

REAL-TIME DYNAMIC HYBRID TESTING OF STRUCTURAL SYSTEMS

Andrei REINHORN¹, Mettupalayam V. SIVASELVAN², Zach LIANG² and Xiaoyun SHAO³

ABSTRACT

The development and implementation of a novel structural testing method involving the combined use of shake tables, actuators, and computational engines for the seismic simulation of structures is presented herein. The hybrid simulation is intended to discover through physical testing the behavior of parts or whole substructure assemblies for which knowledge is limited, while the known parts of the structural system can be simulated analytically. The result of the hybrid simulation provides information of the entire system without need for whole system testing. The structure to be simulated is divided into one, or more, experimental and computational substructures. The interface forces between the experimental and computational substructures are imposed by actuators and resulting displacements and velocities are fed back to the computational engine. The earthquake ground motion is applied to the experimental substructures by shake tables. The unique aspect of the above hybrid system is force-based substructuring. The hybrid simulation can be implemented as pseudo-dynamic or real time dynamic methods. While the former has a long history of applications, while the latter was developed recently owing to the availability of newest technologies and investments done by the George E Brown Network for Earthquake Engineering Simulations.

Keywords: Hybrid testing, dynamics, experimentation, analysis, control

1. INTRODUCTION

Simulation of structures under seismic loads is usually performed either experimentally or computationally. Experimental results are used to develop and calibrate computational models of structural components and assemblies. These computational models are used to predict the response of structures. Further experiments are then performed to validate and refine the computational models. Structural simulation is thus an iterative process involving alternate stages of experimentation and computation.

¹ *Clifford C. Furnas Professor*

² *Project Engineer, G. E. Brown Network for Earthq. Eng. Simulation (NEES),*

³ *Ph.D. Candidate,*

Dept. of Civil, Structural and Environmental Eng. University at Buffalo

This paper describes a new method of *real-time dynamic* seismic simulation of structures which involves combined use of experimentation and computation and some of the above iteration can potentially be performed online. The new development was facilitated by the new George E. Brown Network for Earthquake Engineering Simulation (NEES) deployment which provides unique opportunities for integrated experimentation and computing.

This novel structural simulation method involves the combined use of shake tables, actuators, and computational engines. The structure to be simulated is divided

into one or more experimental and computational substructures. The interface *forces* between the experimental and computational substructures are imposed by actuators and resulting displacements and velocities are fed back to the computational engine (See Figure 1). The earthquake ground motion can be applied to the experimental substructures by actuators as interpreted displacements (Pseudo-Dynamic Technique) or by one or more shakes tables

(Real-Time Dynamic Hybrid Technique). The unique aspect of the latter, the real-time dynamic hybrid system is the force-based sub-structuring. Since the shake tables induce inertia forces in the experimental substructures, the actuators have to be operated in dynamic force control as well. The resulting experimental-computational infrastructure is more versatile than previously deployed techniques.

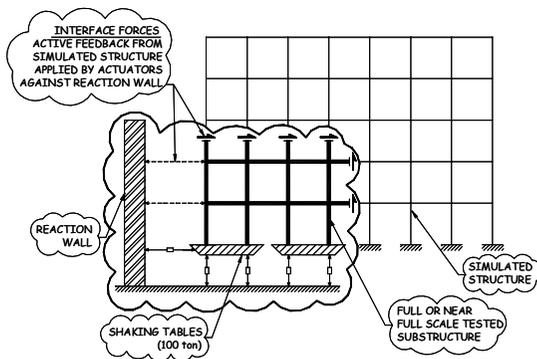


Figure 1- Substructure Testing

2. COMPUTATIONAL ISSUES

The simulation of structural dynamic response became a routine in the design of modern construction. Most simulations are done using computational tools which were verified by alternative analysis techniques or by experiments. The response of inelastic structures or other non linear systems is very difficult to assess. The time domain numerical simulation of structures under dynamic excitation is usually carried out by using either the modal superposition method (for elastic structures), or by direct integration methods. Appropriate assumptions have to be made in order to predict and calculate the response of the simulated structure. In particular, the direct integration methods utilized in dynamic testing are actually performed step-by-step. Not only the analytical errors are accumulated gradually, but the selection of sampling periods also affects the accuracy and stability of this integration process. More modern techniques based on State Space Approach (Sivaselvan and Reinhorn,

2004) can be formulated using system transition matrices derived from exact solutions. Such solutions are exact for elastic structures and present minimal errors for inelastic structures (Chu et al., 2002). Most recently analytical techniques based on Hamiltonian-Lagrangian formulations (Sivaselvan and Reinhorn, 2004) proved that inelastic problems with severe degradation, sudden breaks and repetitive impacts, as well as progressively collapsing structural assemblies can be solved with stable solutions using energy minimization techniques. These techniques and others developed in recent years still need experimental verification and identification of unknown phenomena neglected in modeling.

3. SUBSTRUCTURE TESTING OF LARGE SPECIMENS

Several experimental procedures are used to simulate and test the behavior of structural systems and components under earthquake loads. These include (1) Quasi-static testing (2) Shake-table testing (3) Effective force testing (4) Pseudo-dynamic testing and (5) Real Time Dynamic Hybrid testing (this paper). The Real-Time Dynamic Hybrid simulation, a form of substructure testing technique, allows only parts of the structure for which the analytical understanding is incomplete to be tested experimentally.

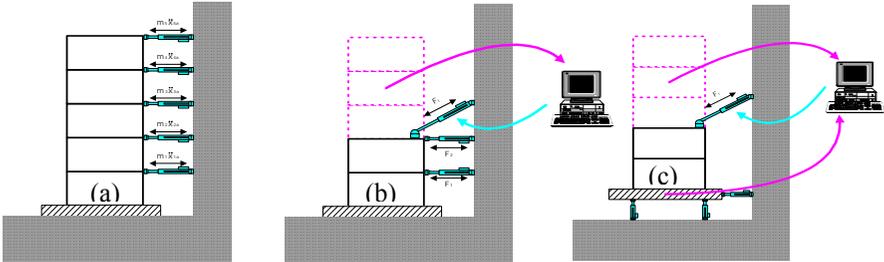


Figure 2 Modern methods for “dynamic” testing (a) Effective Force (b) Pseudo-dynamic (c) Real-Time Dynamic

But in contrast to other existing testing methods, the last testing method allows substructures to be tested in the context of structural assemblies under dynamic conditions so that they can be subject to realistic load histories. The real-time testing allows the rate-dependent effects to be captured accurately. Moreover when the real time evaluation of the structure is combined with real time identification of properties the resulting computational system becomes a reliable tool for analytical studies.

The substructure testing was developed in the 80’s and formulated by numerous researchers (Nakashima 1985, Mahin et al 1985, Shing et al, 1985). As a traditional form of substructure testing technique, the pseudo dynamic test is an experimental technique for simulating the earthquake response of structures and structural components in the time domain. The test was developed in the early 1970s, having a

history of nearly thirty years. In this test, the structural system is represented as a discrete spring-mass system, and its dynamic response to earthquakes is solved numerically using direct integration. Unlike conventional direct integration algorithms, in the pseudo dynamic test the restoring forces of the system are not modeled but are directly measured from a test conducted in parallel.

Because of various advantages of this test over the shaking table test, which is known to be the most direct method to simulate the earthquake responses of structures, the test has been introduced in many research institutions throughout the world. As an extension of this testing technique, the pseudo dynamic test with a real-time control was developed in the 1990s. A few of the notable developments are presented in Nakashima et al. (2003).

Real-time dynamic hybrid testing, the main subject of this paper, extends the above testing techniques by allowing for testing substructures under realistic dynamic loads and for representing rate-dependent and distributed inertia effects accurately. While the fast pseudo-dynamic (mentioned above) and the real-time dynamic hybrid testing use substructures for physical testing and online computations to simulate the global system in real-time, the latter technique includes the inertia effects are part of the physical system testing.

The newly developed George E Brown Network for Earthquake Engineering Simulation, developed experimental and computational infrastructure for implementation of Pseudo-Dynamic Testing (University of Illinois, Lehigh University), Fast Pseudo-Dynamic Testing (University of Colorado, University of California at Berkeley, Univeristy at Buffalo) and the most advanced Real-Time Dynamic Hybrid Testing (University at Buffalo). Description of those installations can be found at <http://www.nees.org/>

FORMULATION OF NEW HYBRID TESTING TECHNIQUE

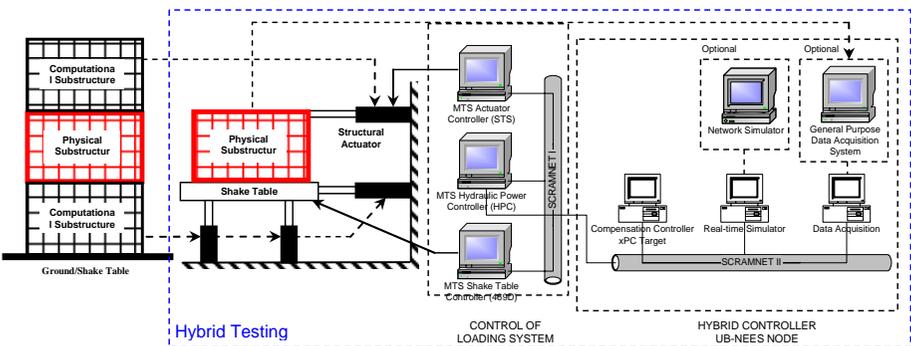


Figure 3 Schematic of Real-time Dynamic Hybrid Test System

Real-time Dynamic Hybrid Testing (RTDHT) shown in Figure 2(c) is a novel structural testing method involving the combined use of shake tables, actuators, and computational engines for the seismic simulation of structures.

The structure to be simulated is divided into a physical substructure and one or more computational substructures. The interface forces between the physical and computational substructures are imposed by actuators and resulting displacements and velocities are fed back to the computational engine. The earthquake ground motion, or motion of other computational substructures, is applied to the experimental substructure by shake tables. A schematic of the RTDHT system is shown in Figure 3. A detailed description of the implementation follows:

SUBSTRUCTURING METHODS:

The RTDHT implies first determining the model of the physical substructure being tested within the whole structural model identifying the interface parameters. A three-story model is shown in Figure 3 with its parameters. If u_g is the motion of the ground with respect to the inertial reference frame. u_i and x_i are the motions of the i^{th} story with respect to the fixed reference frame and with respect to the ground respectively, then $u_i = u_g + x_i$. Defining the first and third floor in Figure as *computational substructures* and the second floor as the *experimental substructure* as shown also in Figure 3, the equations of motion in the inertial reference frame are then given by:

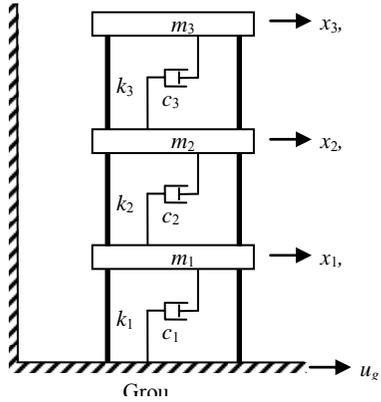


Figure 4. Three story model

$$\begin{aligned}
 m_1 \ddot{u}_1 + (c_1 + c_2) \dot{x}_1 - c_2 \dot{x}_2 + (k_1 + k_2) x_1 - k_2 x_2 &= 0 \rightarrow \text{Computational Substructure 2} \\
 m_2 \ddot{u}_2 - c_2 \dot{x}_1 + (c_2 + c_3) \dot{x}_2 - c_3 \dot{x}_3 - k_2 x_1 + (k_2 + k_3) x_2 - k_3 x_3 &= 0 \rightarrow \text{Experimental Substructure} \\
 m_2 \ddot{u}_2 - c_3 \dot{x}_2 + c_3 \dot{x}_3 - k_3 x_2 + k_3 x_3 &= 0 \rightarrow \text{Computational Substructure 1}
 \end{aligned} \tag{1}$$

By considering the influence of the *experimental substructure* as external disturbance, the equations of the *computational substructures* may be written as:

$$\begin{aligned}
 m_1 \ddot{x}_1 + c_1 \dot{x}_1 + k_1 x_1 &= -m_1 \ddot{u}_g + \underbrace{k_2 (x_2 - x_1) + c_2 (\dot{x}_2 - \dot{x}_1)}_{\substack{\text{Force measured at the base} \\ \text{of experimental substructure}}} \\
 m_3 \ddot{x}_3 + c_3 \dot{x}_3 + k_3 x_3 &= -m_3 \ddot{u}_g + \underbrace{k_3 x_2 + c_3 \dot{x}_2}_{\substack{(k_3 * \text{displacement} + c_3 * \text{velocity}) \text{ of} \\ \text{experimental substructure}}}
 \end{aligned} \tag{2}$$

The equation governing the *experimental substructure* rearranged using the relative displacement $x_{21} = x_2 - x_1$. Then equation (2) becomes:

$$m_2 (\ddot{u}_1 + \ddot{x}_{21}) + c_2 \dot{x}_{21} + k_2 x_{21} = k_3 (x_3 - x_2) \tag{3}$$

Being able to use both a shake table and an actuator to excite the experimental substructure introduces several possibilities for the application of the first floor acceleration \ddot{u}_1 and the thirds story force $k_3(x_3 - x_2)$: (a) Apply the acceleration using the shake table and the force using the actuator.; alternatively (b) Apply the ground acceleration using the actuator as well (as in the Effective Force method); (c) Yet another alternative is obtained by rearranging equation (3) as follows:

$$m_2 \left[\underbrace{\ddot{u}_1 - \frac{k_3}{m_2}(x_3 - x_2)}_{\text{Equivalent acceleration}} + \ddot{x}_{21} \right] + c_2 \dot{x}_{21} + k_2 x_{21} = 0 \quad (4)$$

The equivalent acceleration can be applied using the shake table only. However, the first story acceleration and the third story force can each be divided into two components, one to be applied by the shake table, and the other by the actuator. The actuator is assumed fixed in the inertial reference frame, while the structure is in a non-inertial frame attached to the shake table. The actions are shown below:

$$\begin{aligned} \text{Shake table acceleration, } \ddot{u}_t &= \underbrace{\alpha_1(s) \ddot{u}_1}_{\substack{\text{First story contribution} \\ \text{to shake table acceleration}}} - \underbrace{\alpha_3(s) \frac{k_3}{m_2} (x_3 - x_2)}_{\substack{\text{Third story contribution} \\ \text{to shake table acceleration}}} \\ \text{Actuator Force, } F_a &= - \underbrace{[1 - \alpha_1(s)] m_2 \ddot{u}_1}_{\substack{\text{First story contribution} \\ \text{to actuator force}}} + \underbrace{[1 - \alpha_3(s)] k_3 (x_3 - x_2)}_{\substack{\text{Third story contribution} \\ \text{to actuator force}}} \end{aligned} \quad (5)$$

where $\alpha_1(s)$ and $\alpha_3(s)$ are frequency dependent splitting function such as for example band-pass filters. Such a splitting has several advantages discussed by Kausel (1998), Reinhorn and Sivaselvan (2004). The above substructuring and force splitting strategies are:

- If $\alpha_1(s) \neq 0$ and $\alpha_3(s) \neq 0$, then the control requires a shake table and an actuator to implement the substructure testing.
- If $\alpha_1(s) = 0$ and $\alpha_3(s) = 0$, however, two possibilities exist:
 - In dynamic testing, the inertia is part of the experimental system, whereas in pseudo-dynamic testing, inertia effects are computed.
 - Thus for hybrid testing ($\alpha_1(s) \neq 0$ or $\alpha_3(s) \neq 0$) or dynamic hybrid testing, the actuator should operate in force control.

Such a unified view of hybrid simultaneous computation and experimentation testing systems provides a better perspective to develop algorithms and software.

DYNAMIC FORCE CONTROL

The implementation of the RTDHT requires therefore implementation of force control in the hydraulic actuators. This control is sensitive to the acceleration and force measurements, to the modeling of the compressibility of fluid, to the nonlinearities of the servo control system (servo valves) and other stiffness. The authors developed two approaches for dynamic force control:

The first approach is using the convolution method with a compensation technique that is based on identification of the frequency response function (FRF) of the system and modifying the force input by the inverse of the FRF. The operation is done in the time domain by evaluating the convolution integral. The forces are calculated based on Equation 6 with $\alpha_1(s) = 1$ and $\alpha_3(s) = 0$. Without the compensation the implementation is not feasible. The system was tested for free vibrations, and base motion –white noise and earthquakes. The performance for the white noise of the 2-dof and the 1-dof hybrid set-up is shown in Figure 5. The hybrid system simulates the 2-dof over the entire frequency range except for the very low frequencies with errors of up to 5%.

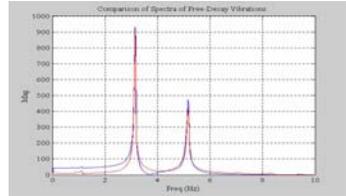


Figure 5 Pilot test for white noise

The second approach is based on control characteristics of hydraulic actuators. A hydraulic actuator is a rate-type device or velocity source; however, hydraulic actuators are typically designed for good position control. In contrast for force control, a force source is required. Thus force control using hydraulic actuators is an inherently difficult problem. Actuators designed for position control have stiff oil columns, making force control very sensitive to control parameters and often leading to instabilities. Moreover friction, stick-slip, breakaway forces on seals, backlash etc. cause force noise, making force a difficult variable to control.

Motivated by these observations and by the fact that causality requires a flexible component in order to apply a force in the force control scheme described here, a spring is introduced between the actuator and the structure as shown in Figure 6. Notice that the scheme (1) intentionally introduced series spring, K_{LC} , which assumes the role of the oil spring and (2) there is no force feedback loop.

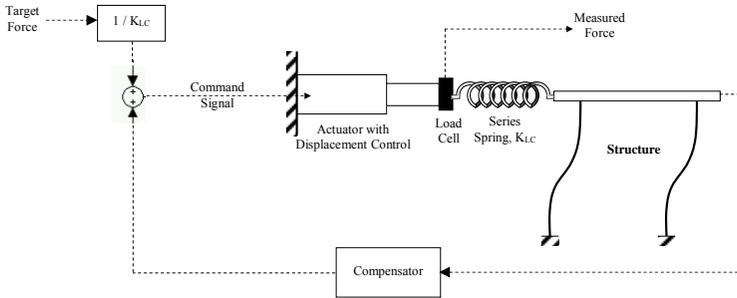


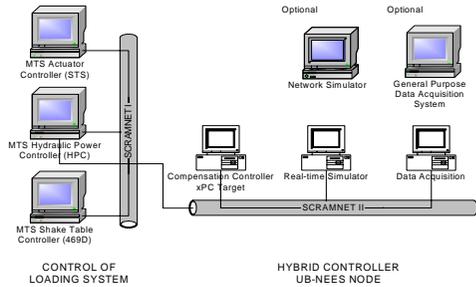
Figure 6. Proposed force control scheme

The actuator behaves as a displacement device. Hence the actuator in the control scheme of Figure 6 is operated in closed-loop displacement control with a PIDF controller. Although the system as a whole controls force function, *internally the actuator operates in closed-loop displacement control*. Hence, there is no need for an additional force feedback loop to ensure stability. More details on these developments are presented elsewhere by Reinhorn et al, 2004.

DISTRIBUTED REAL-TIME ARCHITECTURE

The real-time hybrid system is implemented using a distributed architecture that uses Shared Random Access Memory Network (SCRAMNET™), a very low-latency replicated shared memory fiber optic network. The architecture of hardware-software controller (see right side of Figure 3) allows for flexibility in the design of the real-time operating system and in the implementation of the components used. There are three units which form the controller:

1. **The Compensation Controller** which contains the cascade control loop for force control presented above. This controller also compensates for time-delays that are inherent in the physical system.
 2. **The Real-time Simulator** which simulates the computational substructures. The architecture has been designed so that this simulator could be seamlessly replaced by one at a remote location or a Supercomputer, if necessary.
 3. **The Data Acquisition System (DAQ)** that is used for feedback from the experimental substructure as well as for archiving information during the test.
- Figure 7 Computational Infrastructure



The controller operates in a synchronous-asynchronous manner. The controller was developed to allow parallel operations of each of the three units while sharing only essential information through a “pool” memory provided by the 1μsec update rate SCRAMNET. Each individual component / unit operates at each own time rate,

accessing the shared memory when needed, without delaying other units. The compensation controller is designed to compensate also for all other latencies in communications, computing and hydraulic operations. The current implementation at University at Buffalo uses the architecture shown above which allows substituting the Simulation Component with any computational device - such as a supercomputer operating in a Grid.

REAL TIME HYBRID TESTING IMPLEMENTATION

A series of hybrid tests were performed on a two-story structure with the first story built on the shake table and the second story simulated (see Figure 7).

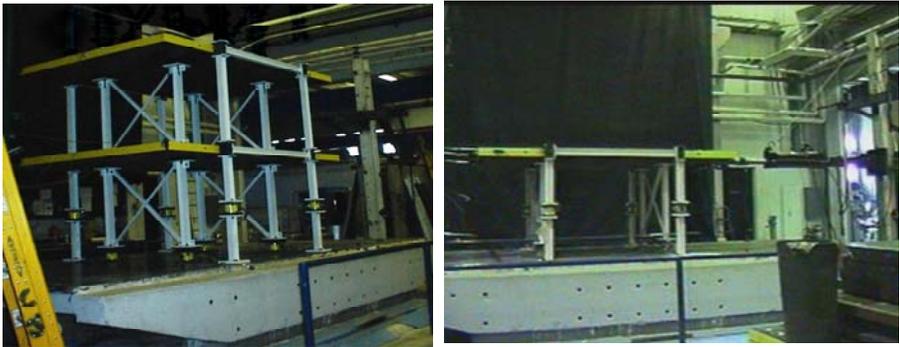


Figure 7 – Two stories (left) and hybrid test on shake table (right)

A sample result from a sine-sweep test is shown in the frequency domain in Figure 8. The result is compared with a computational simulation of the two story model. The result shows a small discrepancy in the damping representation. This is the subject of current work.

The results from real-time hybrid tests are presented for two cases:

- Two stories structure – tested and analyzed using h shake table motion.
- Hybrid system: one story with an actuator on physically tested on shake table

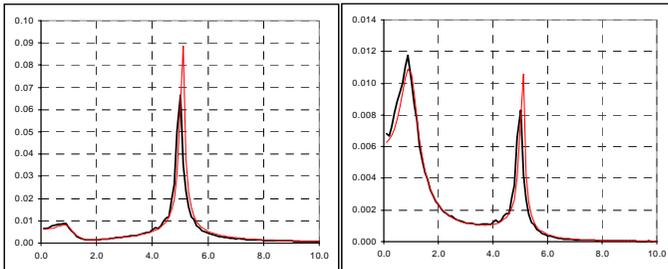


Figure 8 – Results of simulation experiments

The results in Figure 8 (on left) show the transfer function of the system measured during the experiment and the reference computation at first floor. Figure 8 (on right) shows the computed response of the virtual second story from measured data versus the analytical simulation. The hybrid test is capable to achieve both amplitude and frequency content with minor differences – attributed to the resolution of the data acquisition system. The rest of discrepancies are believed to stem from unmodelled damping in the system and from some latency.

CONCLUDING REMARKS

The Real Time Dynamic Hybrid Testing System is implementing combined physical testing and computational simulations to enable dynamic testing of sub-structures including the rate and inertial effects while considering the whole system. The paper presents a new force control scheme with a predictive compensation procedure which enabled the real-time implementation. The new system was tested through bench tests and medium scale pilot testing successfully. The procedures are implemented in the full / large scale University at Buffalo NEES node which includes two six degree of freedom shake tables and three high speed dynamic actuators and a structural testing system controller (STS) capable to implement the control algorithms presented above.

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