Development of a digitally-controlled three-axis earthquake shake table

S. Ammanagi, V. Poornima, A. Sera and R. Sunder*

BiSS Research, 41A, 1A Cross, AECS 2nd Stage, RMV Extension, Bangalore 560 094, India

An eight-actuator shake table was developed for evaluating specimen response under conditions that closely simulate actual earthquakes. The system contains a number of unique hardware and software features that considerably reduce the cost of earthquake simulation testing. These include single-ended actuator assemblies, contamination-insensitive servo-hydraulics and a robust DSP-based control and data acquisition system. Tests to simulate a number of three-axis earthquake time histories appear to suggest satisfactory table response.

Keywords: Earthquake simulation, multi-channel servo-control, three-axis shake table, 6-DOF motion control.

CIVIL constructions and engineering structures are designed to withstand a variety of operational loads and environmental conditions over decades of safe and economic usage. Earthquakes are part of this environment. Apart from destruction of life and property, they can have serious indirect consequences. Quake-induced damage to the controls of a nuclear power reactor may lead to meltdown with catastrophic consequences. Advances in numerical simulation permit virtual rendering of different scenarios in order to minimize the hazards associated with earthquake-related mishaps. However, the complex nature of material and system response combined with a variety of potential failure modes, restricts the reliability of virtual simulation. Regulatory authorities therefore stipulate tests on real structures and components under simulated conditions of concern to validate structural integrity.

A structure in the vicinity of an earthquake will experience random vibrations caused by the movement of its foundation. One may assume similar response if the base of the structure is shaken in a laboratory environment using the acceleration – time history recorded during the earthquake. By the same token, laboratory reproduction of associated displacement – time history would also have the same effect. This is the basis for the application of three-axis shake tables to earthquake simulation.

A single-axis shake table that can handle a test payload of about 1000 kg costs about US $120,000 and can be readily purchased in the global market. A three-axis earthquake shake table for the same payload may cost much more than US $1,000,000. National laboratories set aside as much as US $5,000,000 or more to set up earthquake test facilities. Even this amount is a small fraction of the investment made on the development of the world's largest 1200 ton shake table in Japan[1].

Cost of equipment affects cost of testing. More expensive testing increases the installed cost of safety-critical equipment. The taxpayer eventually bears the burden by paying more for related products and services. The team at BiSS Research, Bangalore was motivated by this opportunity and embarked on an in-house and internally funded R&D effort in 2003 to come up with a country-specific solution to three-axis earthquake testing. This facility was recently installed at the Indian Institute of Science (IISc), Bangalore as part of the National Programme on Education in Earthquake Engineering (NPEEE). Table 1 summarizes the specifications of the same.

The next section explains the concept behind three-axis earthquake simulation. This is followed by the description of the different components that make up the test system. Sample test results from simulation of actual three-axis earthquake histories recorded in El Centro (California), Kalamata (Greece) and Chi Chi (Taiwan) are shown to compare favourably with data from overseas test centres[2]. Problems faced during development and scope and implications of future work are described.

Table 1. Specifications of the shake table installed at IISc, Bangalore

Description	Value
Table size (m)	1 × 1
Table mass (kg)	170
Maximum specimen mass (t)	0.5
Maximum specimen, c.g. height (m)	0.5
Controlled degrees of freedom	6
Translation and rotation	*X*, *Y* and *Z*
Longitudinal (*X*) or lateral (*Y*)	
± Displacement (mm)	220
± Velocity (m/s)	0.57
± Acceleration (*g*) – full payload	2.0 (3 g empty)
Vertical (*Z*)	
± Displacement (mm)	100
± Velocity (m/s)	0.57
± Acceleration (*g*) – full payload	2.0 (3 g empty)

*For correspondence. (e-mail: r.sunder@vsnl.com)

Concept of three-axis earthquake shake table

Consider a plane represented by the triangle ABC shown in Figure 1. It may also be viewed as a shake table uniquely positioned in space, whose position and orientation are uniquely defined by the spatial coordinates x, y, z of points A, B, C. The three-axis translational or rotational movement of the table, or a combination of the two can be uniquely defined by a set of nine equations that describe variation of x, y and z versus time for the points A, B and C.

Let us now consider the same table ABC 'fastened' through straight and flexible links (the equivalent of telescoping legs on a camera tripod) to fixed points D, E, F, G, H and I as shown in Figure 2 *a*. As seen in Figure 2 *b* and *c*, these six points are on the stationary ground plane, while the table ABC is free to move as shown in translational motion (Figure 2 *b* and *c*) or rotational (as in Figure 2 *d*). The two 'stretchable' legs AD and AE connect point A to ground, while BF, BG and CH, CI likewise connect points B and C respectively, to the ground. Note that these legs can only extend or retract. They cannot flex.

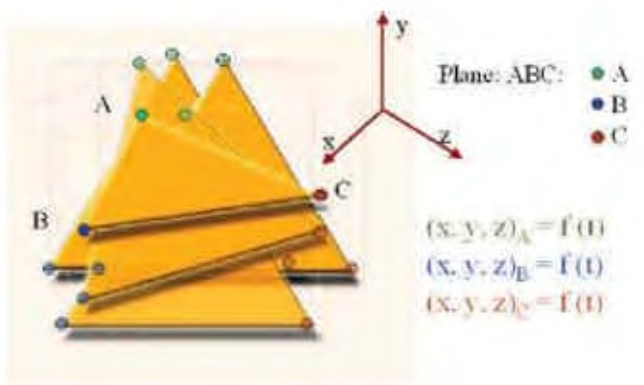

Figure 1. Concept behind a three-axis shake table for earthquake simulation. The position of plane ABC in space is adequately represented by the spatial coordinates of ABC. Consequently, any translational or rotational movement of the plane is adequately described by equations of motion in space of A, B and C. Thus, a total of nine time functions (X, Y and Z-axis motion of A, B, C) subject to the constraint of fixed distance between A, B and C determine spatial motion.

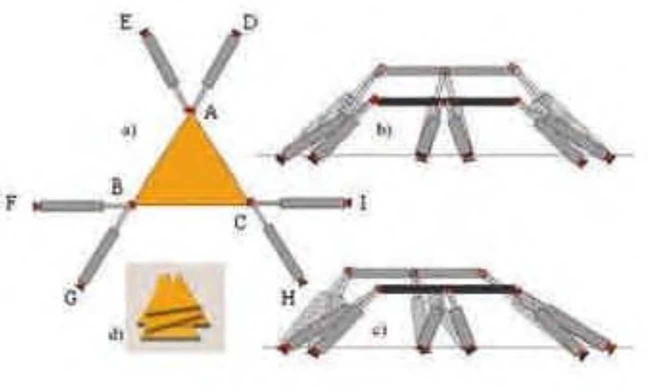

Figure 2. Schematic of the underlying concept behind a Stewart table[3]. The six actuators shown represent the minimum number of axial actuators required for translational as well as rotational table motion. Stewart tables are widely used in simulators, but do not seem to be popular in earthquake simulation studies.

If the table is moved to any desired point within the above envelope, instantaneous length of each of the six legs is readily computed from the spatial coordinates of points A–I. Conversely, the table position is uniquely determined from the lengths of the six legs. This is the operational concept behind the so-called Stewart table[3].

A Stewart table is mounted on six servo-controlled linear actuators whose individual strokes determine the table position. Servo-control is employed to ensure precision extension or retraction of the actuator rod. A transducer such as an LVDT provides continuous rod position feedback. The difference between required and actual position drives a servo that will move the rod in the direction that will reduce this difference.

Stewart tables of low and moderate performance and payload typically use linear-electric actuation. The rest are servo-hydraulic. Among the several advantages of servo-hydraulic actuation are high instantaneous energy availability that permits unmatched force and performance ratings. Also, servo-hydraulics can achieve direction reversal specifications that cannot be matched by electrical drives. It is not surprising therefore that earthquake shake tables are typically driven by servo-hydraulics.

Figure 3 shows a prototype Stewart platform developed at BiSS. This was the original design proposed for the IISc project. All the building blocks required for the IISc project were developed, tested and fine-tuned on the BiSS Stewart table. These included the hydraulic pump and piping, the servo-actuator assemblies and most importantly, the multi-channel control hardware and software at the heart of multi-axis earthquake simulation technology.

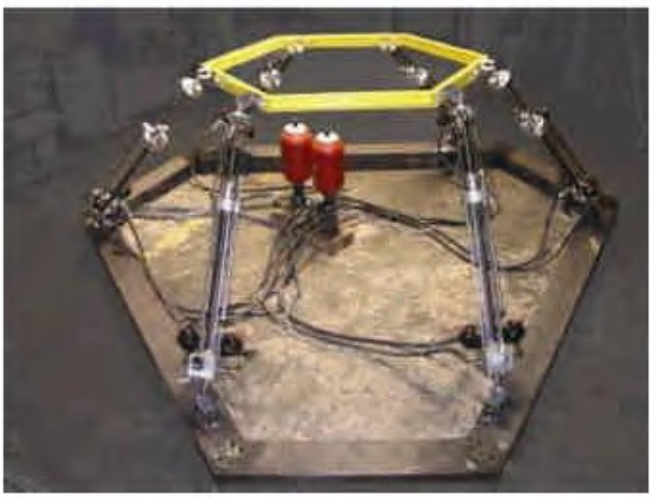

Figure 3. Stewart table technology demonstrator developed at BiSS Research, Bangalore.

The BiSS Stewart table demonstrated synchronous dynamic control of multiple actuators with real-time digital servo-loop update of 8 kHz, incorporating required multichannel control waveform generation, data acquisition, safety interlocks, etc. In doing so, several technological problems had to be overcome, many of which have been discussed in the literature[2,4–7].

Stewart tables are equally capable of both translational as well as rotational motion. Translational movement typically dominates earthquake spectra. Though it was operational in 2003 and capable of all the movements associated with earthquake simulation, the Stewart table configuration was eventually discarded in favour of the 'classical' eight-actuator design. In earthquake simulation applications, the rotational capability of the Stewart table is not fully exploited. This may explain why Stewart tables are not used in earthquake simulation[2].

Three-axis earthquake shake table at IISc

The schematic of a classical three-axis earthquake shake table is given in Figure 4. Most tables around the world use this configuration. This was the design adopted for the IISc project. Unlike the Stewart table, it carries actuators aligned along the three directions of potential table movement. Thus, we have two actuators each, aligned along the X and the Y-axis and four positioned along the Z (vertical) axis. These four resemble the legs of a table.

The horizontal actuators along X and Y-axis are placed in opposing configuration. This enhances control of table rotation without compromising translational movement capability.

Figure 5 shows a photograph of the IISc table installation. The table and actuator assembly are mounted on a reinforced concrete foundation that is isolated from the laboratory floor. Table position is more or less level with the laboratory floor to facilitate payload location. A unique feature of the facility is that the entire hydraulic drive including pump and accumulators are housed within the pit, making it extremely compact and easy to maintain, apart from cost savings by avoiding additional enclosures, piping, sub-stations, etc. A single catering manifold with oversize flow sections and 60 L accumulator charge is located right under the table (Figure 5) to connect the pressure and return line hosing to the eight actuators around it.

All eight actuators are mounted with 24 lpm contamination-insensitive direct-drive (DDV) Bosch servo-valves that provide for a maximum table velocity of 0.6 m/s in any single direction and up to 0.85 m/s along a diagonal. Thus, the maximum possible cumulative flow would be 192 lpm. However, under actual earthquake spectra, required flow is unlikely to exceed about 90 lpm as table movement is largely restricted to the horizontal direction and also considering that maximum flow requirement during actuator rod retraction reduces by about 35%. Keeping these in view, the facility was equipped with a 65 lpm servo-controlled variable frequency pump. This feature saves power in two ways: by avoiding excess oil flow altogether and further, by avoiding power consumption to cool the excess oil thus heated. Energy consumption for the entire facility reduces to less than 10 kVA under idling conditions and peaks at about 40 kVA during those few moments that the pump needs to deliver its peak flow of 65 lpm. A conventional table of comparable specification would demand a connected load of at least 100 kVA.

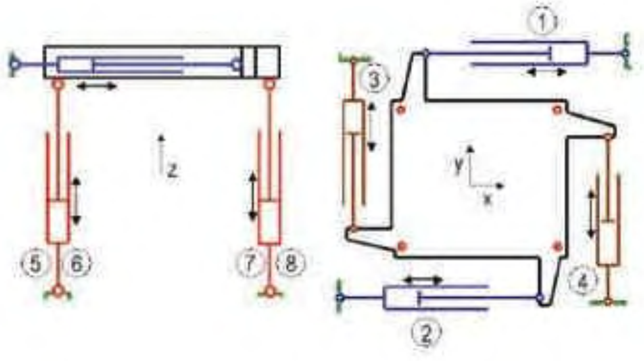

Figure 4. Schematic of eight-actuator shake table for three-axis earthquake simulation. Four vertical actuators (5–8) are shown in red. X-axis movement is provided by actuators 1, 2 (blue), while actuators 3, 4 (brown) provide Y-axis movement. Any table movement including translation and rotation will demand precision movement of all eight actuators. Failure to meet this requirement will cause extreme internal forces within the system induced by physical constraint imposed by the rigid table assembly.

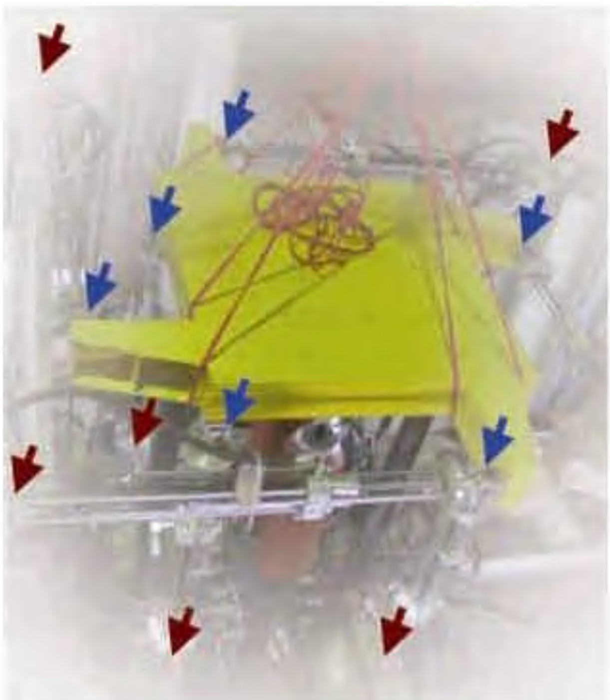

Figure 5. Eight-actuator three-axis earthquake shake table being installed at Civil Engineering Department, Indian Institute of Science, Bangalore. Blue arrows point to visible table-end mounting points of actuators, while brown arrows point to base end.

The table as shown in Figure 5 is of 1000×1000 mm size and designed for a payload of up to 500 kg that can be bolted down rigidly for the experiment. The four horizontal actuators are of ± 250 mm stroke, while the four vertical actuators carry ± 150 mm stroke. Thus, the table can move in excess of 450 mm along the X and Y axis or almost 700 mm along the diagonal. This stroke range is about 50% greater than most tables described in the literature, including those operational in the country.

Conventional shake tables use two-stage servo-valves, which by nature are extremely sensitive to contamination. The actuators on the IISc shake table are driven by DDVs. Over the years, it has emerged that DDVs are best suited to Indian operational environment that is characterized by dust, dirt and relatively rough handling. With relaxed filtration requirements and zero maintenance, the DDV solution increases reliability at reduced cost.

Servo-actuator design

The large stroke range combined with low force rating raised serious problems related to lateral stiffness and potential buckling. In order to reduce actuator length, we chose single-ended double-acting actuator design, where the effective cross-section on either side of the piston is unequal. In compression, they develop a force of 15 kN, while in tension, the rating drops by about 40%. This implies unequal servo-response in tension and compression, essentially meaning that in compression, actuator movement will be 40% more sluggish than in tension, given constant servo-gain settings. This shortcoming was overcome by suitable changes to the digital servo-loop control algorithm in order to render actuator response identical in both directions.

For the vertical actuators, the single-ended solution actually turns into an advantage considering that in vertical motion, one has always to contend with 1 g load acting downwards due to gravity – it does help to have a greater force rating in compression, which single-ended actuators do by design.

A fundamental assumption in shake table design is that all actuators only see axial loading. This is guaranteed by ensuring three-DOF of rotation at either mounting end using suitable spherical joint bearings. Any violation of this assumption due to fouling at extreme positions or bearing seizure is likely to cause side loads that will damage actuator seals. Unfortunately, one still needs to contend with inevitable side loads induced by lateral oscillation of the actuator.

During horizontal table movement in the X or Y-axis, two actuators will remain stationary (only their rods will extend or retract), while the remaining six actuators will see negligible rod movement, but considerable lateral oscillation. During vertical table movement, the four vertical actuators will remain stationary, while all four horizontal actuators will see considerable lateral oscillation. The inertia loads due to lateral oscillation will be borne by the actuator assembly and be seen as side loads on the seals and bending moments, tending to flex the actuator assembly. In order to minimize this component, the actuators are equipped with light-weight Al-alloy heads and heavier components moved to the base area.

All the above measures contributed to a high-stroke, high performance table of relatively low payload. Initial experience suggests that the rig itself, including hydraulics and servo-actuators withstands the consequences of continuous movement and oscillation during earthquake simulation testing. However, under harmonic vibrations, it was found that resonance frequency is closely related to instantaneous system stiffness that in turn is determined by the extent to which actuators are extended. Thus, resonance frequency increased from 15 Hz at mid position to in excess of 50 Hz when initial table position is selected to correspond to retracted actuator rods. This is the position when table is lowered in height and rotated clockwise.

The eight-actuator configuration may appear to be best suited to earthquake simulation. However, it has its disadvantages. For a start, it requires eight servo-actuators as opposed to six for the Stewart table. This implies a 30% increase in hardware cost including real-time controls. An even more serious problem is associated with structural response constraint imposed by the two additional actuators.

The problem of structural constraint

Consider the case of a four-legged table as opposed to a tripod. The stability of a tripod is not affected by small differences in the length of its legs. In contrast, a four-legged table with the same problem would be unstable, requiring the shims one inserts under the shorter leg to keep the table steady. An imperfect table or floor leads to the table being wobbly as one of the legs momentarily loses contact with the floor. Imagine for a moment the prospect of the four legs being rigidly fastened to the floor. In this event, any imperfection would lead to proportional internal forces within the table. Equilibrium will demand a combination of stretching one or two legs, compression of the others and flexing of the table surface itself. If table stiffness is negligible, the forces developed will also be negligible in view of decreased resistance to bridge the geometric imperfections. However, earthquake shake tables are designed to be extremely stiff. As a consequence, any error in positioning one or more actuators or any error in spatial coordinates or a combination of the two, will cause extreme loads – even if there is no payload on the table. Individual servo-actuators on an earthquake simulator can thus see very high forces caused exclusively by geometric errors in their movement, or in computed coordinates.

The above forces are induced by structural constraint, are independent of payload and appear unavoidable in engineering practice. They will have a static component associated with error under static conditions. In addition, they will also have a dynamic component due to instantaneous errors during table movement. Given the high stiffness of the hardware, one may assume that these forces will be determined by the combination of two significant parameters. These are actuator position, as it determines oil volume in the cylinder along with its stiffness, and position error, as it determines oil pressure in the cylinder as driven by accumulating oil. The latter is driven by instantaneous position error and servo-gain settings. These two components from all eight actuators will interact with each other and also with the inertia component from table and payload to induce undesirable vibrations and loss of payload capacity.

Stewart tables will not face the above problem because, for any position of each its six actuators, there will be a unique position of the table. However, in eight-actuator earthquake shake tables, the reverse applies: a unique combination of the extension of the eight actuators is essential for a given table position. As structural constraint inhibits geometric adjustments to overcome errors, position errors will necessarily translate into internal forces. These forces can impose a visible 'trembling' of the table as it moves, or sometimes, even when stationary, as the actuators literally work against each other[2], rather than together. The problem turns particularly frustrating when it combines with oil column resonance to magnify the effect of even small position errors. Note that internal forces can by themselves cause position errors even in those actuators that would, in free condition, move without error. Combine this with the prospect of variable actuator stiffness as a function of rod extension (due to variable oil volume) and the problem becomes even more formidable.

In the case of the eight-actuator earthquake shake table, one has to deal with the spatial coordinates of the eight mounting points of actuators combined with the assembled variable length of each of the eight actuators. Engineering implementation of these is determined by geometric tolerances in civil engineering associated with the base structure as well as the machining and assembly-level dimensional tolerances. The distance between the actuator mounting points is determined by the cumulative length of the bearings at the two ends, the threaded connectors between the mounts and the actuator, and the length of the actuator itself. These together will contribute to a systematic error in spatial coordinates.

In Figure 5, showing a photograph of the table installation at IISc, the blue arrows point to the visible table-end mounting points of the actuators, while the brown arrows show the base-end mounting points. This figure illustrates how difficult it may be to translate into engineering practice, dimensional tolerances as envisaged by the drawings. This problem was resolved by introducing flexibility into the software for adjusting actual dimensions at system set-up and incorporating those into the application software.

Link length (distance between actuator mounting points) is controlled by actuator rod extension. Position error caused by this component will be the sum of position transducer feedback error and servo-control error (difference between desired and actual rod position during table movement). Transducer feedback error comes from scale, offset and linearity components that theoretically accrue from errors in transducer response and noise in electronics and data acquisition. Analogue transducers are used to sense actuator position. Their specifications are related to full-scale. Thus, measurement error as well as signal noise will increase with stroke range.

A process was established for iterative correction of spatial coordinates of fixed-base mounting points, length of actuator assemblies (that can change depending on threading coverage on connectors) and feedback transducer calibration as well as linearization. This process takes several hours and must be repeated each time any actuator assembly is replaced or relocated on the test rig. Typical actuator position errors in actual testing were of the order of 0.05 mm.

General laboratory instrumentation employs active filters with low cut-off frequency to improve the quality of acquired data. The ability to do this on transducers that serve as servo-feedbacks is limited by the very nature of servo-control. Filtering in instrumentation is accompanied by phase lag and this can adversely affect servo response by adding to the servo phase lag and thereby limiting servo response. Therefore, even though limit frequency of the table was set to 50 Hz, the eight-pole filter cut-off frequency on actuator stroke feedback was set at 2 kHz.

All the above measures helped reduce real-time table position error down to less than 0.3 mm under static table positions at different points on the spatial table movement envelope. Bringing position error to within this margin relieves internal forces. This was confirmed by free rotation of all eight actuators at any table position at high hydraulic pressure as an indication that abnormal internal loads were absent.

A digital rendering of conventional PID control scheme was initially employed for servo control. All eight-actuators were independently servo-tuned with the rod-end disconnected from the table. The table was then connected. While there appeared to be no problem under static conditions, initiation of any table movement invariably caused a certain trembling of the table, which sometimes appeared to multiply by resonance. It was apparent that the problem of structural constraint imposed by the eight-actuator solution needs to be subdued under dynamic conditions. And obviously, conventional PID control scheme was not adequate for the purpose. A new real-time control algorithm was developed, whose description is forthcoming.

Control and data acquisition scheme

The BiSS 2350 Open Architecture Digital Signal Processor (DSP)-based controller was employed as the control and data acquisition system for the shake table. The unit is built around a TMS 3205402 100 MIPs 16-bit DSP and eight independent channels of 16-bit analog codecs I/O at up to 22 kHz. The 2350 controller includes a motherboard with a bus onto which up to six plug-in cards can be connected. The motherboard contains all the basic hardware required to connect to power drives, including servo-hydraulics, digital I/O drives to control and monitor external devices and a watchdog timer for emergency shut down in the unlikely event of a system crash. The plug-in cards contain signal conditioning and provision for acquisition of additional signal channels.

For the IISc shake table, the 2350 controller is configured with 24 channels of analogue data acquisition along with eight channels of control waveform generation and LVDT signal conditioning in order to control and track table movement. The remaining channels are connected to BiSS MEMS accelerometers mounted at different locations on the table to track three-axis acceleration history. The 2350 controller is housed in a box the size of a desktop PC. It is connected to an industry standard PC on an MS-Windows platform. Shake table operation is controlled by two CPUs working together in real-time. The DSP on the 2350 controller performs true real-time operations, including data acquisition across 24 input channels, set point generation and 32-bit digital servo-loop update computations, digital I/O sense and real-time monitoring of multiple safety interlocks, primarily related to limit position of the servo-actuators. Servo-loop update is performed at 6 to 8 kHz on each of the actuators, which compares favourably with most single channel systems in the market.

The embedded real-time code running on the DSP is downloaded at start-up time from the PC through a USB cable. The same interface is used for real-time data transfer during table operation.

The application program running on the PC operates in real-time, but is asynchronous with respect to the shake table. Thus, while the 2350 clocks its own operations strictly in sync with the 6 to 8 kHz loop update schedule, the application program on the PC exchanges data packets with the controller at not more than 2–5 Hz. Ring buffers at both ends bridge the time difference between the two. This relaxes real-time demands on the PC and the application software can therefore operate in the MS-Windows time-sharing environment that most users are comfortable with.

A custom earthquake shake table application was developed to meet specific requirements of shake table operation. This includes code for transformation of table position to actuator rod extension (referred to as inverse kinematic problem[2]), transformation of actuator position readouts to table position (referred to as direct kinematic problem) and real-time control waveform generation for three-axis table translation in harmonics or in accordance with available or synthesized three-axis earthquake displacement-time histories. The transformation process was also set up to convert acceleration and velocity-time histories to displacement-time history, which is the mode of control of the shake table.

The features described above constitute a rudimentary framework to permit three-axis seismic testing closely simulating actual earthquakes with full 6-DOF movement control. By implication, performance of the real-time software already in place will not be affected by the complexity of future table movement requirements, provided they fall within the known performance envelope of the system.

Finally, one may note that multiple 2350 controllers can be connected to the USB bus for modular expansion of system data acquisition capability. This will enable testing of larger structural assemblies incorporating multipoint three-axis accelerometers and strain bridges.

Servo-control algorithm for eight-actuator shake table

Most conventional servo-hydraulic actuators are controlled by the classical PID scheme. The P (proportional) component is given by the product of P-gain and instantaneous loop error. Loop error is the difference between required and achieved feedback readout. The I-component is the product of I-gain and the error function integrated over a time interval representing system time constant. The D-component is the product of D-gain and derivative of the error versus time function. The P-component is typically adequate in many quasi-static applications. The I-component improves system dynamic response and the D-component serves as mass compensation by attenuating system response to avoid oscillations associated with hunting.

Over the few decades that earthquake simulators have been built, considerable development effort has progressed to improve table performance[3]. From a servo-control viewpoint, earthquake shake tables are distinctly different from other applications in more than one way. To start with, the focus in servo-control is on displacement, while the focus of earthquake simulation is on acceleration history. Although acceleration is theoretically related to displacement, immense noise as well as error is introduced by the very nature of the latter being the second derivative of the former. By implication, it is theoretically impossible to get the same quality of acceleration control as seen in displacement response. Thus, the acceleration trace under simple sinusoidal servo-controlled displacement will barely resemble a sine wave. The poor quality of the acceleration waveform is in fact accentuated at lower frequencies where servo-control is more precise and in fact, far improved at higher frequency where the reverse is true of control quality. This paradox may be explained by the very nature of table response, whereby, as frequency increases, the table begins to act as a damper, thereby smoothening out its own acceleration response.

The other distinct feature of shake tables is that they involve the combined response of several rigidly connected actuators. Thus, while each of the eight actuators may be independently controlled, they are capable of distorting each other's response.

The first problem has been addressed in the literature by adding velocity and acceleration components to the PID loop[2]. Further improvements have been claimed by the introduction of the so-called MCS algorithm, with specific application to shake tables[5,7]. In fact, it has been shown that implementation of the MCS algorithm considerably improves table performance in two ways. It improves waveform fidelity by reproducing the required displacement time history more faithfully. Further, it has been shown that the phase lag between required and achieved waveform is reduced to about 70–80 ms. However, it is not clear how the MCS algorithm addresses crosstalk between actuators, which is the natural consequence of making the system structurally constrained.

Our development process was driven by the identification of the significance of structural constraint. The existing PID scheme appeared to work excellently with the actuators disconnected from the table. In fact, we were able to achieve a phase lag as low as 50 ms across all eight channels, which compares favourably with the best reported in the literature. However, the moment all eight actuators were connected to the table, the system would go into a deafening resonance, sometimes even under static conditions. This was somewhat relieved by reduced overall gains, whereby phase lag doubled but the table remained steady. However, at the onset of any table movement, an audible trembling would occur, as mentioned previously. This would be subdued by further reduction in gains, leading to more increase in phase lag.

The above response was highly reproducible, suggesting the need to minimize actuator crosstalk through reduction or elimination of the effect of structural constraint. The objective was to come up with a superior servo-loop update procedure that would give more number of gain settings to play with, so that static as well as dynamic and both high as well as low frequency response could be handled in order to improve the precision of dynamic servo-control.

In an attempt to improve servo response, we replaced the PID scheme with the pseudo-derivative feedback (PDF) scheme proposed by Phelan[8]. This scheme includes just two components that are simple to implement: integral gain as in PID and pseudo-derivative feedback, which is a derivative of the feedback itself (rather than of error as in PID). Previous work had demonstrated the efficacy of this scheme in servo-hydraulics[9]. To improve dynamic response under low amplitude and high frequency, a velocity-sensitive component was added. Finally, the system servo-equation was rendered nonlinear by introducing a component that increases system response at higher error, while avoiding the noise-jitter associated with high gain at low frequency or under static conditions.

Table response appeared to improve dramatically after these changes were introduced. Under static conditions, position error readouts on individual actuators are typically under 0.1 mm. It will be seen from actual table movement waveforms that under dynamic conditions simulating actual earthquakes, table position error seldom exceeds 0.5 mm, while phase lag remains as low as 30 ms, which appears lower than those reported in the literature.

It may be noted that the corrections mentioned above are performed at the point of system assembly or re-assembly after repair. No further tuning appears necessary in actual earthquake simulation testing with or without payload. This seems to be an improvement over many existing tables[2]. All the test results presented below were obtained without any readjustment of system settings, including servo-gain constants.

Three-axis table response under constant amplitude cycling

Constant amplitude cycling was used to tune servo-response in all three-axes before proceeding to actual earthquake histories. Good displacement response was obtained over

Figure 6. Control cabin (background) and pit with shake table (foreground). Controller containing electronics and DSP (1) and host computer (2) for the test facility.

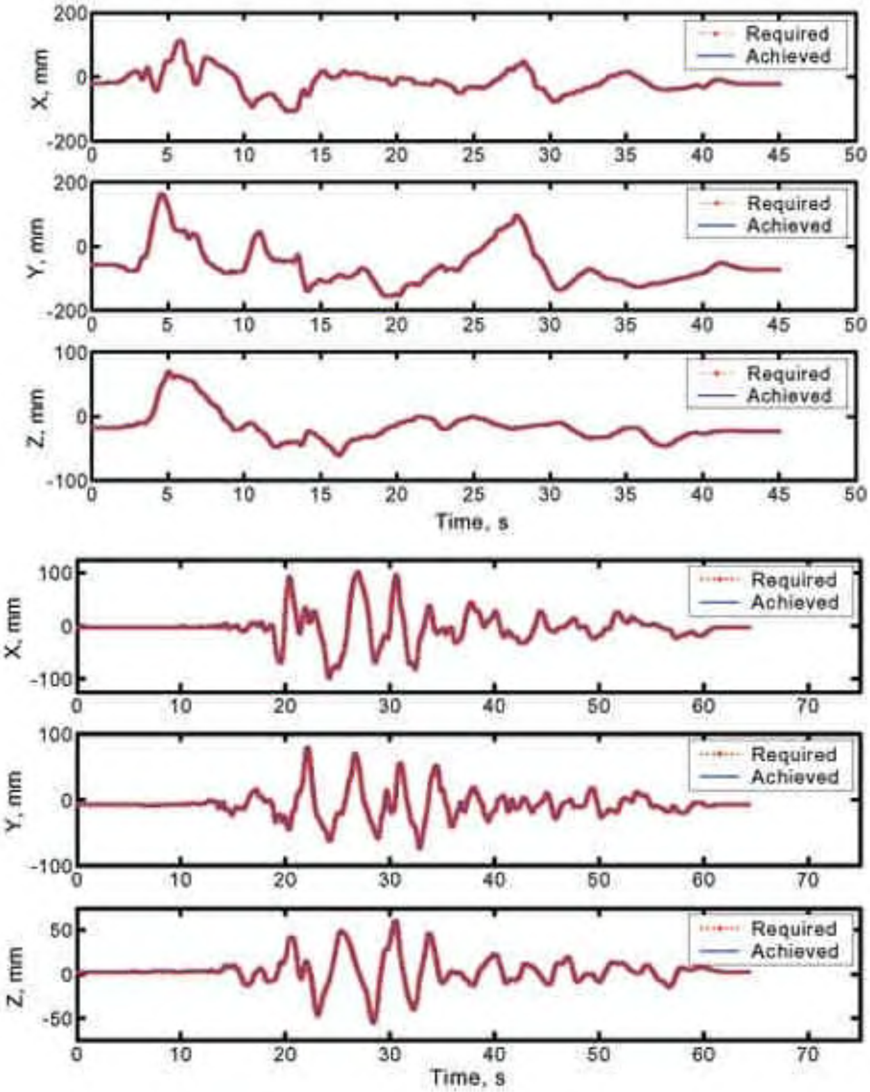

Figure 7. Three-axis table response computed from actuator position. (Top) El Centro (bottom) Chi-Chi. These are 'first shot' responses with payload after initial tuning without payload under harmonic movement.

a wide bandwidth of amplitude and frequency without having to modify servo-gain settings. Thus, near-perfect response in all three axes was obtained under large amplitude and small frequency, that was also by far, the least sensitive to small changes in servo-settings. It also did not seem to matter whether all three axes were active, or just one. Also, phase between oscillations along different axes did not seem to matter. However, when viewed in terms of acceleration, the signal appears noisy, which does not come as a surprise given the experience of other workers in the area. These observations relate to oscillations in excess of 30 mm stroke and less than 3 Hz frequency.

As frequency goes up and amplitude comes down, table response becomes more and more sensitive to the feed-forward and derivative gain components of the servo settings. This is not altogether unexpected given that rate sensitivity increases with frequency at a constant time interval for numerical differentiation. With increasing frequency, quality of the acceleration signal improves to take a clean, sinusoidal shape, as opposed to the noisy and spiky waveform at lower frequency.

At frequency below 10 Hz, negligible crosstalk was observed between the three axes. When the table is oscillated along any one axis, there is hardly any perceptible oscillation along the other two axes. With increasing frequency visible crosstalk emerges. As described earlier this may be reduced to under 5–10% by suitably selecting initial table position. One may note that accelerometers used to evaluate table performance are also prone to about 5% crosstalk. One may note that this crosstalk emanates from two sources. One is flexing of the actuator. The major component accrues from the lateral oscil-

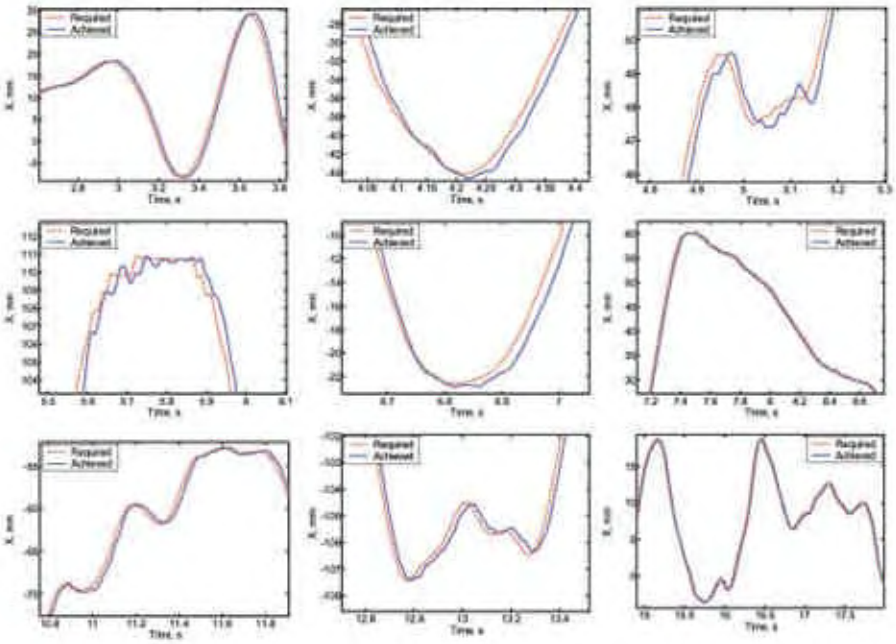

Figure 8. Zoomed-in transient segments at turning points on the El Centro *X*-axis displacement-time history. Time lag of about 30 ms and displacement error less than 0.5 appear to suggest table response that compares favourably with those reported elsewhere[2].

Table 2. Chebyshev type-II digital filter characteristics used in processing acquired data

Test		Filter characteristics			
		N	R	LP	HP
El Centro	*X*	4	40	0.2	15
	Y	4	40	0.2	15
	Z	4	40	0.2	15
Chi-Chi	*X*	3	60	0.1	30
	Y	3	60	0.14	40
	Z	3	60	0.14	40
Kalamata	*X*	4	50	0.25	50
	Y	4	50	0.25	50
	Z	4	50	0.25	50

lation of the LVDT core. This induces an oscillation in position feedback signal, which in turn causes 'unsolicited' table oscillation as the servo-algorithm responds to 'correct' erroneously perceived servo-error. Nylon guides were introduced to dampen LVDT core vibrations.

Lateral oscillation of actuators is inevitable in a three-axes shake table. In order to minimize or eliminate its adverse effect on the quality of testing and also on the durability of the rig itself, several options may be independently pursued. The problem is bound to become less severe with increasing table payload as actuators get 'fatter' without getting longer, thereby becoming more immune to the effect of lateral oscillation. One may explore the possibility of reducing stroke specification if table payload is low. Finally, use of a displacement transducer that is immune to the effect of lateral oscillation would considerably improve table performance. It may be noted however, that table operation under many actual earthquake spectra is unlikely to see much crosstalk between axes because of the absence of a substantial high-frequency component. This appears to be the case with all three spectra whose test results appear below.

Three-axis table response under El Centro and Chi-Chi earthquake spectra

Results from tests under three different earthquake spectra are presented below. These were obtained using a 350 kg flexible payload. These are 'first-shot' results without any iterative tuning. The El Centro and Kalamata earthquake spectra were chosen because they had been used in a comprehensive review of different shake tables[2]. The Chi-Chi earthquake was selected because it is also severe and involves considerable movement along all three axes. In case of the El Centro and Chi-Chi spectra, the payload was mounted on a steel frame of $450 \times 450 \times 450$ mm with estimated natural frequency of about 13 Hz. This was expected to investigate payload-table interaction. In case of the Kalamata spectrum, the payload was hard-fastened to the table.

Figure 7 shows the required and achieved El Centro and Chi-Chi displacement-time history along all three axes. Not shown is the Kalamata spectrum, whose response was also of the same quality.

Table 3. Maximum response error for peak value of displacement and acceleration

	Maximum time history error (%)					
	X		*Y*		*Z*	
Test	Acceleration	Displacement	Acceleration	Displacement	Acceleration	Displacement
El Centro	33.0579	0.0344	36.6842	0.8281	30.7190	0.5494
Chi-Chi	2.2356	0.1200	12.0278	0.3961	128.2419	0.2922
Kalamata	31.4215	0.1812	91.3470	3.9275	11.1933	0.9021

Table 4. Resonance frequencies of the table at flexible payload of 350 kg

Axis	Frequency (Hz)
X	21.85
Y	22.75
Z	24.76

Table response in terms of displacement-time history appears to compare favourably with that obtained under similar spectra by other workers[2]. This applies to all three earthquake spectra. Excellent table response is confirmed by zoomed-in segments of required versus achieved displacement-time history that appears as Figure 8. The error at any point does not exceed 0.5 mm, which would be 0.25% of actuator stroke. This appears to compare favourably with available data from the literature[2]. The phase lag between required and achieved table movement waveform is under 30 ms, which is less than half of that reported by other authors[2].

Figures 9–11 show table response for the three spectra in terms of acceleration. Shown in the figures are original data, processed data from BiSS MEMS accelerometers mounted on the table as well as from data obtained as second derivative of measured displacement-time history.

Table 2 lists the filter settings used in processing acceleration data. Table 3 lists the maximum percentage errors in table response measured for peak displacement and acceleration data. Table 4 lists the table resonance frequencies based on analysis of table response.

These data appear to compare well with those reported in the literature for the El Centro and Kalamata spectra. A more complete picture will emerge as variations in spectra and payloads as well as introduction of rotational component are investigated.

In summary, one may note the excellent displacement-history response obtained as indicated in Table 3 that shows a maximum 4% error in table position – considering particularly that no re-adjustment of system settings was involved. At the same time, while the maximum acceleration error of 120% may be comparable with those reported in the literature, it does underscore the scope for future improvement. Further, one may note that the acceleration-history response shown in Figures 9–11 involved a subjective element by way of filter settings listed in Table 2. This cannot be avoided in the absence of a standard practice for benchmarking that would also include specification of signal acquisition quality and post-processing.

Discussion

The shake table controls are based on a low-end digital signal processor that is widely used in consumer electronics and therefore is inexpensive, readily available, not subject to any dual-use embargoes and likely to be in production for at least the next ten years. Other unique features of the technology are the use of single-ended, double-acting actuators, contamination-insensitive industrial servo-hydraulics and energy-efficient hydraulic drive. All these together add up to a technology that makes three-axis, six-DOF seismic testing much more accessible and affordable than was hitherto possible. It may be noted that the building blocks of both hardware and software used on the IISc shake table are the same as in other single as well as *n*-channel test control applications from BiSS Research. Apart from reducing the set-up cost of the system, this ‘open architecture’ design approach also implies reduced cost and superior support for other *n*-channel applications including Stewart tables and multi-poster test rigs for automobiles, railway coaches, etc.

There appears to be much scope for future improvement and enhancement. There are no apparent obstacles in scaling up the new technology to higher table payloads. Going by the actual expenditure incurred towards the IISc project, tables with payload of 5000 to 50,000 kg can be profitably constructed at a fraction of prevailing cost. This would imply considerable direct benefits to the taxpayer and the potential for much wider public access to the technology of three-axis earthquake simulation.

Conclusion

- A three-axis, six-DOF, 500 kg payload earthquake shake table was developed using eight 15 kN, 300–500 mm stroke single-ended double-acting actuators.
- Table movement is digitally controlled by a DSP-based controller performing up to 6000 servo-loop updates a second on all eight channels. Servo gain settings re-

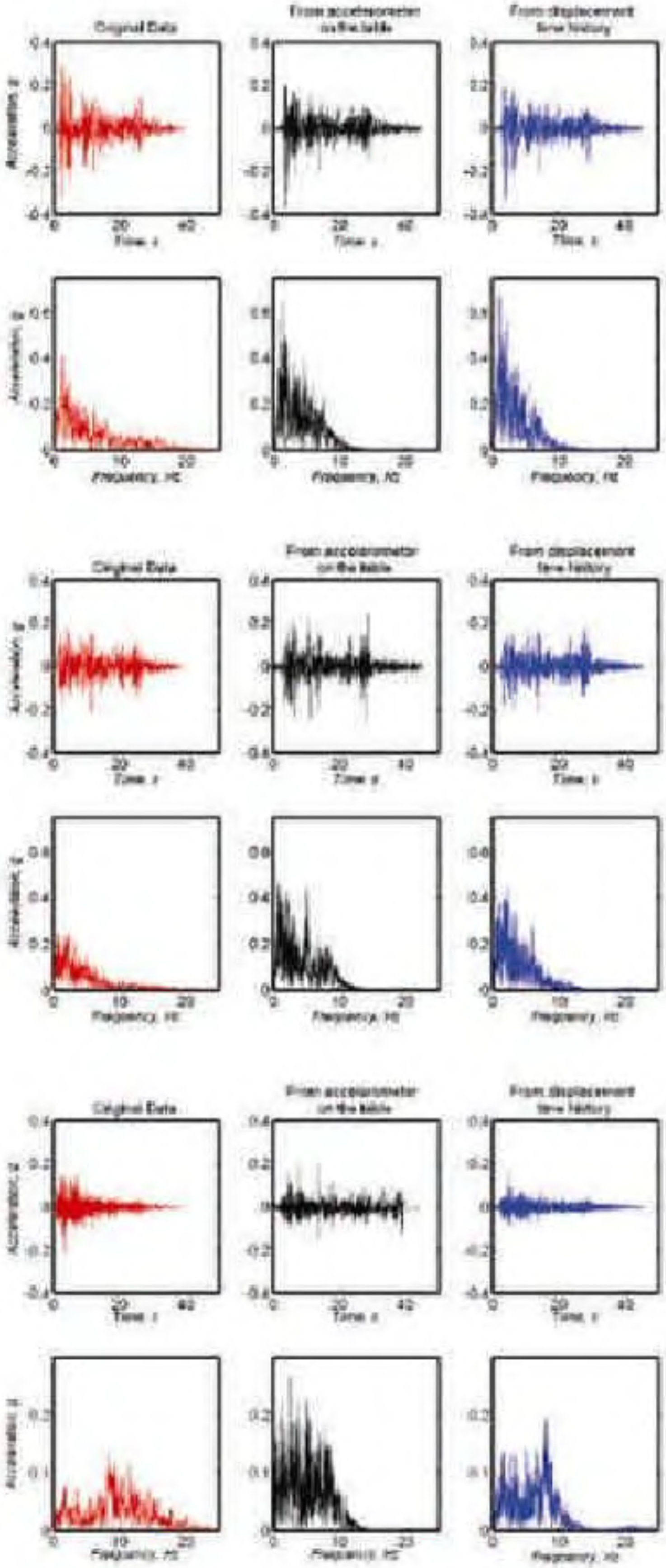

Figure 9. X (top), Y (middle) and Z (bottom) table response to El-Centro spectrum.

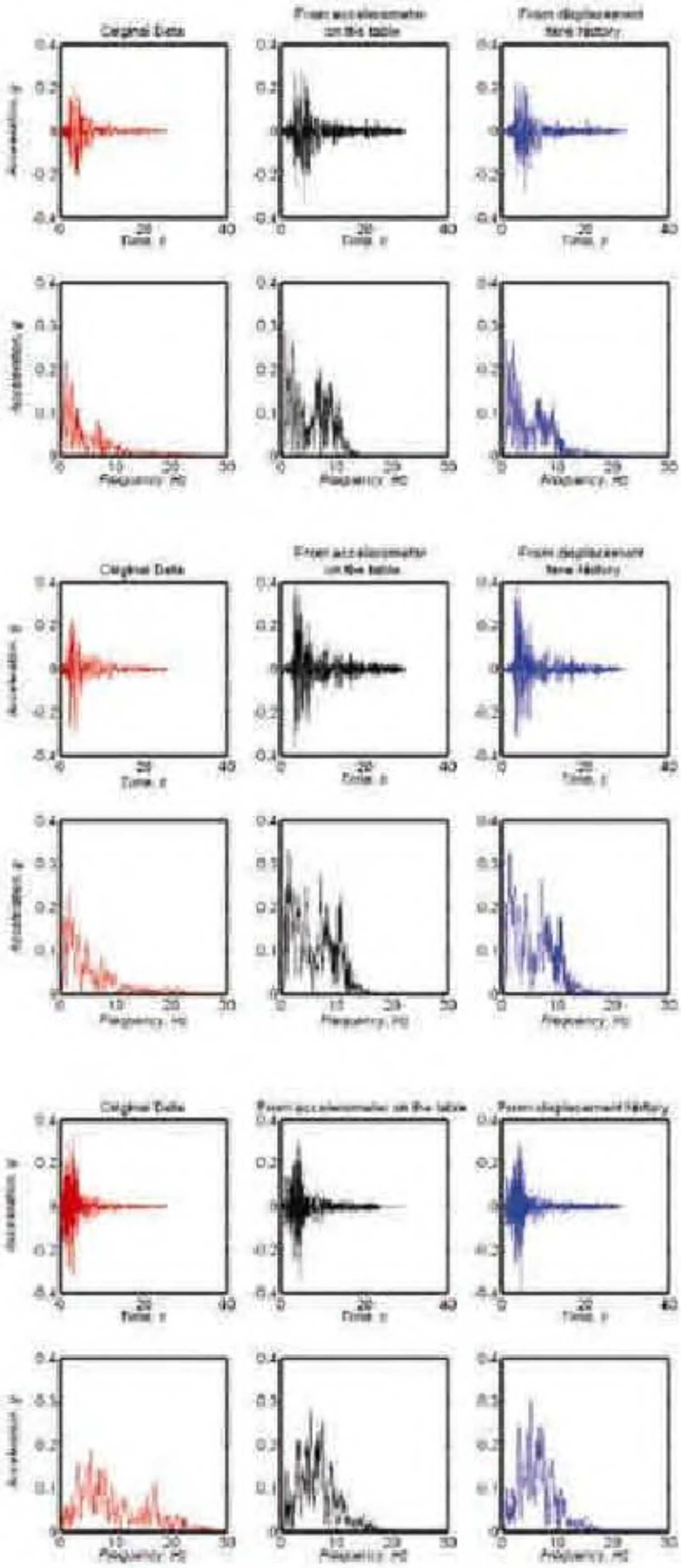

Figure 10. *X* (top), *Y* (middle) and *Z* (bottom) table response to Kalamata spectrum.

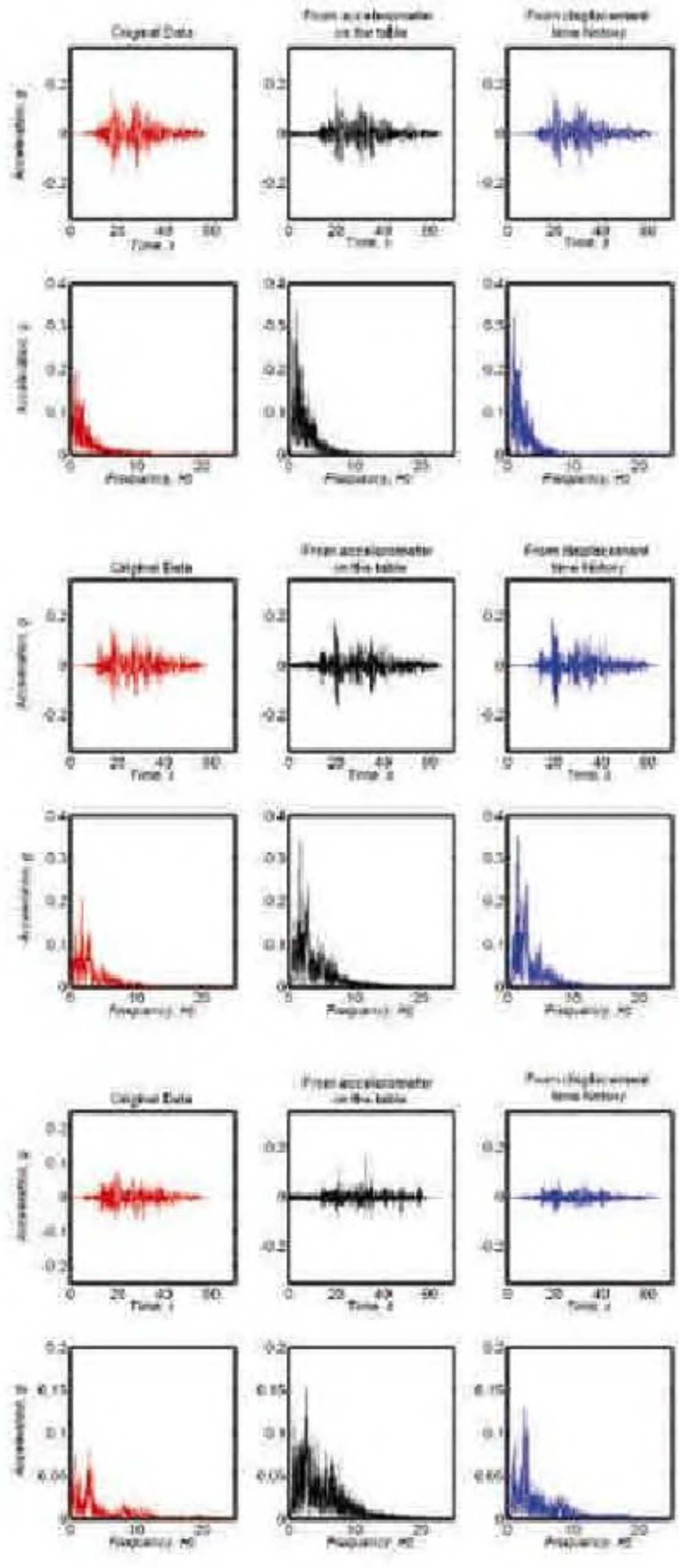

Figure 11. *X* (top), *Y* (middle) and *Z* (bottom) table response to Chi-Chi spectrum.

mained unchanged for various payloads and earthquake spectra that were tested.

- Some of the features of the table including the use of single-ended actuators, direct-drive contamination-insensitive valves and variable frequency servo-controlled pump make the technology more reliable and less expensive than conventional options.
- Tests on the table using El Centro, Kalamata and Chi-Chi earthquake records indicate table response and accuracy that compare favourably with those reported elsewhere. Three-axis table movement error was under 4% and phase lag between required and achieved position was of the order of 30 ms.
- Measured acceleration data appear to compare well with required signatures. However, there is scope for further improvement of acceleration response.
- Several engineering aspects of the shake table hold the promise of improvement. These include system protection from damage due to debris, greater variety of applications including frequency sweep, resonant mode identification, etc.
- Stiff shake tables of physically constrained configuration demand high precision in actuator movement as well as in computed spatial coordinates. This appears to be an inevitable problem specific to real-time control of eight-actuator earthquake shake tables.
- Digital servo-control technology for three-axis shake tables opens the possibility of constructing tables of much larger capacity. This combined with country-specific technologies such as contamination-insensitive servo-hydraulics and unprecedented energy efficiency carry the promise of commercially viable seismic testing.

1. Ogawa, N., Ohtani, K., Katayama, T. and Shibata, H., Construction of a 3-dimensional large-scale shaking table and development of core technology. *Philos. Trans. R. Soc. London, Ser. A*, 2001, **359**, 1725–1751.
2. Crewe, A. J. and Severn, R. T., The European collaborative programme on evaluating the performance of shaking tables. *Philos. Trans. R. Soc. London, Ser. A*, 2001, **359**, 1671–1696.
3. Stewart, D., A platform with six degrees of freedom. *Proc. Inst. Mech. Eng.*, 1965, **180**, 371–386.
4. Lung-Wen Tsai, *Robot Analysis, The Mechanics of Serial and Parallel Manipulators*, John Wiley, New York, 1999.
5. Gomez, E., Application of the MCS algorithm to the control system of the Bristol shaking table. Ph D thesis, University of Bristol.
6. Gomez, E. G. and Stoten, D. P., A comparative study of the adaptive MCS control algorithm on European shaking tables, In Proceedings of the 12th World Conference on Earthquake Engineering, Auckland, New Zealand, January 2000, pap. 2626.
7. Stoten, D. P. and Gomez, E. G., Adaptive control of shaking tables using the minimum control synthesis algorithm. *Philos. Trans. R. Soc. London, Ser. A*, 2001, **359**, 1697–1723.
8. Sunder, R. and Venkatesh, C. S., Microprocessor-based controller for actuators in structural testing. *Automation in Fatigue and Fracture Testing and Analysis, ASTM STP1231* (ed. Amzallag, C.), American Society for Testing and Materials, Philadelphia, 1994, pp. 70–83.
9. Phelan, R. M., *Automatic Control Systems*, Cornell University Press, Ithaca, NY, 1977.

ACKNOWLEDGEMENTS. The authors are grateful to the Department of Civil Engineering, Indian Institute of Science for the opening that made this development possible, and, to Prof. R. N. Iyengar for encouragement. The servo-actuator assemblies were designed, built and installed at site by Diwakar, Hebbar, Rajesh, Sadat, Vijay and Yogesh. The custom low noise signal conditioners for LVDTs were designed by Nagarathna and fine-tuned at site by Rincy. Multi-channel software support was provided by Sumana. On-site cabling and instrumentation was performed by Girish, Ravi and Shiva Kumar. The hydraulics were designed by Thilak Kumar and the on-site hydraulics assembly was performed by Cheluvaraj and Jayanna. The civil works for this facility were carried out by Giriraju.

Received 17 January 2005; revised accepted 20 February 2006