Acceleration Tracking Performance of the UCSD-NEES Shake Table

J. E. Luco[1]; O. Ozcelik[2]; and J. P. Conte[3]

Abstract: The main objective of this paper is to investigate the tracking (signal reproduction) capability of the UCSD-NEES shake table system through a series of broadband and harmonic experiments with different tuning and test amplitudes. The second objective is to obtain quantitative relations between different measures of the signal reproduction error and the amplitude of the reference excitation used to tune the shake table controller. These relations can be used as guidelines in planning of future seismic tests on the UCSD-NEES shake table or on large shake tables with similar controllers. The third objective is to evaluate the effectiveness of the existing iterative correction/tuning procedure for the UCSD-NEES shake table. The final objective of the paper is to propose some improvements to the current shake table tuning practice.

DOI: 10.1061/(ASCE)ST.1943-541X.0000137

CE Database subject headings: Structural dynamics; Shake table tests; Structural control; Full-scale tests; Structural tests; Earthquakes; Simulation.

Author keywords: Dynamics; Shake table; Control; Full-scale structural tests; Earthquake simulation.

Introduction

Large servohydraulic shake tables such as the UCSD-NEES large high performance outdoor shake table (LHPOST) at the Univ. of California, San Diego, are complex systems designed to subject large-scale structural or geotechnical specimens to extreme seismic loads such as those found in the near source region of major earthquakes. These facilities are used to investigate aspects of structural and geotechnical seismic behavior that cannot be readily extrapolated from testing at smaller scales or under quasistatic or pseudodynamic conditions. The severity of the earthquake ground motions that must be reproduced by these shake table systems is illustrated by the technical specifications of the LHPOST which include a stroke of ± 0.75 m, a peak horizontal velocity of 1.8 m/s, a peak horizontal acceleration of 4.2 g for bare table conditions and 1.2 g for a rigid payload of 3.92 MN, a horizontal force capacity of 6.8 MN, an overturning moment capacity of 50 MN m, a vertical payload capacity of 20 MN, a platen area of 7.6 m$\times$12.2 m, and a platen effective mass of 144 tons. The frequency bandwidth of LHPOST is 0–25 Hz (Ozcelik et al. 2008; Van Den Einde et al. 2004).

A typical shake table system includes a variety of mechanical (reaction block, platen, yaw/pitch/roll restraining systems, vertical and lateral bearings, and specimen), hydraulic (pumps, hydraulic lines, accumulator bank, inline and close-coupled accumulators, servovalves, and actuators), and electronic (controller, various types of transducers, signal conditioning units, and data acquisition system) components. The complexity of the system arises from the multiple sources of interaction among its various components (Ozcelik et al. 2008; Zhao et al. 2005; Thoen and Laplace 2004; Williams et al. 2001; Conte and Trombetti 2000; Kusner et al. 1992; Dyke et al. 1995; Clark 1983).

The severity of the simulated ground motions, the size of the specimens, and the complexity of the shake table system require the use of a robust controller to guide the platen in following (tracking) a prescribed (reference, commanded/target) motion. Most existing shake table systems operate in displacement control mode in which a displacement feedback loop is used to control the motion of the table. In this case, the control signal is the weighted error between the commanded and feedback (i.e., achieved) displacements. In servohydraulic control systems, force stabilization is provided by an additional actuator force feedback loop which contributes to damp out the oil column resonance (Conte and Trombetti 2000; Thoen and Laplace 2004). Since the seismic response of structures is driven by inertia forces, the key element in shake table tests is the capability of the system to accurately reproduce on the table prescribed acceleration records which are usually broadband signals. For this reason, the displacement control strategy is usually augmented with additional feedforward control signals in order to increase the fidelity in acceleration reproduction. Feedforward gains usually act on the commanded (target) velocity and/or acceleration command signals (Crewe 1998; Thoen 2004). The controller of the LHPOST falls in the category of displacement control with additional feedforward terms (e.g., velocity, acceleration, and jerk: third time derivative of displacement). It has also additional features such as notch filters and adaptive and iterative control techniques to improve the system performance and to compensate for linear and/or nonlinear sources of signal distortion (Thoen 2004).

[1]Dept. of Structural Engineering, Univ. of California–San Diego, 9500 Gilman Dr. La Jolla, CA 92093 (corresponding author) E-mail: jeluco@ucsd.edu.

[2]Assistant Professor, Dept. of Civil Engineering, Dokuz Eylul Univ., Tinaztepe Kampusu, Buca/Izmir 35320, Turkey; formerly, Graduate Student, Univ. of California–San Diego, San Diego, CA. E-mail: ozgur.ozcelik@deu.edu.tr

[3]Dept. of Structural Engineering, Univ. of California–San Diego, 9500 Gilman Dr. La Jolla, CA 92093. E-mail: jpconte@ucsd.edu

Note. This manuscript was submitted on September 17, 2008; approved on October 24, 2009; published online on October 29, 2009. Discussion period open until October 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Structural Engineering***, Vol. 136, No. 5, May 1, 2010. ©ASCE, ISSN 0733-9445/2010/5-481–490/$25.00.

The process of "tuning" the shake table to optimize signal reproduction (i.e., maximize fidelity in reproducing the target motion on the platen) requires adjusting a number of control parameters (e.g., feedback and feedforward gains) and some preconditioning of the commanded motion. Since there may be a significant dynamic interaction between the specimen and the table, the tuning process must be conducted with the specimen mounted on the table. The need to prevent premature damage to the specimen requires that the shake table tuning process be conducted with scaled-down input motions of amplitudes much lower than those of the final or actual tests. Even when this precaution is followed, the specimen is subjected to many cycles of motion in the course of tuning, and low-level fatigue damage can result (Thoen and Laplace 2004). A major concern with tuning at low amplitude motion is that the fidelity achieved at low amplitudes may not hold for the actual larger amplitude tests. It should be noted that high fidelity in signal reproduction is not required in all shake table tests. In many cases, comparisons between the experimentally observed and analytically predicted structural responses can be done a posteriori using the achieved platen motion as input for the computation of the response. In other cases, such as those involving hybrid testing or geographically distributed testing, accurate tracking is paramount.

The first objective of this paper is to investigate the tracking (signal reproduction) capability of the UCSD-NEES shake table system by a series of broadband and harmonic experiments with different tuning and test amplitudes. A second objective is to obtain quantitative relations between different measures of the signal reproduction error and the amplitude of the reference excitation used to tune the shake table. These relations can be used as guidelines for the planning of future seismic tests on the LHPOST or on large shake tables with similar controllers. The third objective is to evaluate the effectiveness of the existing iterative correction/tuning procedure for the UCSD-NEES shake table. The final objective is to propose some improvements to the current shake table tuning practice.

469D Control Software and Tuning of Shake Tables

The three variable controller (TVC) of the LHPOST is an integral part of the MTS control software 469D (Thoen 2004). The TVC can be set to run under displacement, velocity, and acceleration modes. In acceleration and velocity modes (velocity mode is rarely, if ever, used for shake table tests), the controller is still in displacement control, but the control signal to the servovalves is a blend of weighted displacement error and feedforward terms including weighted velocity, acceleration, and jerk command signals.

The process of adjusting multiple control parameters (e.g., feedback and feedforward gains) and of preconditioning the input motion to optimize signal reproduction (tracking) capability of the shake table system is called tuning. Ideally, a tuned shake table system would have a total transfer function between the command (reference) and feedback signals characterized by a unit gain and zero phase shift across the entire operating frequency range under loaded table conditions (i.e., with specimen mounted on the table). The current shake table tuning practice involves a three-step process. The first step involves an iterative process in which the control parameters of the TVC are (manually) adjusted iteratively in small increments while the loaded table is in motion. Typically, this step is performed under a band-limited (e.g., 0.25–25 Hz) white noise (WN) input acceleration with an RMS

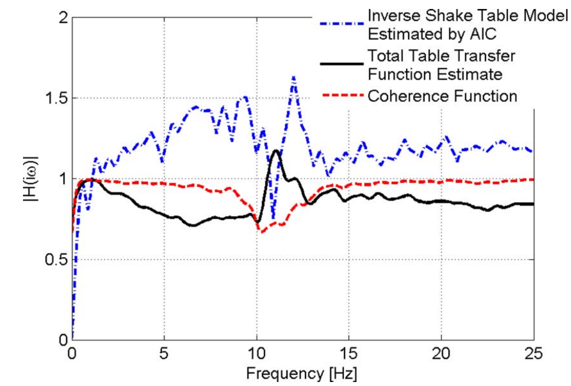

Fig. 1. Magnitude of total table transfer function estimate after TVC tuning and estimated inverse shake table model

amplitude sufficiently high to obtain a good signal-to-noise ratio in the feedback acceleration and a reliable estimate of the table total transfer function between command and feedback accelerations but low enough to avoid damaging the specimen. The parameter adjustment process continues until the total table transfer function (estimated recursively) is deemed satisfactory. As an illustration, Fig. 1 shows the amplitude of the resulting total table transfer function estimate after TVC tuning of the LHPOST (under bare table condition) using a WN acceleration input with 7%-g RMS amplitude and, an approximate peak ground acceleration (PGA) of 0.25-g.

Many shake table tests, but not all, require high fidelity in signal reproduction. In such cases, the tuning process requires two additional steps. The second step consists of obtaining an estimate of the inverse model of the plant. This inverse model is obtained using the adaptive inverse controller (AIC) technique (Thoen 2004) in which the parameters of the inverse model are estimated by an adaptive inverse modeling process also known as adaptive controller "training" (Widrow and Stearns 1985). The quality of the estimated inverse model depends on the noise level, input amplitude level, and nonlinearities in the system. Inverse model estimation with AIC is also performed under WN acceleration with RMS amplitude coinciding with that used in the first step to "fine tune" the TVC parameters. An example of the magnitude response of the estimated inverse model of the LHPOST (under bare table condition) at the end of AIC training is shown in Fig. 1.

The third step in the tuning process involves the use of an iterative signal matching technique. The iterative time history matching technique used in the 469D software is called online iteration (OLI). It is a procedure that repeatedly modifies the command input to the shake table (e.g., drive file containing a distorted version of the reference/target earthquake acceleration record) to optimize the match between the actual table motion and the desired (e.g., target/reference) motion (Thoen 2004). This online iterative technique generates the next command to the table (i.e., next drive file) by running the table in real time with the current drive file as the command to the table, calculating (offline) the error between the desired and feedback (i.e., achieved) motions, and updating the current drive file by adding to it a fraction (i.e., determined by the iteration gain) of the response error filtered through the inverse plant model. The general trend of the response RMS error versus the iteration number during an OLI process is shown in Fig. 2. The response RMS error is defined as the RMS of the error between desired/reference and feedback (i.e., achieved) acceleration signals. Fig. 2 shows that the response RMS error initially decreases with the iteration number,

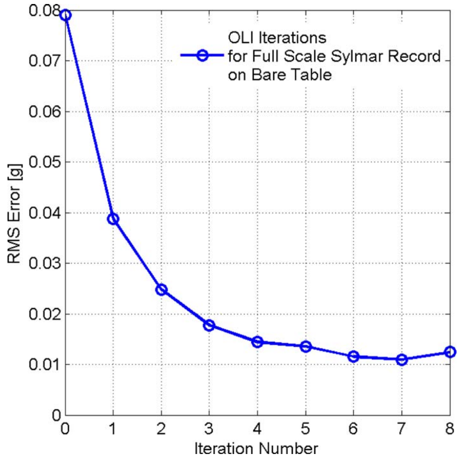

Fig. 2. Response RMS error versus OLI iteration number for Sylmar record at 0.852-g calibration PGA amplitude (for this OLI case, the converged drive file is reached at the seventh iteration)

reaches a minimum, and starts increasing. The drive file producing the minimum response RMS error is considered to be the "converged drive file." In principle, OLI can correct for any remaining deficiencies after tuning of the TVC and moreover can compensate for existing linear/nonlinear sources of signal distortions within the system (e.g., friction, servovalves, table-specimen interactions, etc.). Application of the OLI process requires a prior estimate of the inverse plant model provided by the AIC program which is wired into the OLI program to serve this purpose (Thoen 2004). The OLI is performed with a scaled-down version of the intended/target table (ground) motion to avoid damaging the specimen. After a satisfactory OLI tuning is achieved, the converged file is scaled up to the amplitude of the intended table motion, and the desired tests are performed on the table. The current tuning process is labor intensive and the results are highly dependent on the level of expertise of the operator.

Shake Table Seismic Performance Test Program

An extensive set of 74 shake table tests was performed in December 2007 and January 2008 to assess the fidelity of LHPOST in reproducing a prescribed platen motion. The tests were designed to quantify the effect that the tuning amplitude has on the level of signal fidelity. For this purpose, four different ground motion (acceleration) records were selected, namely, the 360° component of the 1994 Northridge earthquake recorded at the Sylmar Olive View Med FF station, the north-south component of the 1940 Imperial Valley earthquake recorded at El Centro station, and two harmonic acceleration records with frequencies of 1.0 and 4.1 Hz. It should be noted that 4.1 Hz corresponds to the corner frequency where the table velocity and acceleration limits intersect on the performance envelope of LHPOST. For each of these four acceleration records, the table was tuned at scaled-down or scaled-up versions of the record based on several "calibration PGA" amplitudes and the corresponding OLI converged files were obtained. Each converged drive file was then scaled up or down according to several "test PGA" amplitudes and played on the table. The table fidelity in signal reproduction was assessed by comparison of the original (target/reference) acceleration time history scaled to the test PGA with the table acceleration obtained for a given calibration PGA. The test matrix for each of the four selected acceleration records is given in Table 1. All tests were performed without a specimen on the table and thus represent bare table condition.

The tuning of the table in preparation for the tests followed the standard three-step procedure defined above. The first two steps are common for all of the tests, whereas the third step differs for each acceleration record and calibration PGA. The first two steps (TVC parameter adjustment and AIC inverse model identification) were performed under a band-limited (0.25–25 Hz) WN acceleration input with 7%-g RMS amplitude (0.25-g PGA). During the third step of the tuning process corresponding to the OLI preconditioning of the input motion (performed independently for each of the four acceleration records), the tuning results obtained from the previous two steps were kept fixed.

Test Results

A number of comparisons and measures are used to evaluate the signal reproduction capability of the NEES-UCSD shake table. These include direct comparisons of the acceleration time histories, peak accelerations, and constant ductility response spectra for the achieved and intended (desired) platen acceleration time histories. Also to offer a (cumulative) measure of the error in signal reproduction, the relative RMS error measure defined as

$$\varepsilon_{rel} = \frac{\sqrt{(1/N)\Sigma_{n=1}^{N}(\ddot{x}_{fbk}[n] - \ddot{x}_{des}[n])^2}}{\sqrt{(1/N)\Sigma_{n=1}^{N}(\ddot{x}_{des}[n])^2}} \times 100 \qquad (1)$$

is used. In Eq. (1), $\ddot{x}_{des}$=desired (reference/command) acceleration; $\ddot{x}_{fbk}$=achieved (i.e., feedback) acceleration; and N denotes the number of data point within the time window chosen to calculate the error. For the earthquake records, this time window was chosen to be the time interval between the 5 and 95% contributions of the target/reference acceleration time histories to the Arias intensity ($\int \ddot{x}_{des}^2 dt$). The resulting time windows for the Sylmar and El Centro records were found to be 11.46–16.80 and 12.25–36.81 s, respectively. The achieved table acceleration time history was shifted in time to correct for any delay introduced by the plant. The appropriate shift was determined by minimizing the relative RMS error. In the case of the harmonic acceleration records, the time window for error calculations was chosen so that the maximum acceleration amplitude for a particular test was reached (after two cycles of ramping up) and at least two cycles were included in the window.

Comparison of Acceleration Time Histories

To get an overview of the performance of the LHPOST in terms of fidelity in signal reproduction, it is convenient to compare the achieved and intended acceleration time histories. Fig. 3 shows two acceleration time history reproduction results for the Sylmar earthquake record. Fig. 3(a) corresponds to the case in which the OLI tuning was performed at 0.170-g calibration PGA amplitude, while the test was performed at 0.852-g test PGA amplitude by scaling up the converged drive file with the scale factor of 0.852/0.170=5.01. Fig. 3(b) presents the results for the case in which both OLI and the test were performed at the same PGA amplitude (i.e., calibration PGA=test PGA=0.852 g). In other words, the converged drive file obtained at 0.852-g calibration PGA was reproduced directly on the table without any additional scaling. The results shown in Fig. 3 indicate that a very good signal reproduction fidelity (relative RMS error of 10.9%) is ob-

Table 1. Calibration and Target PGA Test Matrices for Sylmar, El Centro and Harmonic Records

Sylmar record

Calibration PGA (g)	Test PGA (or target PGA) (g)				
0.085	***0.085***	0.170	0.511	0.852	1.193
0.170	0.085	***0.170***	0.511	0.852	1.193
0.511	0.085	0.170	***0.511***	0.852	1.193
0.852	0.085	0.170	0.511	***0.852***	1.193

El Centro record

Calibration PGA (g)	Test PGA (or target PGA) (g)					
0.073	***0.073***	0.146	0.366	0.732	1.098	1.464
0.146	0.073	***0.146***	0.366	0.732	1.098	1.464
0.366	0.073	0.146	***0.366***	0.732	1.098	1.464
0.732	0.073	0.146	0.366	***0.732***	1.098	1.464
1.098	0.073	0.146	0.366	0.732	***1.098***	1.464

4.1-Hz harmonic tests

Calibration PGA (g)	Test PGA (or target PGA) (g)				
0.59	**0.59**	1.18	2.36	3.55	3.81
1.18	N/A	**1.18**	2.36	3.55	3.81
2.36	N/A	N/A	**2.36**	3.55	3.81

1.0-Hz harmonic tests

Calibration PGA (g)	Test PGA (or target PGA) (g)				
0.14	**0.14**	0.29	0.58	0.87	0.93
0.29	N/A	**0.29**	0.58	0.87	0.93
0.58	N/A	N/A	**0.58**	0.87	0.93

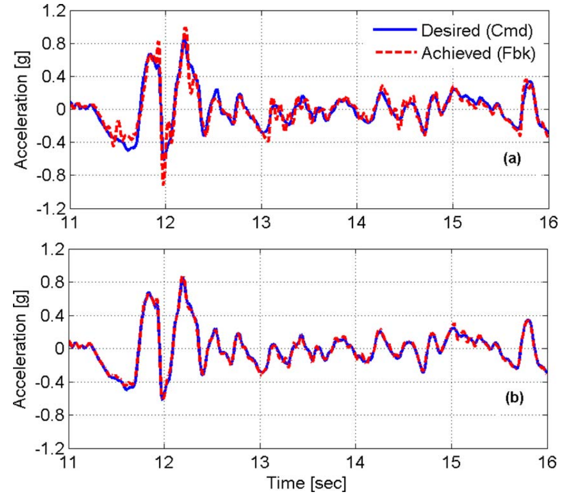

Fig. 3. Sylmar tests: (a) OLI performed at 0.170-g calibration PGA and test performed at 0.852-g test PGA amplitude (relative RMS error of 33.3%); (b) OLI performed at 0.852-g calibration PGA and test performed at 0.852-g test PGA (relative RMS error of 10.9%)

tained when both the OLI tuning and the test are performed at the same high PGA amplitude (0.852 g in this case). On the other hand, the use of a more realistic lower calibration PGA amplitude (0.170 g) and a test with a higher test PGA amplitude (0.852 g) result in significantly lower fidelity in signal reproduction (relative RMS error of 33.3%).

Similar results are shown in Fig. 4 for the El Centro earthquake record. Fig. 4(a) shows the case where OLI was performed at 0.146-g calibration PGA amplitude, while the test was performed at 1.098-g test PGA amplitude by scaling up the converged drive file with the scale factor 1.098/0.146=7.52. Fig. 4(b) shows the case in which both OLI and the test were performed at the same PGA amplitude (i.e., calibration PGA=test PGA=1.098 g). Again, the signal reproduction fidelity is significantly better (reduction of relative RMS error from 35.5 to 16.2%) when the OLI tuning is performed at the same signal amplitude as the test.

Fig. 5 shows the desired and feedback acceleration time history plots for a set of tests with intended harmonic accelerations at the frequency of 4.1 Hz and various amplitudes. The results in Figs. 5(a–d) correspond to cases in which the converged OLI drive file was obtained for 0.591-g calibration PGA and then test results at test PGAs of 0.591, 1.182, 2.364, and 3.547 g were obtained by running the appropriately scaled converged drive file on the table. It is clear from the plots that although a near perfect replica of the desired signal was achieved in Case (a), scaling of the converged drive file to higher test amplitudes resulted in lower signal reproduction fidelity (i.e., increased waveform distortion with increasing scale factor). The relative RMS errors for Cases (a)–(d) are 7.9, 17.0, 22.8, and 22.8%, respectively. Fourier amplitude spectra of the achieved table acceleration time histories (i.e., acceleration feedback) show that odd harmonics of the test frequency are the predominant causes of signal distortion indicating a significant nonlinear system response. Such nonlinear distortions at a signal specific amplitude can be compensated by OLI, but the converged drive file cannot compensate for distortions at a higher signal amplitude. Fig. 5(e) corresponding to the case in which the OLI tuning (calibration) and test were conducted at the same high signal amplitude of 2.364 g shows that

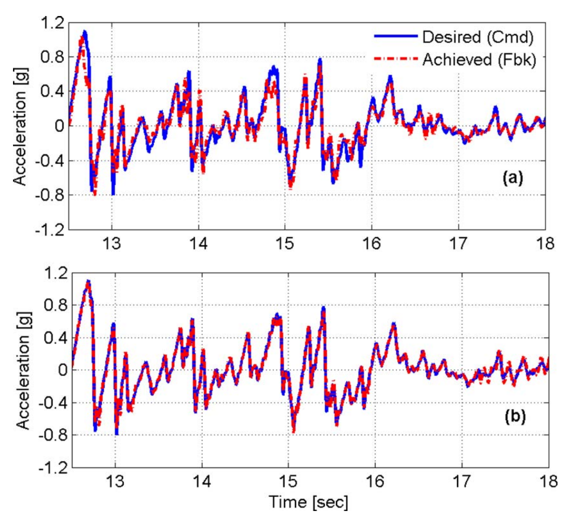

Fig. 4. El Centro tests: (a) OLI performed at 0.146-g calibration PGA and test performed at 1.098-g test PGA amplitude (relative RMS error of 35.5%); (b) OLI performed at 1.098-g calibration PGA and test performed at 1.098-g test PGA (relative RMS error of 16.2%)

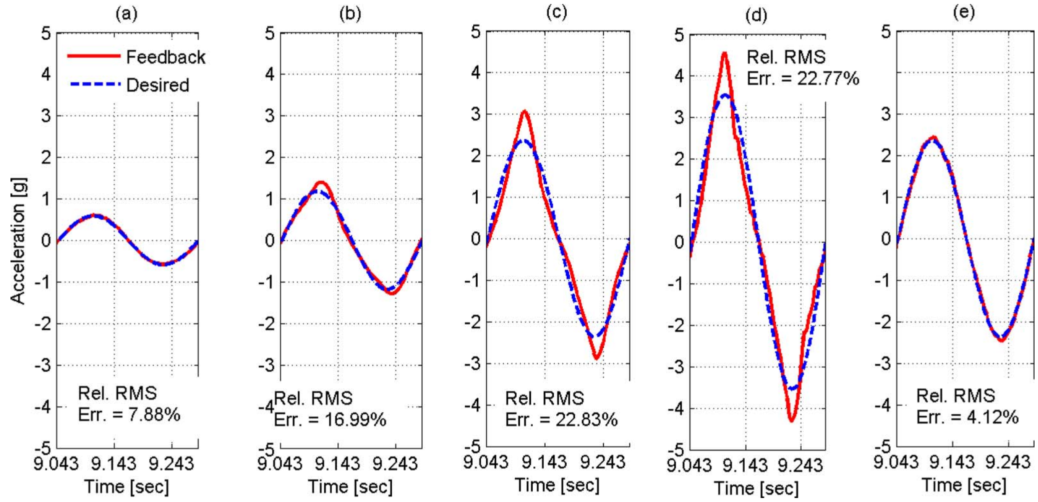

Fig. 5. Harmonic tests at 4.1 Hz with corresponding relative RMS errors: (a) OLI and test are performed at 0.591-g PGA amplitude; OLI is performed at 0.591-g calibration PGA and tests are performed at (b) 1.182; (c) 2.364; (d) 3.547-g test PGA; and (e) calibration PGA is same as test PGA of 2.364 g

OLI is very effective even at high signal amplitudes. However, to obtain good waveform reproduction, OLI tuning and test must be conducted at similar amplitudes.

Additional comparisons between the desired and feedback acceleration time history plots for a set of tests with intended harmonic accelerations at a frequency of 1.0 Hz are shown in Fig. 6. The results in Figs. 6(a–d) correspond to cases in which the converged OLI drive file was obtained for 0.144-g calibration PGA and then test results at test PGAs of 0.144, 0.288, 0.577, and 0.865 g were obtained by running the appropriately scaled converged drive file on the table. The relative RMS errors for Cases (a)–(d) are 38.0, 25.4, 22.8, and 26.3%, respectively. The results in this case show strong signal distortions with frequencies close to the oil column frequency even in Cases (a) and (b). The cases corresponding to Figs. 5(a) and 6(a) differ in frequency (4.1 Hz versus 1 Hz), intended peak acceleration (0.591 g versus 0.144 g), and intended peak displacement (0.9 cm versus 3.6 cm). The main reason for the increased distortion in Fig. 6(a) compared to Fig. 5(a) is not the frequency or the larger displacement but the lower calibration PGA of 0.144 g. The results in Fig. 6(e) corresponding to the case in which the OLI tuning (calibration) and test were conducted at the same high signal amplitude of 0.577 g show that it is possible to obtain good waveform reproduction for the same frequency of 1 Hz and for a larger peak displacement of 14.3 cm when the OLI tuning and the test are conducted at similar but higher amplitudes.

In the case of harmonic excitation, the MTS 469D control software offers the option of using an amplitude harmonic cancellation (AHC) control method instead of OLI to compensate for nonlinear plant distortions. AHC measures the harmonic distortions for a harmonic input with a specified frequency and amplitude, then in real time determines and adapts a distortion

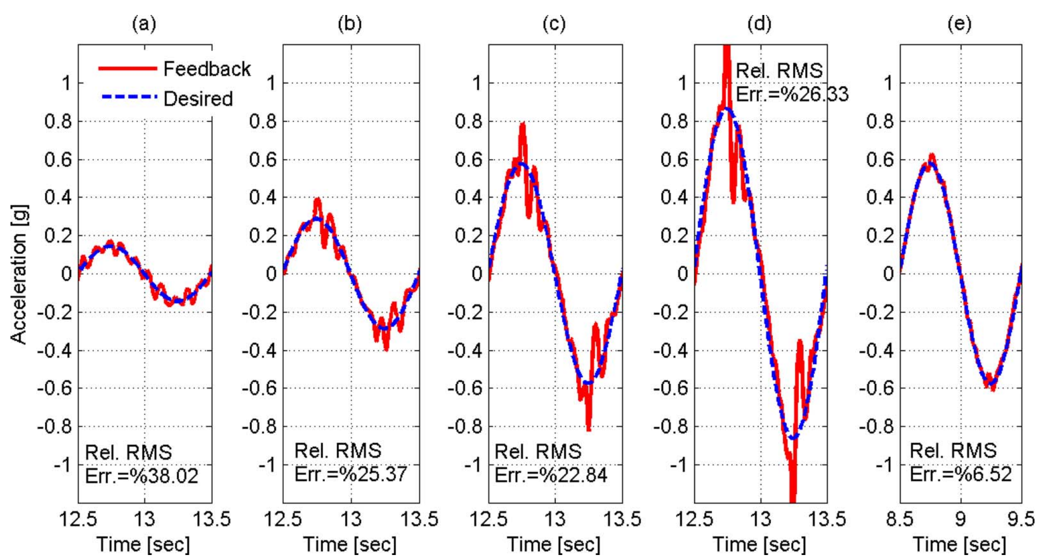

Fig. 6. Harmonic tests at 1.0 Hz with corresponding relative RMS errors: (a) OLI and test are performed at 0.144-g PGA amplitude; OLI is performed at 0.144-g calibration PGA and tests are performed at (b) 0.288; (c) 0.577; (d) 0.865-g test PGA; and (e) calibration PGA is same as Test PGA 0.577 g

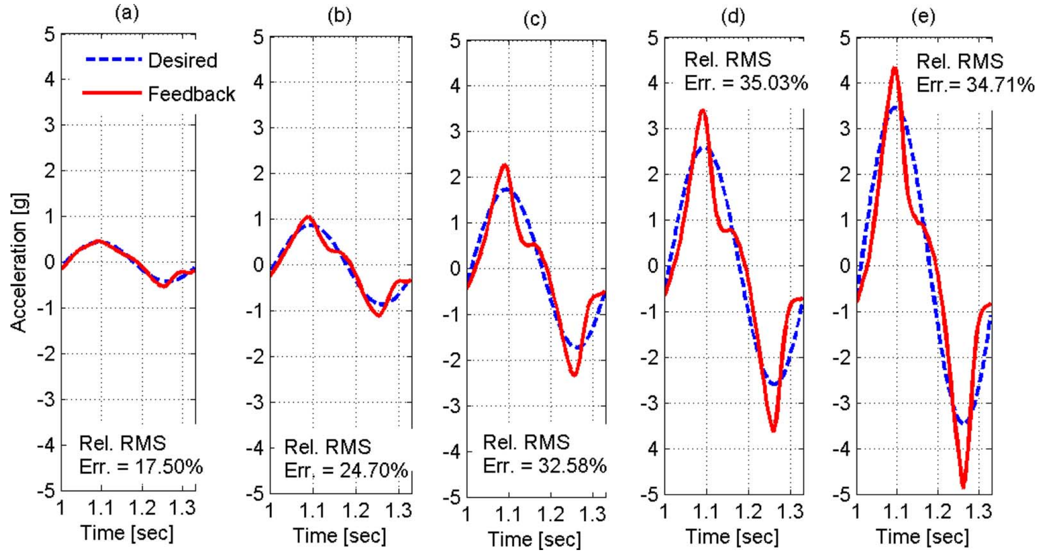

Fig. 7. Harmonic tests at 3.0 Hz with corresponding relative RMS errors: (a) AHC and test are performed at 0.433-g PGA amplitude; AHC is performed at 0.433-g calibration PGA and tests are performed at (b) 0.865; (c) 1.730; (d) 2.595; and (e) 3.460-g test PGA

canceling signal, and adds this signal to the plant input (Thoen 2004). AHC requires that a forward plant model be estimated. An example of application of the AHC method instead of OLI is presented in Fig. 7 which shows results obtained from an earlier (2005) set of harmonic tests at a frequency of 3 Hz. For the tests shown in Fig. 7, the AHC was performed at 0.433-g amplitude and the tests were run at 0.433, 0.865, 1.730, 2.595, and 3.464 g with properly scaled input (drive) files. The time history reproduction results displayed in Fig. 7 are very similar to those obtained from the recent tests with OLI (Fig. 5) indicating that OLI is not significantly better than AHC compensation. The relative RMS errors for the five cases shown in Fig. 7 are 17.5, 24.7, 32.6, 35.0, and 34.7%, respectively. The forward plant model for the earlier tests was estimated by running a WN acceleration with 10%-g RMS amplitude on the table.

Error in Peak Accelerations

For tests involving stiff and brittle specimens, accurate reproduction of the peak acceleration is important. The results shown in Figs. 3–7 indicate that the obtained (achieved) peak accelerations can be significantly higher than the intended (reference) values. The errors of the achieved peak acceleration with respect to the intended peak acceleration are shown in Figs. 8(a and b) for the Sylmar and El Centro earthquake records, respectively. The errors are shown versus target PGA for different calibration PGAs. The error can be as large as 30% for high amplitude tests with calibration PGA less than 10% g. Increasing the calibration PGA tends to reduce the error in peak accelerations. The results obtained for harmonic acceleration signals shown in Figs. 9(a and b) exhibit similar trends as those for earthquake records except that the errors in the harmonic case tend to be larger and, particularly, so for the harmonic test at 1 Hz which was calibrated at lower accelerations. It is also worth noting that the shake table overshoots the target peak accelerations for both harmonic tests.

Reproduction of Elastic and Inelastic Response Spectra

The capability of the shake table to reproduce the response spectrum of the prescribed acceleration time history is another measure of the performance of the table. To investigate the effect of the tuning process on the response spectrum reproduction capability of the table, elastic and inelastic (pseudoacceleration) spectra from reproduced acceleration time histories were calculated and compared with the response spectra of the desired accelera-

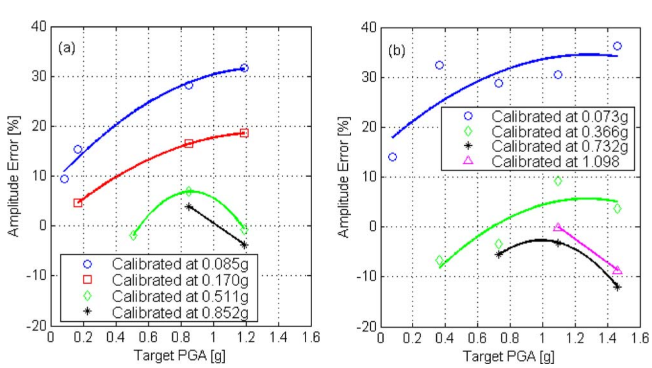

Fig. 8. Error of achieved over intended (target) peak acceleration for (a) Sylmar earthquake record; (b) El Centro earthquake record

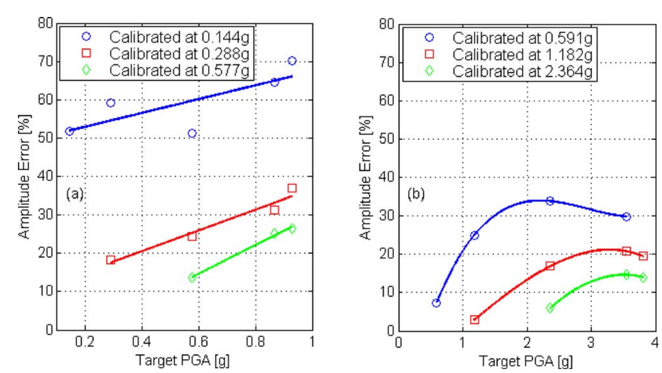

Fig. 9. Error of achieved over intended (target) peak acceleration for harmonic acceleration records at (a) 1.0-; (b) 4.1-Hz frequencies

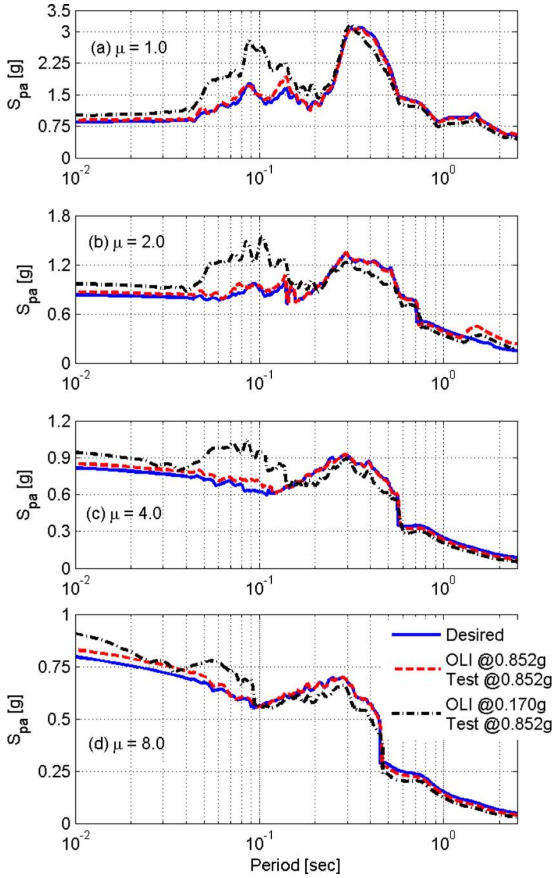

Fig. 10. Desired and achieved constant ductility pseudoacceleration response spectra corresponding to four different displacement ductility levels ($\mu=1$, 2, 4, and 8) for Sylmar earthquake record

tion records. For this purpose three different acceleration time histories have been considered: (i) the original Sylmar earthquake record with 0.852-g PGA amplitude; (ii) the acceleration time history achieved by the table when the command input to the table was a modified version of the original Sylmar record which was obtained by performing OLI at 0.170-g calibration PGA and scaling the converged drive file to 0.852-g test PGA; and (iii) the acceleration time history achieved by the table when the command input to the table was again obtained by OLI but this time performed at 0.852-g calibration PGA, which coincides with the test PGA.

Fig. 10 shows the 3% damped elastic ($\mu=1$) and inelastic constant ductility ($\mu=2$, $\mu=4$, and $\mu=8$) pseudoacceleration response spectra corresponding to the three acceleration time histories mentioned above. These constant ductility spectra are based on an elastoperfectly plastic SDOF oscillator. The displacement ductility μ is defined as the ratio of the peak displacement response to the yield displacement. It is clear from the results shown in Fig. 10 that the elastic and inelastic response spectra of the achieved table motion are in good agreement with the corresponding spectra of the desired target table motion when the tuning (calibration) amplitude matches the test amplitude (0.852 g). On the other hand, major discrepancies between the desired and achieved response spectra can be observed when the table is tuned at an amplitude (0.170 g) significantly lower than the test amplitude. The largest errors in the achieved response spectra are observed in the vicinity of the period $T=0.09$ s which corresponds to the oil column resonance of the shake table. The errors are positive for periods shorter than 0.2 s, while they are mostly negative for periods longer than 0.3 s.

In the period range from 0.02 to 0.2 s, the maximum errors in the achieved spectra for ductility levels $\mu=1$, 2, 4, and 8 correspond to 84.7, 70.1, 47.6, and 21.7%, respectively. Thus at short periods, the error tends to decrease as the ductility (i.e., level of inelasticity) increases. In the period range from 0.2 to 0.5 s, the maximum errors in the achieved spectra are 19.2, 15.0, 15.1, and 14.3% for $\mu=1$, 2, 4, and 8, respectively. Finally, in the period range from 0.5 to 1.5 s, the maximum spectral errors for $\mu=1$, 2, 4, and 8 are 14.0, 43.7, 16.3, and 17.8%, respectively.

Relative RMS Error

The relative RMS errors obtained for the Sylmar and El Centro earthquake records are plotted in Figs. 11(a and b) as a function of target PGA for different values of calibration PGA. The following trends can be observed: (i) the relative RMS error for calibration PGA lower than 0.17 g and high test GPA can reach values in the range from 35 to 55%; (ii) the relative RMS error can be reduced by increasing the calibration PGA amplitude; (iii) the smallest relative RMS errors of 10.9 and 16.2% are achieved

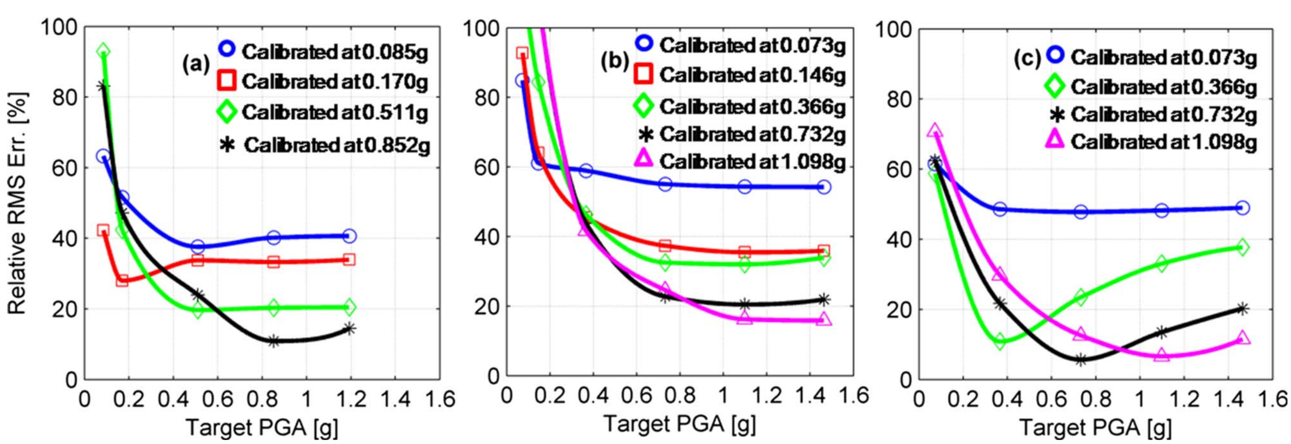

Fig. 11. Relative RMS error versus target (or test) PGA curves for (a) Sylmar; (b) El Centro earthquake records (AIC training was performed under 7%-g RMS WN acceleration); and (c) El Centro earthquake record (earlier AIC training was performed under 10%-g RMS WN acceleration)

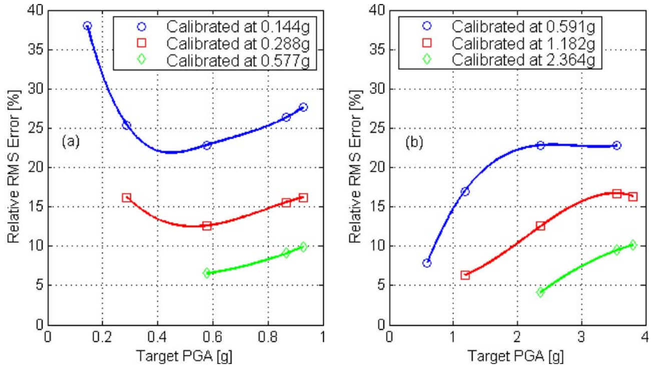

Fig. 12. Relative RMS error versus target (or test) PGA curves for harmonic acceleration records at (a) 1.0-; (b) 4.1-Hz frequencies

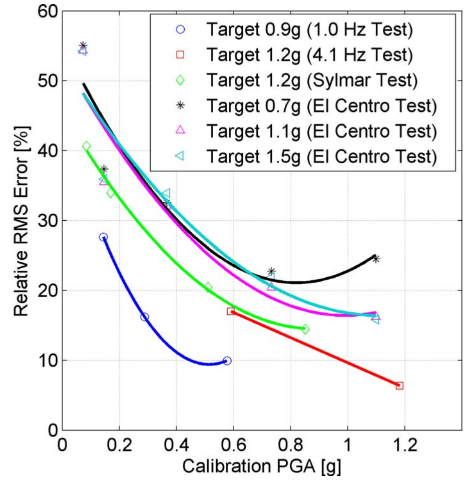

Fig. 13. RMS error versus calibration PGA curves for harmonic and earthquake tests with target PGA amplitudes between 0.9 and 1.5 g

at a calibration PGA of 0.852 and 1.098 g for the Sylmar and El Centro records, respectively; (iv) poor signal reproduction fidelity is obtained when both the calibration and test PGA amplitudes are low; (v) the relative RMS error is relatively independent of target PGA for target PGA amplitudes exceeding 0.75–0.80 g; and (vi) in the unlikely case of high calibration PGA and low test PGA, the system performs very poorly in terms of signal reproduction fidelity. The relative RMS errors obtained in an earlier set of tests (performed in September 2005) are shown in Fig. 11(c). The tuning procedure followed for these earlier tests was the same as for the recent tests except that TVC parameter adjustments and AIC training were performed under 10%-g RMS WN acceleration input (0.35-g PGA) for the earlier tests and 7%-g RMS WN acceleration input (0.25-g PGA) for the recent tests. For OLI, the same 1940 Imperial Valley El Centro record was used to perform OLI in the earlier and recent tests. Comparison of the results in Figs. 11(b and c) indicates that although the trends observed for the calibration PGA of 0.073 g in the two series of tests are similar, higher fidelity in signal reproduction (i.e., smaller relative RMS errors) was achieved in the earlier tests. In addition, the earlier relative RMS error curves [Fig. 11(c)] reach their minima when the calibration PGA coincides with the test PGA. This is a more intuitive result since the table should perform best at the amplitude level at which OLI has been performed. Two possible reasons can be given to explain the differences observed between the two series of tests: (1) the quality of the inverse model estimation increases with the RMS amplitude of the WN acceleration input and (2) the table performance in terms of signal reproduction fidelity depends on the level of experience of the table operator.

The relative RMS error curves obtained for harmonic tests at frequencies of 1.0 and 4.1 Hz are shown in Fig. 12. The general trends are the following: (i) for a calibration PGA of 0.144 g, the relative RMS error exceeds 20%; (ii) the relative RMS error decreases as the calibration PGA increases; (iii) minimum relative RMS errors of the order of 5–8% can be achieved for calibration PGA larger than 0.577 g when the test and calibration PGAs coincide; and (iv) the relative RMS errors for a given calibration PGA appear to reach an asymptotic value as the test PGA increases.

Table Performance Curves

The relative RMS error data shown in Figs. 11 and 12 have been used to construct the table performance curves shown in Figs. 13–15. These curves relate the calibration PGA and test PGA for a desired level of fidelity in signal reproduction as measured by the relative RMS error. These curves are intended to serve as guidance in the selection of appropriate calibration amplitudes for

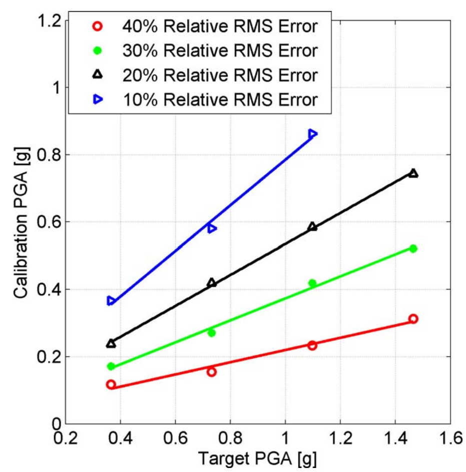

Fig. 14. Table performance curves obtained from the earlier set of tests for El Centro earthquake record (the inverse plant model was estimated while running 10%-g RMS WN acceleration on the table)

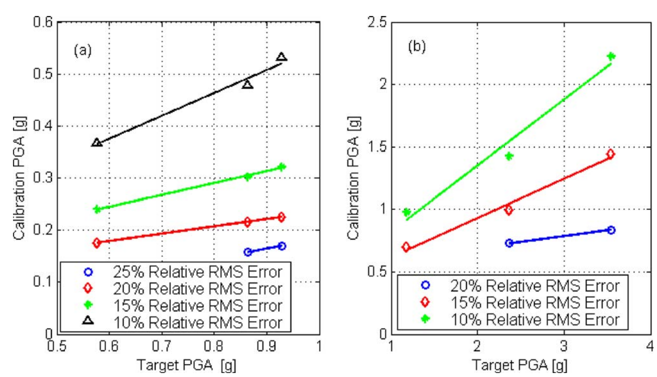

Fig. 15. Table performance curves for harmonic acceleration records at (a) 1.0-; (b) 4.1-Hz frequencies (the inverse plant model was estimated while running 7%-g RMS WN acceleration on the table)

future tests with preselected test PGA and relative RMS error. The curves quantify the trade-off between higher signal reproduction fidelity (lower relative RMS error) and probability of premature damage to the specimen by use of larger calibration amplitudes.

Fig. 13 shows a set of RMS error versus calibration PGA curves for harmonic tests at (i) 1.0-Hz and 0.9-g target amplitude and (ii) 4.1-Hz and 1.2-g target amplitude, Sylmar earthquake test with 1.2-g target PGA, and El Centro earthquake tests with 0.7-, 1.1-, and 1.5-g target PGA. The relative RMS error trends in Fig. 13 clearly show that achieving higher signal reproduction fidelity requires higher calibration PGA for both harmonic and earthquake acceleration records.

Fig. 14 shows the table seismic performance curves obtained from the earlier set of tests for the El Centro record (with TVC-OLI table tuning performed using 10%-g RMS WN acceleration input with 0.35-g peak acceleration). These seismic performance curves can be used to determine the calibration PGA to perform OLI, which is required for a desired level of signal reproduction fidelity. For example, these curves indicate that 0.36-g calibration PGA is necessary to achieve 30% relative RMS error in reproducing the El Centro earthquake acceleration record scaled to 1.0 g on the table. The results given in Fig. 14 show the same trend observed in Fig. 13, namely, that higher fidelity in signal reproduction requires a higher calibration PGA which in turn increases the risk of premature damage imparted to the specimen during table tuning.

The table seismic performance curves for harmonic acceleration records at 1.0- and 4.1-Hz frequencies are shown in Figs. 15(a and b), respectively. To illustrate the use of these curves, it is assumed that a harmonic record with a frequency of 4.1 Hz and an amplitude of 3.0 g needs to be reproduced on the shake table. If a relative RMS error of 20% is considered satisfactory for the planned test, then the seismic performance curves in Fig. 15(b) indicate that the OLI must be performed at a calibration PGA of 0.76 g.

Conclusions

Based on the results obtained from earthquake and harmonic tests performed on the UCSD-NEES shake table, the following conclusions can be drawn:

1. High fidelity in reproduction of the platen acceleration (10–20% relative RMS error) is achievable for both harmonic and earthquake input records only if OLI is performed at sufficiently high calibration amplitude. Large relative RMS errors should be expected when the calibration PGA is significantly smaller than the actual test PGA. At reasonable calibration PGA levels (i.e., amplitudes not posing too much risk to specimen during tuning), the relative RMS error ranges between 30–40% and 30–60% for the Sylmar and El Centro earthquake acceleration records, respectively.
2. For calibration PGA of the order of 7–8% g and at higher test PGA, the achieved platen peak acceleration can be 30% higher than the intended (reference) peak acceleration for earthquake tests and substantially higher (50–60%) for harmonic tests.
3. Elastic and inelastic (pseudoacceleration) constant ductility response spectra can be accurately reproduced if the calibration PGA is sufficiently high (e.g., calibration at 0.852-g PGA). In cases of low calibration PGA and high test PGA (e.g., calibration at 0.170-g PGA and testing at 0.852-g PGA for Sylmar record), the performance of the table in reproducing elastic (especially) and inelastic response spectra deteriorates and large errors may be observed in the period range below 0.2 s.
4. While it is possible to obtain an almost perfect replica of a harmonic acceleration input for a given calibration PGA by performing OLI, when the converged drive input corresponding to this calibration PGA is scaled up to another test PGA level, the signal fidelity deteriorates very quickly and large RMS errors and waveform distortions (due to the odd harmonics of the test frequency) are obtained. The same observation holds for the AHC compensation method available in the 469D controller. It can be concluded that shake tables are highly nonlinear systems and therefore a signal reproduction fidelity level achieved by tuning the table using a specific calibration amplitude cannot be maintained at a different test amplitude.
5. Sets of table seismic performance curves were derived using extensive shake table test results. These curves provide the shake table user with a quantitative guide to decide on the level of calibration PGA that should be used to achieve a desired level of signal reproduction fidelity for a given test PGA. The curves help us to resolve the crucial problem of balancing the increased risk of premature damage to specimens by increasing the calibration amplitude with the need for adequate signal reproduction fidelity.
6. The RMS amplitude of the WN acceleration input used for tuning the TVC parameters is also important for obtaining better signal reproduction fidelity as revealed by comparisons of the recent and earlier El Centro test results. A minimum RMS acceleration amplitude of 0.07–0.10 g appears to be necessary.
7. The level of shake table tuning achieved with the current state-of-the-art shake table controller of the NEES-UCSD table is highly dependent on the skills and the level of experience of the operator.
8. The results presented herein are based on bare table tests. The mass and other dynamic characteristics of the specimen also have a significant effect on the performance of the shake table.
9. The frequency content of the excitation also has an effect on the level of signal distortion. Significant distortions are found when the predominant frequency of the excitation or its odd multiples approach the oil column frequency.
10. Finally, the difficulties encountered when tuning at low table motion amplitude and testing at higher amplitude point to the need for (i) a virtual tuning tool based on an accurate and reliable mathematical model of the complete shake table system and, eventually, (ii) a more advanced controller based on the state-of-the-art in nonlinear and adaptive control.

Acknowledgments

The writers would like to thank Donald S. Morris, James Batti, Dan C. Radulescu, and Laurance T. Berman from the Englekirk Structural Engineering Center at Camp Elliot Field Station and Terry Nelson from MTS Systems Corporation for their contributions during the tests that produced the data used in this study. This work was supported by NEESinc through a NEES facility enhancement project. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect those of the sponsors.

References

Clark, A. (1983). "Sinusoidal and random motion analysis of mass loaded actuators and valves." *Proc., 39th Annual Meeting on National Conf. on Fluid Power*, Vol. XXXVII, Los Angeles.

Conte, J. P., and Trombetti, T. L. (2000). "Linear dynamic modeling of a uniaxial servo-hydraulic shaking table system." *Earthquake Eng. Struct. Dyn.*, 29(9), 1375–1404.

Crewe, A. J. (1998). "The characterization and optimization of earthquake shaking table performance." Ph.D. thesis, Univ. of Bristol.

Dyke, S. J., Spencer, B. J., Quast, P., and Sain, M. K. (1995). "Role of control-structure interaction in protective system design." *J. Eng. Mech.*, 121(2), 322–338.

Kusner, D. A., Rood, J. D., and Burton, G. W. (1992). "Signal reproduction fidelity of servohydraulic testing equipment." *Proc., 10th World Conf. on Earthquake Engineering*, Rotterdam, The Netherlands, 2683–2688.

Ozcelik, O., Luco, E. J., Conte, J. P., Trombetti, T. L., and Restrepo, J. I. (2008). "Experimental characterization, modeling and identification of the UCSD-NEES shake table mechanical system." *Earthquake Eng. Struct. Dyn.*, 37, 243–264.

Thoen, B. K. (2004). *469D seismic digital control software*, MTS.

Thoen, B. K., and Laplace, P. N. (2004). "Offline tuning of shaking table." *Proc. 13th World Conf. on Earthquake Engineering*, Aug. 1–6, Vancouver, B.C., Paper No. 960.

Van Den Einde, L., et al. (2004). "Development of the George E. Brown Jr. network for earthquake engineering simulation (NEES) large high performance outdoor shake table at the University of California, San Diego." *Proc. 13th World Conf. on Earthquake Engineering*, Aug. 1–6, Vancouver, B.C., Paper No. 3281.

Widrow, B., and Stearns, S. D. (1985). *Adaptive signal processing*, Prentice-Hall, Englewood Cliffs, N.J.

Williams, D. M., Williams, M. S., and Blakeborough, A. (2001). "Numerical modeling of a servohydraulic testing system for structures." *J. Eng. Mech.*, 127(8), 816–827.

Zhao, J., Shield, C., French, C., and Posbergh, T. (2005). "Nonlinear system modeling and velocity feedback compensation for effective force testing." *J. Eng. Mech.*, 131(3), 244–253.