Strategies for Operation of Single and Multiple Shake Tables

Patrick N. Laplace[1] **Bradford K. Thoen**[2]

ABSTRACT

Research using multiple shake tables present new and unique challenges in controls. Typical single shake table tests with large specimens must cope with significant specimen force feedback that can increase tracking error due to specimen gain, damping, and non-linearity. Multiple shaking tables with distributed specimens can produce cross-coupling forces due to inertial and response effects and forces due to static differential displacements. Although many various control architectures exist, basic simplified techniques can yield excellent results without risk to control stability. Off-line simulation techniques can also prove invaluable for studying system response before the real system is operated.

1. Introduction

Current shake table systems provide the capability of testing various structures subjected to real time input excitation, retaining real dynamic response such as inertial and damping effects. Typical high-performance shaking tables have high bandwidth capabilities provided by complex digital controllers. These controllers require extensive knowledge by the operator to achieve the desired table performance, which can vary greatly depending on the response of the system. The addition of a test specimen onto the shaking table increases the controller complexity due to the resonant force feedback during table excitation.

Many control schemes have been developed, such as MCS (minimal control synthesis), MRAC (model reference adaptive control), MFAC (model-free adaptive control), and AFC (adaptive filter compensation). These control schemes can be very effective in many cases with systems and specimens that have minimal sudden response changes and few large non-linearites. Many of these control systems are adaptive, thus requiring time to re-tune to sudden changes in the plant and specimen response. Many also remove the operator from direct control of the system, and have the potential to adapt to instability. With seismic research, the large non-linear excursion can occur within hundreds of milliseconds. These non-linear excursions can be pre and post-ceded by linear regions, such that the adaptive controllers may 昳e-adapt? to linear elastic response. Some controllers may also require a basic model of the specimen to be in the loop to assist in compensation. The accuracy of the compensation then depends in part to the accuracy of the model.

In an ideal research situation, multiple structural specimens would be constructed and tested under the same motions to produce a statistically un-biased study. Since construction of structural specimens involve significant time and cost, generally, only one specimen is constructed for a particular point of study. Due to the one-specimen nature of large seismic-structural testing, basic operation techniques should be developed and utilized. These techniques must involve good control stability throughout the sequence of motions and provide stability during yielding and breaking events. Any stability issues can quickly damage or destroy a specimen and can be very costly.

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[1] Research Assistant Professor / Senior Laboratory Manager, Rogers and Weiner Large Scale Structures Laboratory, University of Nevada, Reno, Reno, NV 89557, Email: laplace@unr.edu

[2] Senior Staff Engineer, MTS systems Corporation, 14000 Technology Drive, Eden Prairie, MN 55344 Email: Brad.Thoen@mts.com

The Large Scale Structures Laboratory (LSSL) at the University of Nevada, Reno has researched hundreds of specimens ranging from computer monitor brackets to 2-span bridges (Figure 1). A wealth of experience has been developed in the control of shake tables using harmonic motion, synthetic and near-field motions, single and multiple tables, and off-line simulation. The LSSL currently contains three 50 ton capacity bi-axial shake tables manufactured by MTS systems and driven exclusively by state of the art MTS software.

2. Offline Iteration with Nonlinear Specimen

Offline iteration has proven very successful for many seismic tests, and can be implemented easily and efficiently. Modifications can be made during testing to compensate for specimen and plant changes, and safely and effectively deal with significant non-linearities. The MTS software packed for the LLSL contains iteration capability in the primary 469D software and secondary capabilities in a package called STEX. STEX has significant capabilities for derivation of drive files using various techniques and an extensive analysis suite.

The following basic sequence for off-line iteration is used extensively for many different research scenarios. The MTS 469D control software and the MTS STEX offline software has been used exclusively on all research conducted at the LSSL.

2.1 Specimen Characterization

Before any excitation is applied to the shake table system, the specimen parameters are measured in their untested state. This can be done with the shake table in a soft state with all 469D gains (except displacement gain) set to zero. With only displacement gain, a low amplitude square wave displacement input with a long period can be applied to the system. This produces a free vibration response in the specimen. This data provides the initial state as a reference point of the specimen before tuning.

2.2 Specimen Tuning

For a shaking table to have matched command and feedback, the transfer function between these terms should be as close to unity gain as possible in the bandwidth of interest for linear systems. Although typical earthquake excitation frequencies have lesser energy content above 5 Hz, matching is generally desired up to and beyond 20 Hz. It is generally not possible to achieve unity gain without significant excitation to the specimen. This excitation can cause degradation or damage if the duration and amplitude are not carefully controlled. This may have the undesired effect of low-level damage or fatiguing, even if the specimen is tuned while in the elastic range (Laplace, 2001, Laplace 1999).

The tuning process begins with all gain, lead, and notch filter terms at zero. A low level random motion is applied to the shaking table while monitoring both the plant FRF and all the instrumentation on the specimen. These terms are incrementally adjusted while keeping the excitation levels below set peak instrument levels. This is an iterative process since the terms interact; changing one term has a desired effect in one frequency region and an undesired effect in another. Although unity gain response can be quickly achieved when tuning a bare table, tuning a table loaded with a difficult resonant specimen may require considerable operator time and expertise. Even then, unity gain may never be achieved with high resonant specimens. Although unity gain can increase the convergence rate during offline iteration, a weak FRF can still be compensated for quite easily offline. Tuning a specimen can then be done very quickly and at a low level of excitation.

2.2 Inverse FRF

An inverse FRF should be measured once basic tuning is completed. This can be done with similar excitation levels as used in the forward tuning. It is this inverse FRF that will be used and modified throughout the testing protocol.

2.3 First Drive Calculation

Typical testing involves scaling the desired input acceleration amplitude down to a low level and running the shake table system using this scaled input as the first motion. The measured inverse FRF is used to modify this desired input motion to create the first drive file. This drive file is then used as the command to the shake table. If the inverse FRF is correctly measured and the level of excitation is similar to the level used during tuning, then the shake table tracking errors should be minimal.

2.3 Subsequent Drive Calculations up To Yielding

The inverse FRF does not contain non-linear information since it is only a linear filter. To begin to compensate for any non-linearities, an error time history needs to be recorded in the first drive response. A portion of the inverse of this error (adjusted for delay) is added to the previously recorded drive signal. This new error+drive modified time history is then filtered through the inverse FRF to create the second drive file. This new drive is then scaled up to the next desired amplitude, as is typically done in seismic testing. Experience has shown only 30 to 50% of the error time history is needed to correct for any tracking errors and non-linearities in the next event. Since this new drive file contains previous error time history, it can uniquely compensate for nonlinearities, even if the event scaling is amplified.

2.4 Subsequent Drive Calculations Through and Past Yielding

If a significant yielding event is occurring, the inverse FRFs may no longer be accurate measurements of the plant and specimen dynamics. Since the inverse FRF has been stored as a static reference, it can easily be modified to track the specimen/plant changes. Several techniques can be used to track the shifting amplitude and frequency of the yielding/degrading system. By measuring the changing frequency content and changing FRFs in the plant and specimen feedbacks, the operator can apply basic modifications to the inverse FRF to modify the next drive signal. The previous time history error signal is still used to modify the next drive signal.

3. Example Results for SDOF Specimen on Single Table

Figure 1 shows the tracking between the target and achieved motions for a 40 ton bridge column subject to the Northridge Rinaldi near-field motion at 1.35 x the recorded event amplitude. The plant and specimen were tuned for approximately 120 seconds of low-level random motion. Twelve incremental events were applied between 0.05x and 1.35x the recorded earthquake acceleration. The inverse FRF was slightly modified during the test to compensate for the shifting frequency and amplitude of the specimen. Approximately 30% of the measured error time history was applied to the next drive for each event. A very close match was achieved for a highly non-linear bridge column subjected to a high velocity near-field earthquake motion.

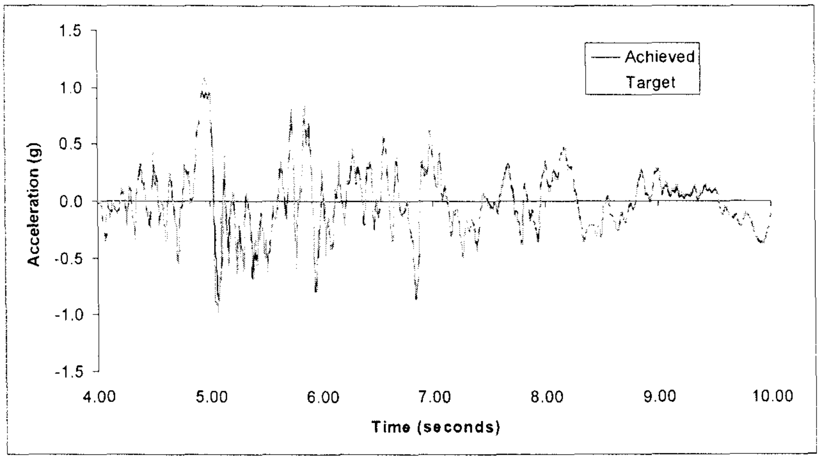

Figure 1: SDOF large nonlinear bridge column subject to near field motion

Figure 2 shows the target versus feedback acceleration time histories for a synthetic earthquake motion of 1g amplitude and frequency bandwidth between 1 and 33Hz. Figure 3 and Figure 4 show a spectral match after the first and fourth iteration respectively.

The spectral and time history matching of the latter examples show the capability of these simple techniques for compensating amplitude and frequency response of the specimen and plant dynamics.

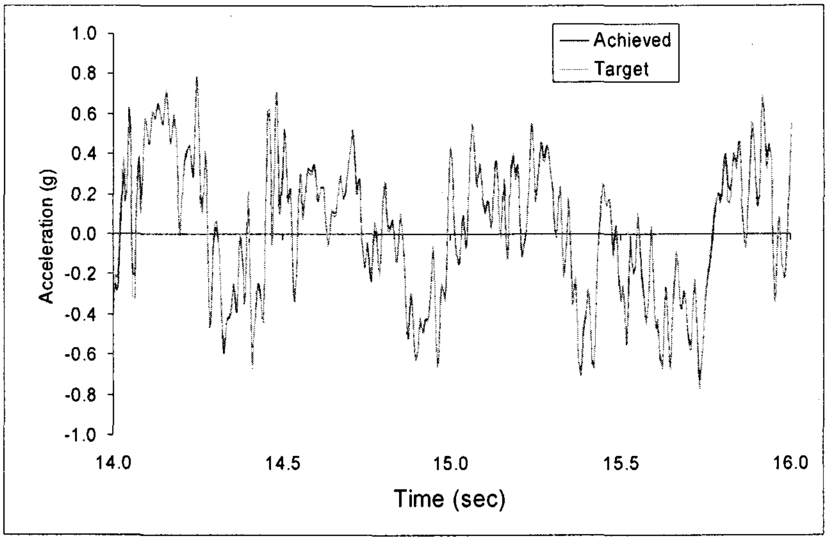

Figure 2: Table response due to Synthetic motion between 1 ? 33 Hz

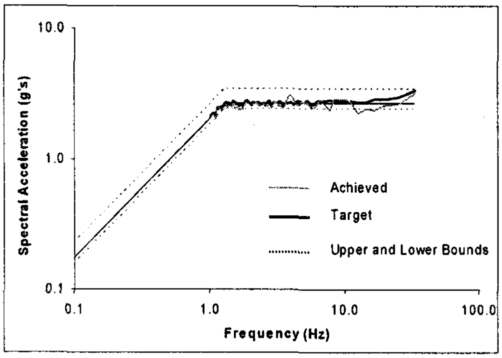

Figure 3. First Iteration Spectral Response

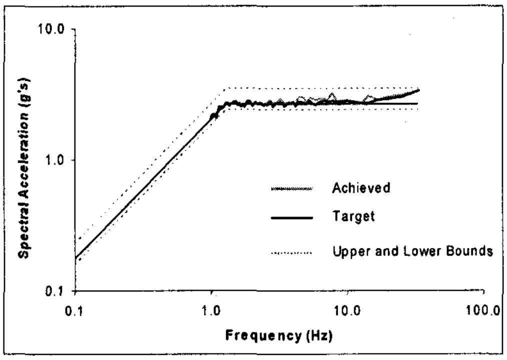

Figure 4. Fourth iteration spectral response

4. Example Results for MDOF Specimen on Three Shake Tables

Figure 5 shows a 2-span continuous steel girder bridge subjected to over 700 coherent, incoherent, uniaxial and biaxial earthquake motions. Figure 6 shows a 130 ton 2-span post-tensioned concrete bridge also subjected to coherent, incoherent, uniaxial and biaxial motions.

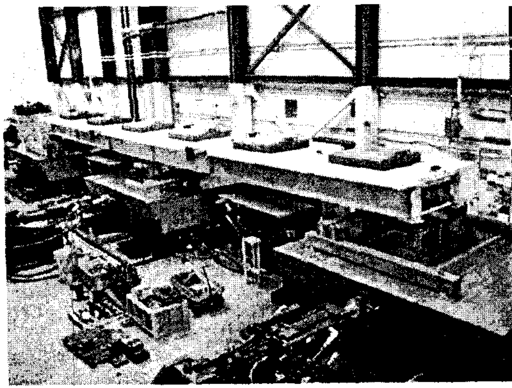
Figure 5. UNR Two-span steel girder bridge

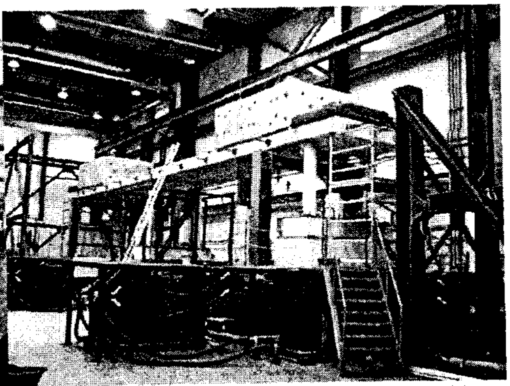
Figure 6. UNR Pre-NEESR 2-Span concrete bridge

Figure 7 shows the target-achieved time histories for the post-tensioned bridge during the yielding event. The tracking begins to diverge during the event, especially on Table 3, which carries the stiffer portion of the yielding structure.

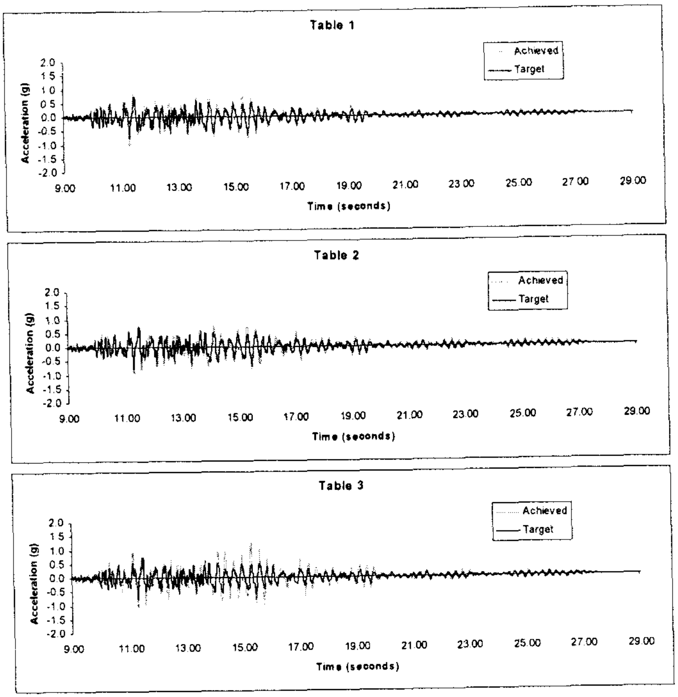

Figure 7. Response during major yielding event

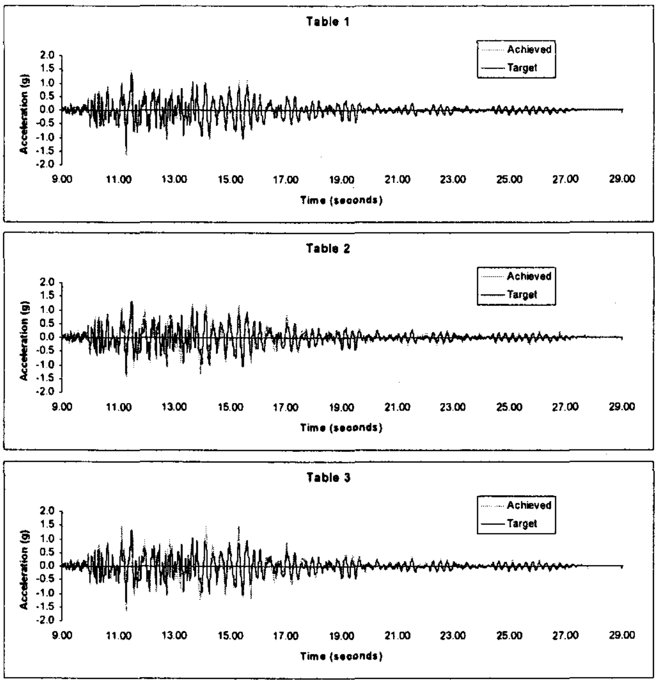

Figure 8. Response after major yielding event

Figure 8 shows the target-achieved time histories for the post-tensioned bridge during the event immediately after the yielding event. Only minor changes were made to the inverses FRF to track the changing frequency and damping. A significant improvement can be seen.

5. Offline Simulation

A numerical simulation model of the 3 shake table system at the LSSL was undertaken as a joint effort between MTS and UNR. The simulation model numerically represents the shake table system and any attached specimen. Although numerical simulations of servo-hydraulic systems have been presented in the past, the uniqueness of this model is that it retains the real-time controller software in the simulation. This removes any uncertainties in controller modeling and provides the operator the same familiarity with the simulation as with the real system controllers.

If the simulation model correctly represents the real system, the operator can adjust the real-time controller settings until either unity gain is achieved or the desired FRF is obtained. Once all the controller parameters are determined, these can be directly transferred to the real system thus achieving an optimally tuned state.

The actual seismic table control system on which the simulation is based (Figure 9) consists of a Controller Graphical User Interface (GUI), a Realtime Controller (Thoen 2004), and the mechanical system comprising a hydraulic actuator, table, and test specimen. Closed loop control is accomplished by a state-variable controller within the Realtime Controller that computes servovalve command updates on the basis of displacement, acceleration, and force sensor feedbacks.

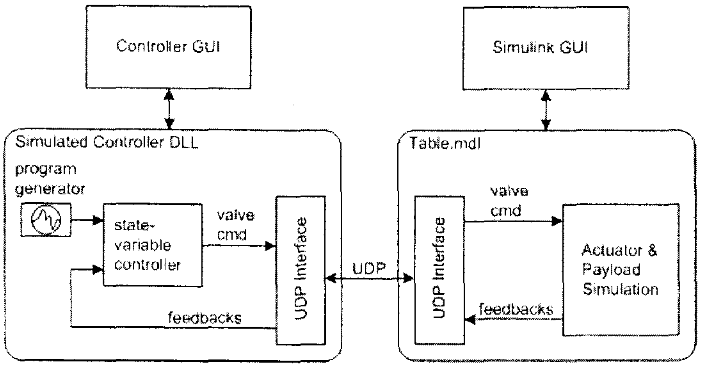

Figure 9. Simulated seismic table control system

In the simulated seismic control system shown in Figure 9, the actuator, table, and specimen is replaced with a Matlab (Mathworks 2004) Simulink model. The Controller GUI is the same as that of the actual seismic control system, except the Realtime Controller is replaced by a Windows DLL that executes control software in non-realtime. Because sensor conditioner hardware does not exist in the Simulated Controller, the sensor feedbacks come instead from the Simulink model via User Datagram Protocol (UDP), which is the communication mechanism used to link the Simulated Controller program with the Simulink program. Likewise, the valve driver hardware does not exist in the Simulated Controller; instead the valve command is sent to Simulink via UDP.

Offline simulation can also be used to study the response of any specimen/plant combination and to verify and understand control techniques such as offline iteration. An example comparison of the real system and the simulated system is shown in Figure 10. The real system was one of the LSSL shake tables subjected to random excitation.

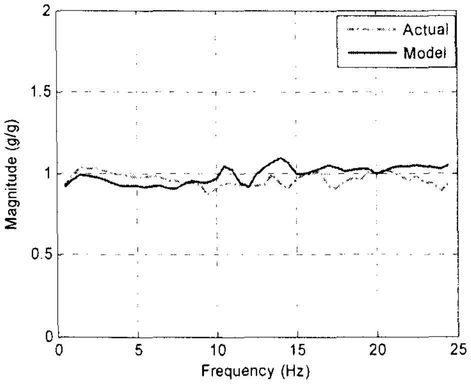

Figure 10. FRF of real table and simulation model

6. Hybrid Development

Real-time hybrid simulation is a method to determine the response of a structure to dynamic excitation. Hybrid simulation is unique since the simulation is composed of one or more physical models and one or more numerical models. Typically, a portion of a structure is attached to a shake table or servo-hydraulic actuator while the rest of the structure is modeled numerically.

The University of Nevada Reno, has been developing a hybrid testing infrastructure for researching real-time hybrid simulations (Figure 11). The infrastructure includes a MTS 469D seismic controller (MTS 2006), MTS FlexTest IIM actuator controller, and multiple National Instruments PXI chassis (National Instruments 2006), all distributed on a Systran ScramNET reflective memory ring.

A hybrid hardware test without the simulation in the loop will be performed on the NEESR 4-span bridge in the summer of 2006 (Figure 12).

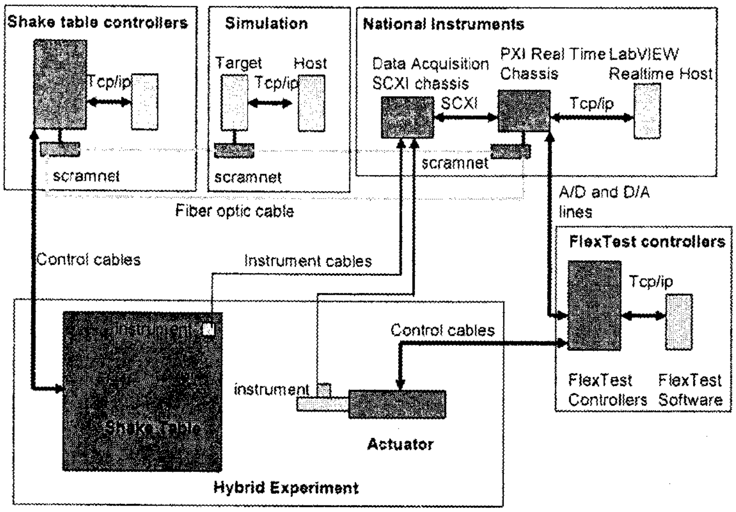

Figure 11. Basic Hybrid Network

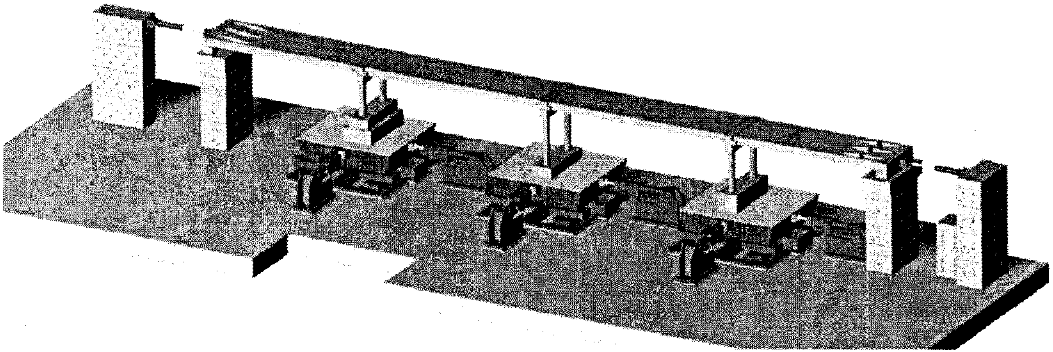

Figure 12: NEESR 4-Span Bridge

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