtained from the last iteration are shown, respectively, over section of time domain plot in Figs. 15(a) and 16(a). Fig. 15(a) corresponds to the case of the 10 Hz elastic specimen in which the E-W component of the 1940 Imperial Valley Earthquake record was used. Fig. 16(a) corresponds to the 5 Hz elastic specimen in which the N-S component of the El-Centro record was used. Figs. 15(b) and 16(b) show the achieved response spectrum results (frequency range 0.5-50 Hz and for a damping ratio of 5%) for the 10 Hz and the 5 Hz elastic specimens, respectively, using the same components of the El-Centro record. These plots indicate that good signals reproduction fidelity is obtained.

For the two 20 t elastic specimens, error in percentage between the feedback and the reference in terms of the relative RMS error versus iteration number are shown in Figs. 15(c) and 16(c). It can be seen from Fig. 15(c) that the relative RMS error for the first iteration was 32% for longitudinal direction. The relative RMS error tends to reach a minimum value of the order of 16%



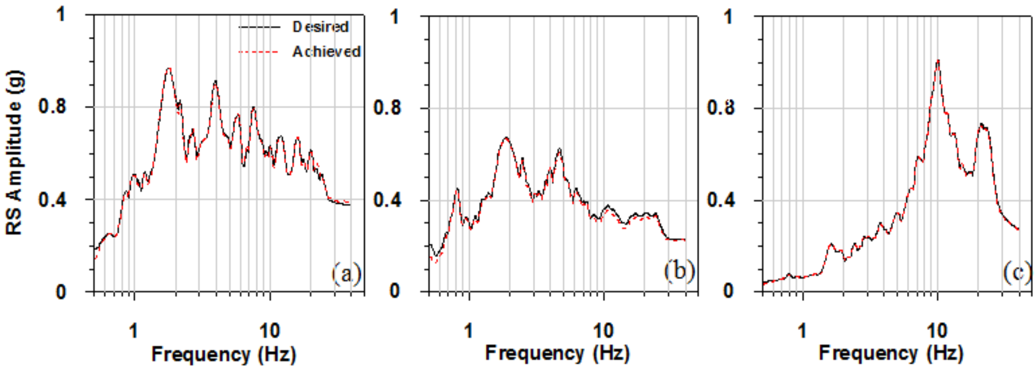
(a) Long direction (b) Lateral direction (c) Vertical direction

Fig. 10 Earthquake test of bare table (time history)



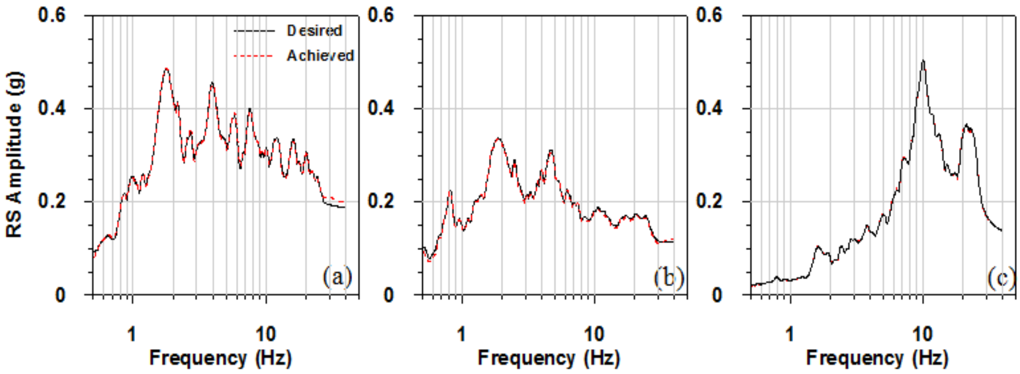
(a) Long direction (b) Lateral direction (c) Vertical direction

Fig. 11 Earthquake test of the 60 t rigid mass (time history)



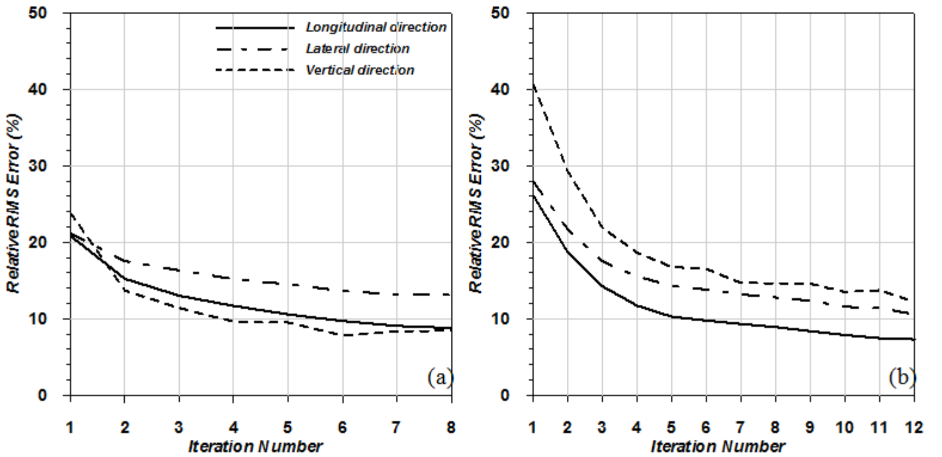
(a) Long direction (b) Lateral direction (c) Vertical direction

Fig. 12 Earthquake test of bare table (response spectrum damping ratio 5%)



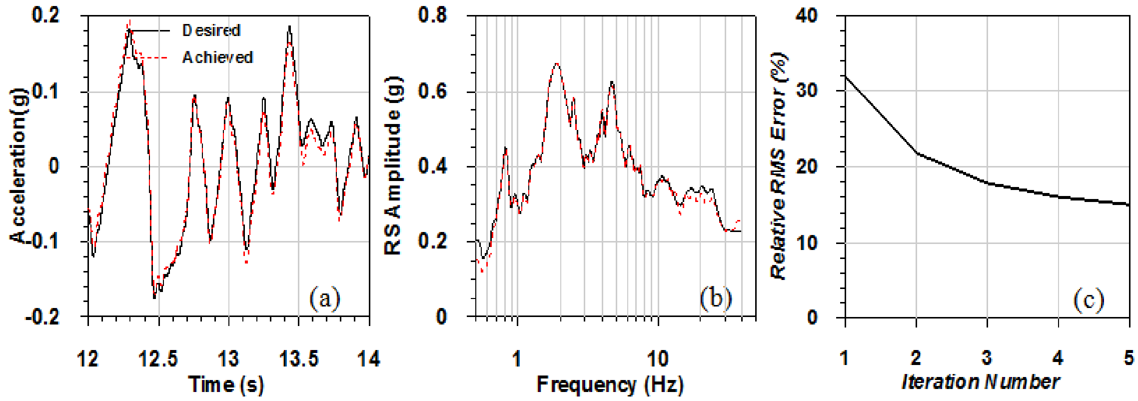
(a) Long direction (b) Lateral direction (c) Vertical direction

Fig. 13 Earthquake test of the 60 t rigid mass (response spectrum damping ratio 5%)



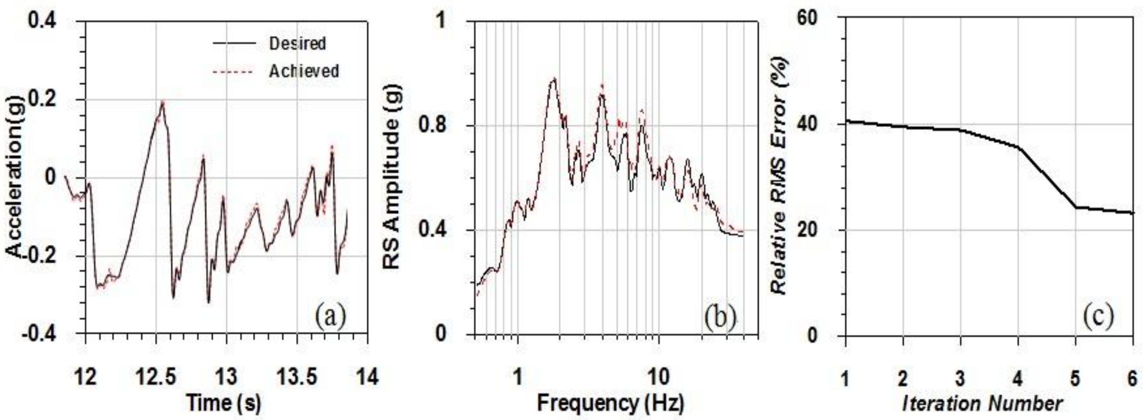
(a) Bare table (b) 60 t rigid mass

Fig. 14 Earthquake test – relative RMS error versus iteration number for El-Centro record



(a) Time history (b) Response spectrum damping ratio 5% (c) Relative RMS error

Fig. 15 Earthquake test of the 20 t elastic specimen with natural frequency 10 Hz



(a) Time history (b) Response spectrum damping ratio 5% (c) Relative RMS error

Fig. 16 –Earthquake test of the 20 t elastic specimen with natural frequency of 5 Hz

at the 5th iteration. Results given in Fig. 16(c) show the same trends as seen in Fig. 15(c), the relative RMS error for the 5 Hz elastic specimen was 40% at the first iteration and 22% at the 6th iteration.

The accuracy of the obtained shaking table motions was mainly due to the compensation methods performed by digital control system (MTS Stex3.0). In fact, when no compensation and corrections were used, the error was very high, indicating that even with a good tuning of the shaking table additional corrections are required to produce adequate control. In the case of the flexible specimen, the tuning process and the drive signal compensation had to be more rigorous if the effects of the shaking table-specimen interaction were to be minimized to acceptable levels.

It can be seen that the obtained relative RMS error for the two 20t elastic specimens were bigger than those obtained for the bare table and the 60 t rigid mass. This is a clear indication about the effects of the dynamic interaction of the shaking table and the specimen.

9. Conclusions

In this paper, the experimental results on the harmonic and earthquake signals tracking performance of the CGS shaking table were presented. The experimental investigations included two sets of tests. In the first set, compensated harmonic tests using advanced adaptive control techniques APC and AHC incorporated into MTS 469D digital controller for two condition of load (bare table and the 60 t rigid mass) were conducted to validate the uni-axial sinusoidal performances curves for the translational degree of freedoms and to evaluate the accuracy and fidelity of the shaking table control settings in signal reproduction. To measure the adequacy of ground motion reproduction capability of the shaking table, a number of comparisons and measures in time domain were used which included direct comparison between peak motions (displacement, velocity and acceleration), total harmonic distortion, root mean square error and relative root mean square error for the achieved and intended response signals. Based on these comparisons, it was found that good agreements were obtained between the theoretical and the generate performance curves of bare table and the 60 t rigid mass conditions. It was also demonstrated that the MTS advanced adaptive control algorithms provides a significant performance improvement of the shaking table system's response to a sine wave command signal across all frequency band of interest and to compensate for linear and/or nonlinear sources of signal distortion. The worst value of RMS error and relative RMS error for all cases was less than 9.9% and 10% for the *THD.*

Subsequently, in the second set, compensated earthquake simulation tests using MTS seismic test executive (Stex3.0) were accomplished using time history acceleration corresponding to the components of the 1940 Imperial Valley Earthquake records at El Centro station and the four load configurations (bare table, 60 t rigid mass and 20 t elastic specimens with natural frequencies of 5 Hz and 10 Hz). It was found that the error between reference and feedback acceleration signal tend to reach a maximum value of the order of 22% in the worst case at the 6th iteration. This level of error was obtained mainly due to the off line iterative test compensation performed by MTS seismic test executive Stex3.0. It is worth to mention that, the iterative procedure and the high number of iteration bring the problem of higher risk of premature damage to the specimen during earthquake test.

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