Upgrading of 5 DOF Seismic Simulation System with the Newest Real-Time Three Variable Digital Control System

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15 WCEE
LISBOA 2012

SUMMARY:
The IZIIS' Dynamic Testing Laboratory marks 40 years of experience in application of the single and multi-axis programmable shaking tables. Its 5 DOF (degree-of-freedom) seismic simulation system proportioned 5.0 x 5.0 m in plan and characterized by a payload of 40.0 t has been operational since 1982. Recently, the out dated analog control system has been replaced with the newest state-of-the art real-time three variable digital control system. The main objective of this paper is to present, in brief, control principles used in the MTS 469D control system and the main features that this digital controller provides: Three-Variable Control (TVC), Degree of Freedom Control, Force Balance Compensation, Differential Pressure Stabilization and Adaptive Control. Also, in this paper will be presented the tracking (signal reproduction) capabilities of the upgraded IZIIS' shaking table system through a series of broadband and harmonic experiments with different tuning and test amplitudes, utilizing adaptive control techniques incorporated in the new digital control system.

Keywords: shaking table, digital controller, three variable control, adaptive control

1. INTRODUCTION

Large servo-hydraulic shaking table systems are essential tools in development of earthquake engineering. If properly used, they provide effective ways to subject specimens of structural components, substructures, or entire structural systems to dynamic excitations similar to those induced by real earthquakes. On the other hand, shaking table experiments represent a good substitution for information on the behaviour of structures obtained under the effect of actual earthquakes.

Although in the first half of the 20th century efforts were made to build a laboratory system for simulation of earthquakes, the first types of earthquake simulators with programmable effect were produced and made available to the earthquake engineering scientists as late as the beginning of the seventies due to the insufficient level of technological knowledge in the mechanical, electrical and electronic industry. It is considered that the era of the modern shaking tables has began with the installation of the 20 x 20ft shaking table at UC Berkeley by MTS Systems Corporation, which was formally opened in 1972 [Severn, 2011]. Since then, more than 110 shaking tables with programmable characteristics have been installed in laboratories worldwide.

The Dynamic Testing Laboratory of the Institute of Earthquake Engineering and Engineering Seismology (IZIIS) at the "Ss. Cyril and Methodius" University, Skopje, R. Macedonia, marks 40 years of experience gathered in application of the single component programmable shaking table and 30 years of experience in application biaxial programmable shaking table. During this period, 170 shaking table projects for different purposes have been carried out. Through the realization of more than 30 projects, IZIIS has extensively contributed to the development and experimental tests on systems based on new technologies – different systems for seismic isolation, passive systems for structural control, dampers for different purposes and application of new materials for repair and strengthening.

The IZIIS' 5 DOF seismic shaking table proportioned 5.0 x 5.0 m in plan and characterized by a payload of 40.0 t has been operational since 1982. Its original analog Three Variable Control (TVC) system, although it was functional, was out dated and the ageing effect contributed for reducing the overall characteristics of the shaking table. Therefore, in order to keep sustainability and top peak performance of the seismic system, high bandwidth response and system fidelity, at the end of Q1 2011, the original analog control system has been replaced with the new digital one.

The new MTS 469D digital controller, which is installed for IZIIS' seismic testing system, is real-time, digital controller that provides three-variable-closed loop control along with adaptive control. It also provides an operator interface to the real-time hardware and permits faster set up and tuning of new specimen configurations. The control hardware architecture is based on Digital Signal Processing technology that optimizes the performance of the embedded control system, and allows for the implementation of advanced control and data filtering operations. This controller is in wide use today at over 20 seismic table installations worldwide. The new controller is configured to allow future use of SCRAMNet connections for hybrid testing.

The MTS 469D controller is manufactured using the latest MTS Model 494 state-of-the-art electronic hardware and does compatible with all existing servo valves, feedback devices, and the existing National Instruments data acquisition hardware. It is populated with the necessary electronic hardware to allow operation of the Seismic Shaking Table in a 6 Degree of Freedom mode. Since the system is presently configured to operate in a 5 Degree of Freedom mode the additional electronic components are considered to be on-board spares at this time.

In this paper will be presented, in brief, control principles used in the MTS 469D control system and the main features that this digital controller provides: Three-Variable Control (TVC), Degree of Freedom Control, Adaptive Control, Differential Pressure Stabilization and Force Balance Compensation. The tracking (signal reproduction) capabilities of the upgraded IZIIS' shaking table system, utilizing adaptive control techniques incorporated in the new digital control system, will also be presented.

2. IZIIS SHAKING TABLE SYSTEM

The Dynamic testing laboratory at IZIIS is equipped with a MTS Systems Corporation servo-hydraulic 5.0 x 5.0 m in plan 5 DOF (degrees-of-freedom) shaking table with nominal 40 t payload capability, (Figure 2.1). The system has been in continuous operation since 1982 and at the end of Q1 2011 the out dated analog Three Variable Control (TVC) system has been replaced with the digital MTS state-of-the-art real-time TVC system of the latest generation.

The table (plate) is made of prestressed reinforced concrete having mass of approximately 33 t. The table is supported by four MTS 206.42s vertical hydraulic actuators located at four corners at a distance of 3.5 m in both orthogonal directions, while in horizontal-lateral direction the shaking table is controlled by two MTS 204.81s hydraulic actuators at a distance of 3.5 m. In the longitudinal direction, two pressurized bearings have been installed, one for controlling the displacement and the other for controlling the force. The horizontal and vertical actuators of the table are supported by reinforced concrete rigid structure. The total mass of the supporting structure is 1200 t and this structure is separated from the rest of the laboratory structure by an expansion joint.

The gravity load due to table and the model mass is sustained by a special system with static supports which utilizes nitrogen. The total bearing capacity for static loads is 720 kN. This system is located in the lower part of each of the four vertical actuators.

In order to provide the required power of the actuators, three inter-connected hydraulic pumps, MTS model 506.71 hydraulic power supplies (HPS), with a maximum flow of 1,250l/min and a maximum pressure of 350 x 105 Pa are used. The required electric power to feed the three pumps is 1,020 A. In order to increase the working flow of the system, four additional pressured accumulators with capacity of 60 litres of hydraulic fluid are used.

Figure 2.1. IZIIS' shaking table

The maximum over turning moment is 460 kNm and the bandwidth of operating frequency is 0.1-80 Hz. The rest of the full-scale characteristics, for zero payload, are given in Table 2.1.

Table 2.1. – IZIIS shaking table full-scale characteristics

Direction	displacement	velocity	acceleration	Force
Y	±150 mm	±1.0 m/s	±3.0 g	±1000 kN
Z	±75 mm	±0.5 m/s	±1.5 g	±1000 kN
Roll	±2.0 deg	±13 deg/s	±200 deg/s2	
Pitch	±2.0 deg	±13 deg/s	±200 deg/s2	
Yaw	±2.0 deg	±26 deg/s	±200 deg/s2	

3. DIGITAL CONTROLLER

The MTS 469D Digital Control System is designed to provide simpler shaking table tuning, system operation, and test execution.

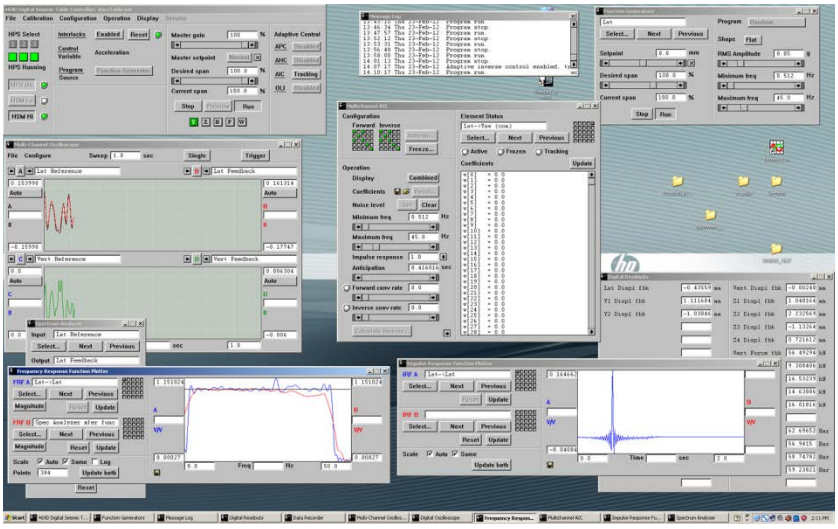

Figure 3.1. – Graphical user interface of the MTS 469D Digital Controller control panel software

The controller consists of MTS console assembly, associated cabling and control software. The MTS console assembly has imbedded processors, real-time MTS 494 series hardware. The control software consists of the real-time control software and the control panel software. The real-time control software drives the processors to generate command and error signals using state-of-the-art Three-Variable-Control (TVC). The control panel software runs on a PC and has a graphical user interface consisting of interactive, modeless dialogs that are used to enter system parameters and execute a test [MTS System Manual, 2011, Thoen, 2004].

An example of graphical user interface of the MTS 469D Digital Controller control panel software is presented in Figure 3.1.

The 469D digital controller provides the following control and compensation techniques:

- High Level Fixed Control Techniques:
  - Three Variable Control (TVC)
  - Degree of Freedom Control
  - Force Balance Compensation
  - Differential Pressure Stabilization
  - Velocity and Acceleration Lead Terms
- Advanced MTS Adaptive Control Techniques
  - Amplitude Phase Control (APC)
  - Adaptive Harmonic Cancellation (AHC)
  - Adaptive Inverse Control (AIC)
  - On Line Iteration (OLI)

3.1. High Level Fixed Control Techniques

3.1.1. Three Variable Control (TVC)

The Three Variable Control (TVC) allows for high fidelity reproduction across a wide frequency bandwidth. TVC includes a reference generator and velocity computer for deriving command and feedback signals in displacement, velocity, and acceleration. The wide frequency bandwidth associated with seismic time histories is best achievable by controlling for displacement at low frequencies, velocity at mid-range frequencies and acceleration at the higher frequencies.

TVC as applied in MTS controllers is a type of state variable control with additional special features to improve fidelity, and it is a common misconception that all three state variables are controlled simultaneously. In fact, only one state variable is the primary control variable, with the others serving only as compensation signals to improve damping and stability. The transfer functions between all the inputs and outputs of the TVC are provided by the MTS Systems Corporation.

3.1.2 Degree of Freedom Control

Motion of a multi-axial seismic table is governed by the collective movement of all system actuators. For desired table motion, actuator motions must be time synchronized. This synchronization is achieved using the Degree of Freedom (DOF) control concept. This control concept allows the user to control table motion in the coordinate domain rather than the actuator domain. This concept provides the means to account for and control all actuator movements in a given DOF by transforming the feedback signals from all actuators in that DOF to provide DOF feedback inputs. It then transforms all DOF composite error signals to provide coordinated actuator control signals.

3.1.3 Force Balance Compensation

Force balance compensation is required in systems where more than one actuator affects the control of any translational or rotational axis (that is, where systems are “over-constrained”). The seismic test system, with many actuators controlling the 6 degrees-of-freedom is a seriously over-constrained system. The force “imbalance” can seriously limit the force capability of the actuator system. If a table is considered a rigid body, three actuators completely define the plane of the table (one each for X motion, Y motion and Yaw control). A fourth actuator, if not perfectly balanced, may exert large forces to try to distort the stiff table into a shape out of the plane of the other actuators. Therefore, due to the high stiffness of a typical seismic table, small errors in the actuator position can cause large internal table forces to be generated. The Force balance function compensates for this effect by essentially adding more degrees-of-freedom, which are all controlled to zero using a PID controller.

3.1.4 Differential Pressure Stabilization

Differential Pressure Stabilization is used for effectively dampening oil column compliance to allow for higher gain settings across a wider bandwidth. In general, in all servo hydraulic shaking tables the actuators will have an oil column resonance within the bandwidth of the earthquake motions. The ability to maintain high gain settings without decreased stability from this resonance is critical for high fidelity seismic waveform reproduction. Differential pressure (ΔP) stabilization is applied to all electronically-controlled axes.

3.2. Advanced MTS Adaptive Control Techniques

The MTS 469D Digital Seismic Table Controller, besides high level fixed control techniques: Three-Variable Control (TVC), Degree of Freedom Control, Force Balance Compensation, Differential Pressure Stabilization, it provides additionally four adaptive and iterative control techniques to improve the system performance and to compensate for linear and/or nonlinear sources of signal distortion [Thoen, 2004]:

- Amplitude Phase Control (APC)
- Adaptive Harmonic Cancellation (AHC)
- Adaptive Inverse Control (AIC)
- On Line Iteration (OLI)

The choice of which adaptive controller to use is determined by two considerations: type of program waveform, and the degree of linearity of the entire system, including hydraulics, mechanics and test specimen.

Amplitude/Phase Control (APC) is used for correcting amplitude and phase errors in sine response waveforms. It is a control compensation technique that augments a fixed-gain controller to correct for closed-loop amplitude and phase irregularities in order to improve control fidelity. It measures control system dynamics directly and modifies the control compensation accordingly in real-time, making it possible to adapt to changing system dynamic. [Thoen, 1992]

In servo-hydraulic seismic systems, due to the servo-valve orifice nonlinearity, spurious harmonics appear in the feedback even when the command is a simple sinusoid. To overcome this, harmonics are added to the controller command waveform with just the right phase and amplitude to cancel the harmonics at the system output. This technique is called “Adaptive Harmonic Cancellation” (AHC) [Thoen, 1992].

Adaptive Harmonic Cancellation (AHC) greatly reduces harmonic distortion of the response of a control system driven by a sinusoidal command. It measures the harmonic distortion directly and adapts in real-time the cancelling waveform that it applies to the control system input. AHC can be augmented with AHC and they complement each other: APC enhances the fundamental frequency component of the system response while AHC cancels the harmonics.

For high fidelity in signal reproduction during shaking table tests the tuning process requires additional control compensation techniques to be implemented. Adaptive Inverse Control (AIC) is a control compensation technique that augments a fixed-gain controller to correct for closed-loop gain and phase irregularities in order to improve control fidelity. The tuning procedure is based on obtaining an estimate of the inverse model of the plant, which is provided by the AIC controller program [Thoen, 2004] in which the parameters of the inverse controller are estimated by an adaptive inverse modelling process. The quality of the estimated inverse model depends on noise level, input amplitude level, and nonlinearities in the system [Luco, et al., 2010]. Training of the system for the estimation of the inverse model with AIC is done under white noise acceleration with RMS amplitude matching to that used in to fine tune the TVC parameters. AIC is optimized to work with non-sinusoidal command waveforms and predominantly linear systems. [Thoen, 1994]

Online Iteration (OLI) is a control technique that repeatedly modifies the command input to a control system on an individual sample-by-sample basis until the control system response is almost a perfect replica of the original desired command. This online technique generates the next command to the table by running the table in real-time with the current drive file as the command to the table, calculating the error between the desired and feedback, and updating the current drive file by adding a fraction of the response error filtered through the inverse plant model on the current drive. The generation of new drive files are continued until satisfactory match is achieved between the desired and feedback signals. Response RMS error is defined as the root mean square of the error between desired and feedback signals. Response RMS error initially decreases with iteration number but after a certain iteration is reached the response RMS error starts increasing. The drive file achieving the minimum response RMS error is considered to be the "converged drive file" [Luco, et al., 2010]. The application of OLI process requires a prior estimate of the inverse plant model provided by the Adaptive Inverse Controller (AIC) program which is wired into the OLI program to serve this purpose [Thoen, 2004]. OLI is intended to complement basic AIC, providing a way of handling nonlinear system applications. [Thoen, 1995]

All adaptive controllers use three modes [Thoen, 2004]:

- Disabled
- Tracking - The frequency response of the system is continuously measured and the applied inverse function is continuously modified to suit changing conditions in the system. In the case of online iteration, a new drive update file is calculated during each pass, and this new file becomes the drive file for the next iteration.
- Frozen - The system continues to use parameters developed during tracking, but the parameters are not updated. In the case of online iteration, a new drive update file is calculated during each pass, but it is not used as the drive file for the next pass.

The adaptive harmonic cancellers and adaptive inverse controller also have a training mode. Training mode is used initially to build coefficients without affecting the system operation. A system model is built but the current signal being played out is not modified. The coefficients can then be saved in a settings file. [Thoen, 2004]

4. TRACKING CAPABILITIES

In order to evaluate the performance of the 469D controller algorithms, after its installation, series of shaking table test on IZIIS' bare table and table loaded with 14 t payload of rigid mass have been conducted. The presented results correspond to table loaded with 14 t of rigid mass.

For performance evaluation of APC and AHC harmonic sine and sine sweep command signals are used, while for AIC and OLI N-S component of Petrovac acceleration record of 1979 Monte Negro earthquake was used.

The acceleration time-histories obtained from the acceleration feedback signals measured during the tests were compared to those of the reference signals. The results are presented in waveform graphs, auto power density plots and shock response spectra plots. The error in % between the feedback and the reference is presented tabular form, also, taking into account the following calculations:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\ddot{x}(i)_{fbk} - \ddot{x}(i)_{ref}\right)^2} \cdot 100 \qquad (4.1)$$

where N denotes total number of data points, while $\ddot{x}(t)_{ref}$ is the reference-command acceleration and $\ddot{x}(t)_{fbk}$ is feedback-achieved

For cumulative measure of the error in signal reproduction, the relative RMS error measure is used defined as [Luco, et al., 2010]

$$RRMS\ Error = \frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\ddot{x}(i)_{fbk} - \ddot{x}(i)_{ref}\right)^2}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\ddot{x}(i)_{ref}\right)^2}} \cdot 100 \tag{4.2}$$

On Figure 4.1 are presented waveform comparison graphs of acceleration time histories of reference and feedback signal due to harmonic excitation in lateral direction with f=6Hz and PGA=0.1g. It can be seen that when APC and AHC are set to tracking (ON) the match is almost perfect.

In Table 4.1 are presented errors in % between the feedback and the reference in terms of RMS error and relative RMS error.

The presented results, both graphical and tabular, indicate the APC and AHC algorithm provides a significant performance improvement across all frequency band.

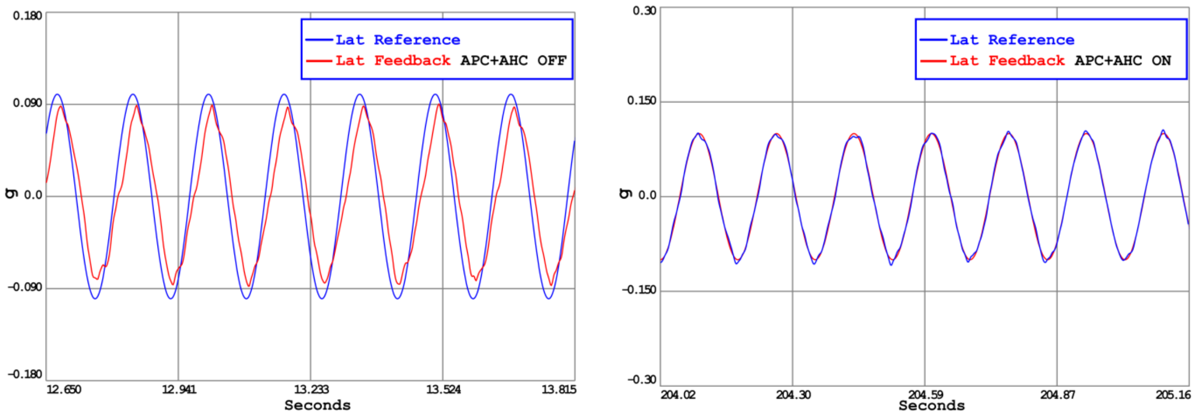

Figure 4.1. – Harmonic excitation F=6 Hz, PGA=0.10g – Lateral direction [Rakicevic, et al., 2012]

Table 4.1 – Comparison of Feedback and Reference signals – harmonic excitation

Excitation	APC	AHC	RMSE (%)	RRMS Error (%)
Y SIN 6 Hz	Disabled	Disabled	2.85	39.90
Y SIN 6 Hz	Tracking	Tracking	0.31	4.41
Z SIN 5 Hz	Disabled	Disabled	1.40	39.66
Z SIN 5 Hz	Tracking	Tracking	0.38	10.66
Z SWEEP	Disabled	Disabled	2.43	68.99
Z SWEEP	Tracking	Tracking	0.39	11.25
Y SWEEP	Disabled	Disabled	1.16	82.00
Y SWEEP	Tracking	Tracking	0.35	24.67

For evaluation of AIC algorithm performance shaking table was trained for three different conditions. At first training of the system for the estimation of the inverse model with AIC was done under white noise acceleration and for lateral-Y degree-of-freedom only. Second training of the system was done for lateral-Y and vertical-Z DOF, while third training was done for all 5DOF active.

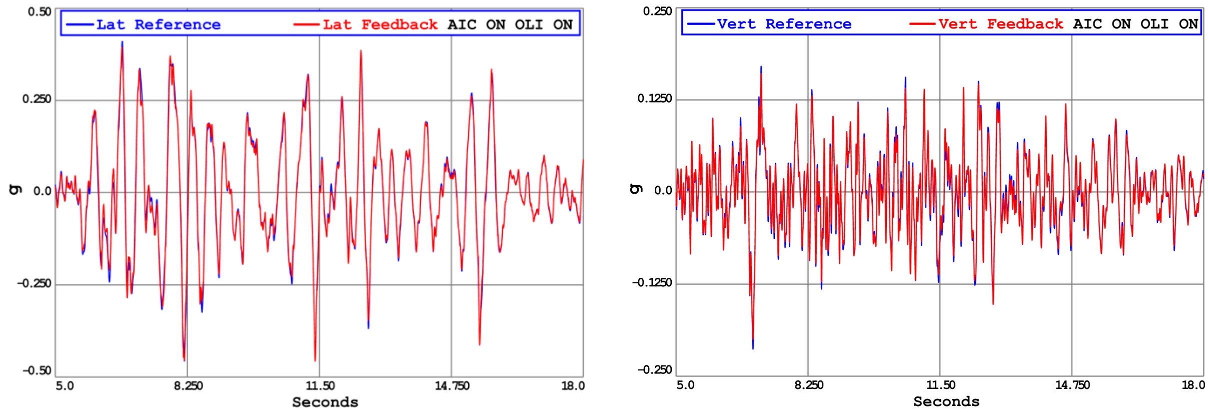

Figure 4.2. – Petrovac Lateral PGA=0.46 and Vertical PGA=0.21g – DOF YZRPY [Rakicevic, et al., 2012]

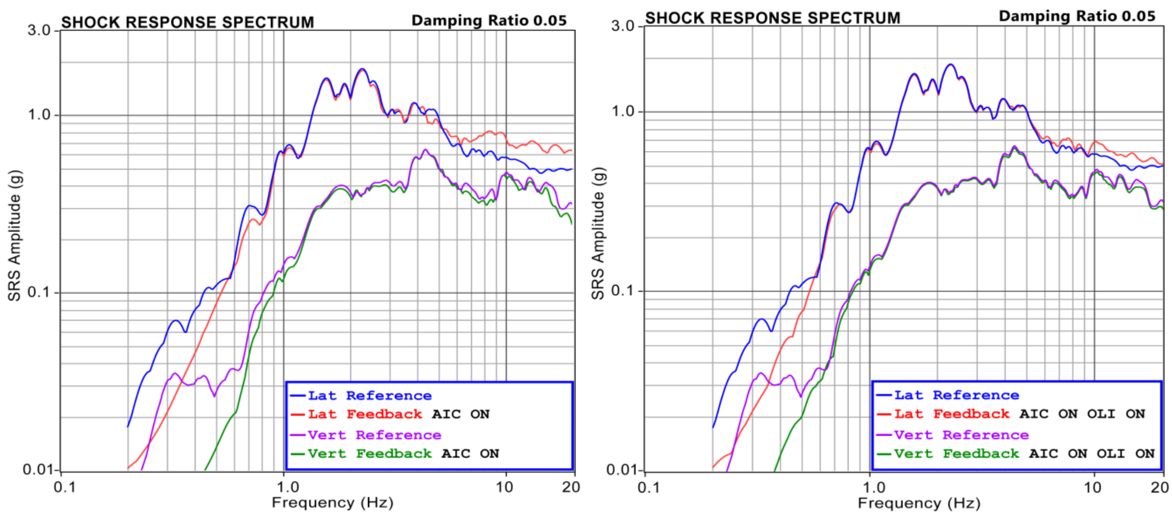

Figure 4.3. – Shock response spectrum – Petrovac Lateral and Vertical direction [Rakicevic, et al., 2012]

Table 4.2. – Comparison of Feedback and Reference signals– earthquake excitation

PETROVAC N-S			LATERAL PGA=0.46 g		VERTICAL PGA=0.21 g	
DOF	AIC	OLI	RMSE (%)	RRMS Error (%)	RMSE (%)	RRMS Error (%)
Y	Disabled	Disabled	2.36	30.13	/	/
Y	Tracking	Disabled	1.86	23.09	/	/
YZ	Disabled	Disabled	2.30	29.44	1.48	52.90
YZ	Tracking	Disabled	1.76	22.33	0.60	21.32
YZRPY	Disabled	Disabled	1.99	25.42	0.78	27.98
YZRPY (1)	Frozen	Tracking	0.77	9.79	0.34	12.24

(1)7-th iteration

For the third case AIC was automatically turned to frozen when OLI was set to tracking. Bi-axial, lateral and vertical simultaneously, command of Petrovac N-s record was used as desired time history file. Total seven iterations were performed and the results from the last iteration are presented in

Figure 4.2 as waveform charts. In Figure 4.3 are presented comparisons of response spectra (shock spectra) of reference and feedback accelerations computed for frequency range 0.5 – 10 Hz and for damping ratio of 0.05

In Table 4.2 are presented errors in % between the feedback and the reference in terms of RMS error and relative RMS error, for all considered cases.

The presented results, both graphical and tabular, indicate the AIC and OLI algorithms provide a significant performance improvement across frequency band of interest.

5. CONCLUSION

The MTS 469D Digital Control System manufactured using the latest MTS Model 494 electronic hardware is a state-of-the-art digital control system for shaking tables that offers advanced control techniques for table tuning, system operation, and test execution in real time. However, shaking table tuning is time consuming process and the results are highly dependent on the skills of the operator. Besides high level fixed control techniques: Three-Variable Control (TVC), Degree of Freedom Control, Force Balance Compensation, Differential Pressure Stabilization, the 469D provides additionally four advanced adaptive and iterative control techniques to improve the system performance and to compensate for linear and/or nonlinear sources of signal distortion.

The presented results from the tests conducted after the installation of 469D controller for IZIIS' shaking table show that MTS advanced adaptive control algorithms provides a significant performance improvement across all frequency band of interest. The upgrade of the existing Seismic Shaking Table System in the Dynamic Testing Laboratory at IZIIS, Skopje, R. Macedonia with this digital control system represents a significant and qualitative step forward in increasing the infrastructure's capacity for experimental earthquake engineering.

AKCNOWLEDGEMENT

The authors express their gratitude to European Commission for received funding for the Seventh Framework Programme Project UREDITEME –Upgrading of Research Equipment for Dynamic Testing of Large Scale Models, Grant Agreement No 230099, under which upgrading of IZIIS' shaking table with the new MTS digital control system was realized. Also, the authors would like to express their gratitude to Dale Maue, Al Clark, Jim Rosenow and Chuck Downer form MTS System Corporation, as well as IZIIS' Dynamic Testing Laboratory staff for their engagement in successful realization of all phases for upgrading IZIIS' seismic testing system.

REFERENCES

Severn, R.T. (2011). The development of shaking tables–A historical note. *Earthquake Engineering & Structural Dynamics*, **40(2)** 195–213.

Seismic Test System User's Manual (2011). MTS System Corporation, 00-217-981 E.

Thoen, B. K. (2004). 469D Seismic Digital Control Software. MTS Corporation.

Thoen, B. (1992). Sinusoidal Signal Amplitude and Phase Control for an Adaptive Feedback Control System. US Patent 5,124,626, June 1992.

Thoen, B. (1994). Crossover and Spectral Preemphasis Networks for Adaptive Inverse Control. US Patent 5,339,016, Aug. 1994.

Thoen, B. (1995). Control Network with On-Line Iteration and Adaptive Filter. US Patent 5,394,071, Feb. 1995.

Luco, J.E., Ozcelik, O. and Conte, J.P. (2010). Acceleration Tracking Performance of the UCSD-NEES Shake Table, *ASCE Journal of Structural Engineering* **136 (5)**, 481-490.

Rakicevic, Z., Garevski, M., Naumovski, N. and Markovski, I. (2012). Adaptive Control Techniques for Seismic Testing Systems. *Proc. 5th European Conference on Structural Control*, Genoa, June 18-20, 2012, p. 242.