

REAL-TIME DYNAMIC HYBRID TESTING OF STRUCTURAL SYSTEMS

Andrei M. Reinhorn¹, Mettupalayam V. Sivaselvan², Scot Weinreber³, Xiaoyun Shao⁴

^{1,2,3,4}University at Buffalo

This paper presents 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. 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. Since the shake tables induce inertia forces in the experimental substructures, the actuators have to be operated in dynamic force control as well, since either the force or the displacement, but not both can be controlled at a given point and at a given instant of time. The resulting testing method is more versatile than existing seismic testing methods. First the substructuring strategy and the numerical integration algorithms associated with the computational substructures are discussed along with the implementation of the computational engine. Then a new dynamic force control strategy developed for this purpose using series elasticity and displacement compensation is briefly reviewed. Issues related to time-delay compensation are also discussed. Finally, an example of a real-time hybrid test implementation, and results from this experiment are presented.

Keywords: *Force control, Dynamic hybrid testing*

1 Introduction

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 ([1]) (3) Effective force testing ([2]) and (4) Pseudo-dynamic testing ([3]) (see **Figure 3**). Real-time dynamic hybrid testing extends these methods by allowing for testing substructures under realistic dynamic loads and for representing rate-dependent and distributed inertia effects accurately. In a recent development a fast pseudo-dynamic method was developed to account for rate dependency. While the fast pseudo-dynamic and the real-time dynamic hybrid testing use sub-structures 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.

Real-time Dynamic Hybrid Testing (RTDHT) shown in Figure 1(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**. The right side in **Figure 3** shows the physical computational infrastructure required for the implementation of the forces and motions at the interface of the physical and computational substructures. The theoretical basis and

¹ Clifford C. Furnas Professor of Structural Engineering, Dept. of Civil, Structural and Environmental Engineering, University at Buffalo (SUNY), Buffalo, NY 14260. Email: Reinhorn@buffalo.edu

² Project Engineer, George E. Brown Network for Earthquake Engineering Simulation (NEES), University at Buffalo (SUNY), Buffalo, NY 14260.

³ Instrumentation Engineer, Structural Engineering and Earthquake Simulation Laboratory (SEESL), Dept. of Civil, Structural and Environmental Engineering, University at Buffalo, Buffalo (SUNY), NY 14260.

⁴ Ph.D. candidate, Dept. of Civil, Structural and Environmental Engineering, University at Buffalo (SUNY), Buffalo, NY 14260.

the implementation of real time dynamic hybrid testing (RTDHT) is presented in the next sections.

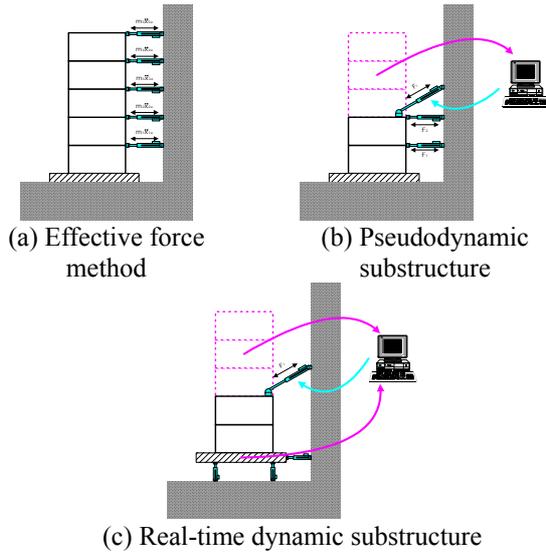


Figure 1: Modern Methods for “dynamic” testing in earthquake engineering.

2 Substructuring

The RTDHT implies first determining the model of the physical substructure being tested within the whole structural model identifying the interface parameters. The computational model must be simple in order to be executed in real time. For the sake of simplicity, derivations are presented here only for a structural configuration shown in **Figure 2**. 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 $u_i = u_g + x_i$.

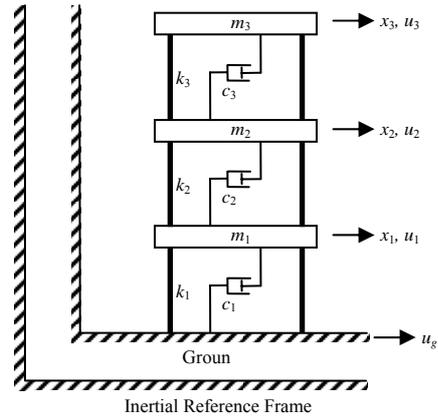


Figure 2: Three story model

The damping is assumed to be of the form shown in Figure 3, in order to preserve a simple formulation for the computational model. Defining the first and third floor in **Figure 2** 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 equation (1). By considering the influence of the *experimental substructure* as external disturbance, the equations of the *computational substructures* may be written as equation (2).

Similarly the equation governing the experimental substructure may be arranged as shown in equation (3). It is useful to introduce the relative displacement $x_{21} = x_2 - x_1$. Then equation (3) can be rewritten as equation (4).

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

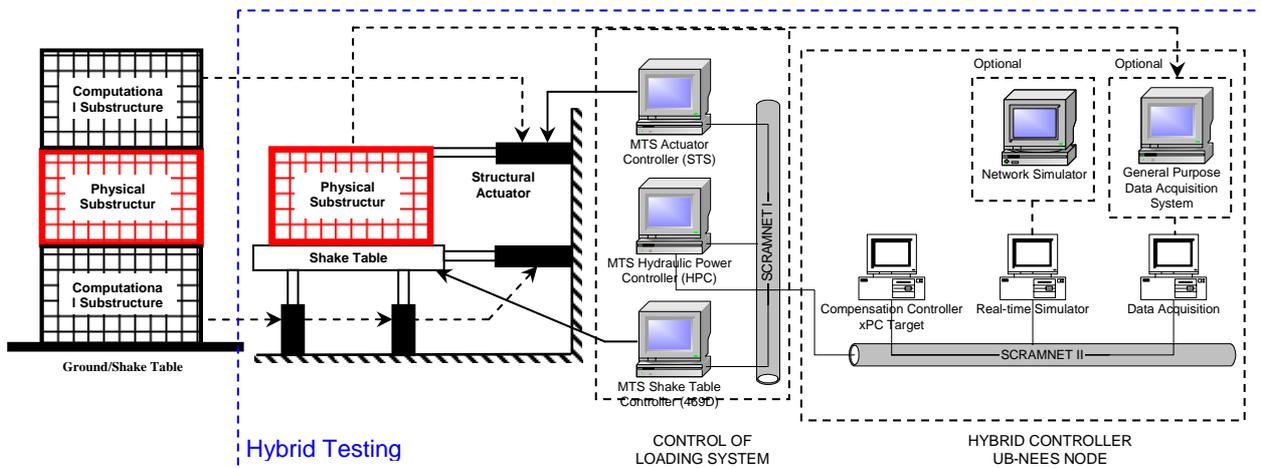


Figure 3: Schematic of real-time dynamic hybrid test system

$$m_1 \ddot{x}_1 + c_1 \dot{x}_1 + k_1 x_1 = -m_1 \ddot{u}_g + \underbrace{k_2 (x_2 - x_1) + c_2 (\dot{x}_2 - \dot{x}_1)}_{\substack{\text{Force measured at the base} \\ \text{of experimental substructure}}} \quad (2)$$

$$m_3 \ddot{x}_3 + c_3 \dot{x}_3 + k_3 x_3 = -m_3 \ddot{u}_g + \underbrace{k_3 x_2 + c_3 \dot{x}_2}_{\substack{(k_3 * \text{displacement} + c_3 * \text{velocity}) \\ \text{of experimental substructure}}} \quad (3)$$

$$m_2 \left(\underbrace{\ddot{u}_g}_{\text{External Load}} + \ddot{x}_2 \right) + c_2 (\dot{x}_2 - \dot{x}_1) + k_2 (x_2 - x_1) = k_3 \left(\underbrace{x_3}_{\text{Computed}} - \underbrace{x_2}_{\text{Measured (Feedback)}} \right) \quad (4)$$

$$m_2 (\ddot{u}_1 + \ddot{x}_{21}) + c_2 \dot{x}_{21} + k_2 x_{21} = k_3 (x_3 - x_2) \quad (4)$$

Being able to use both a shake table and an actuator to excite the experimental substructure introduces several possibilities. A number of alternatives exist for the application of the first floor acceleration \ddot{u}_1 and the third story force $k_3 (x_3 - x_2)$: (a) One possibility is to apply the acceleration using the shake table and the force using the actuator. (b) Another option is to apply the ground acceleration using the actuator as well (as in the Effective Force method). (c) Yet another alternative is obtained by rearranging equation (4) as follows:

$$m_2 \left[\underbrace{\ddot{u}_1 - \frac{k_3}{m_2} (x_3 - x_2)}_{\text{Equivalent acceleration}} + \ddot{x}_{21} \right] + c_2 \dot{x}_{21} + k_2 x_{21} = 0 \quad (5)$$

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:

$$\text{Shake table acceleration, } \ddot{u}_1 = \underbrace{\alpha_1(s) \ddot{u}_g}_{\substack{\text{First story contribution} \\ \text{to shake table acceleration}}} - \alpha_3(s) \underbrace{\frac{k_3}{m_2} (x_3 - x_2)}_{\substack{\text{Third story contribution} \\ \text{to shake table acceleration}}} \quad (6)$$

$$\text{Actuator Force, } F_a = -\underbrace{[1 - \alpha_1(s)] m_2 \ddot{u}_1}_{\substack{\text{First story contribution} \\ \text{to actuator force}}} + \underbrace{[1 - \alpha_3(s)] k_3 (x_3 - x_2)}_{\substack{\text{Third story contribution} \\ \text{to actuator force}}}$$

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. For instance, the oil column frequency of shake tables is relatively low due to their heavy mass and limits their bandwidth. Moreover, shake tables that are restrained by bearings do not perform well at very low frequencies. These frequency components can then be transferred to the actuator. The splitting can also be based on instantaneous or average power minimization for the test. These issues are discussed by [4].

The above substructuring and force splitting strategies are shown schematically in **Figure 4** If $\alpha_1(s) \neq 0$ and $\alpha_2(s) \neq 0$, then the control requires a shake table and an actuator to implement the substructure testing. The actuator therefore has to operate in force control. If $\alpha_1(s) = 0$ and $\alpha_2(s) = 0$, however, two possibilities exist. Let the force input to the actuator in **Figure 5** be F . Then the two possibilities are shown in **Figure 5**. 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 $\alpha_2(s) \neq 0$) or dynamic hybrid testing, the actuator should operate in force control. The force control problem is discussed in a companion paper [5].

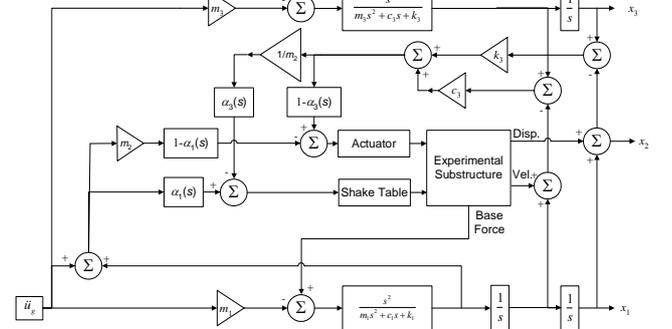
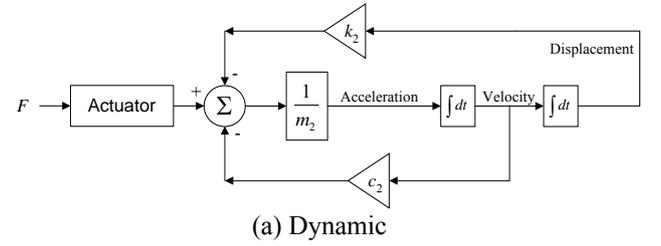
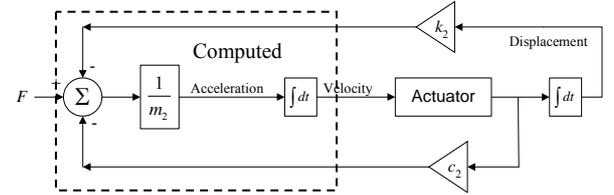


Figure 4: Schematic of hybrid substructuring



(a) Dynamic



(b) Pseudo-dynamic

Figure 5: Dynamic and pseudo-dynamic testing

Such a unified view of hybrid simultaneous computation and experimentation testing systems provides a better perspective to develop algorithms and software. The similarities between compensation strategies in force and displacement control are reviewed for instance by [6].

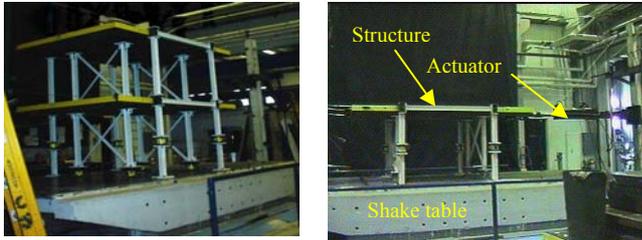
3 Experimental results

The hybrid test setup is shown in **Figure 6**. A hybrid test was performed on a two-story structure with the first story built on the shake table and the second story simulated as shown in **Figure 6**. In relation to **Figure 4**, $u_1 = u_g$, $\alpha_1(s) = 1$ and $\alpha_2(s) = 0$. The control scheme is shown in **Figure 7**. A sample result from a sine-sweep test is shown in the frequency domain in showing the comparison between the shake-table and hybrid test results.

4 Distributed real-time architecture

The real-time hybrid system is implemented using a distributed architecture that uses Shared Random

Access Memory Network (SCRAMNETTM), 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 as shown in the Hybrid Controller.



(a) Two story structure (b) Hybrid test setup
Figure 6: Hybrid test setup

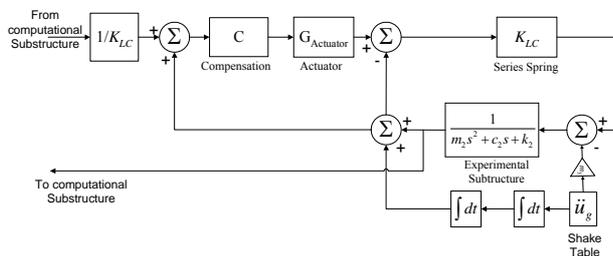
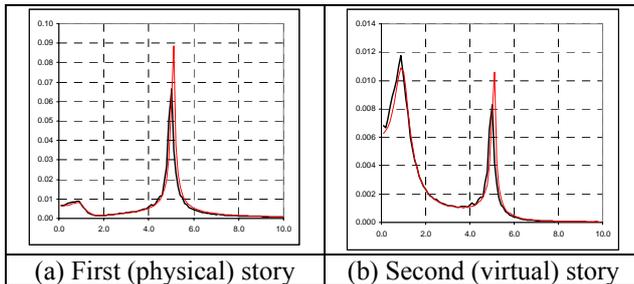


Figure 7: Control scheme for two story hybrid test



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 and those that are introduced by filtering, computation, network communication, etc.
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 that is at a remote location. With the current state-of-the-art, however, network speed would become the bottleneck to real-time operation. This is accommodated using an additional interrupt mechanism.
3. **The Data Acquisition System (DAQ)** that is used for feedback from the experimental substructure as well as for archiving information during the test. The controller operates in a synchronous-asynchronous manner using SCRAMNET interrupts.

5 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 successfully using a pilot setup. 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.

6 Acknowledgments

This research was sponsored by National Science Foundation Grants No. CMS 086611 and 086612 for establishing the University at Buffalo node of the George Brown Jr. Network for Earthquake Engineering Simulations. The authors acknowledge the financial support and the UB team member's participation: Mr. Hanley and Mr. Pitman

References

- [1.] Nagarajaiah, S., Reinhorn, A.M., and Constantinou, M.C., "Experimental-Study of Sliding Isolated Structures with Uplift Restraint." *Journal of Structural Engineering-ASCE*, 1992. **118**(6): 1666-1682.
- [2.] Shield, C.K., French, C.W., and Timm, J., "Development and implementation of the effective force testing method for seismic simulation of large-scale structures." *Philosophical Transactions of the Royal Society of London Series a-Mathematical Physical and Engineering Sciences*, 2001. **359**(1786): 1911-1929.
- [3.] Shing, P.B., Bursi, O.S., and Vannan, M.T., "Pseudodynamic Tests of a Concentrically Braced Frame Using Substructuring Techniques." *Journal of Constructional Steel Research*, 1994. **29**(1-3): 121-148.
- [4.] Kausel, E., "New seismic testing method. I: Fundamental concepts." *Journal of Engineering Mechanics-Asce*, 1998. **124**(5): 565-570.
- [5.] Reinhorn, A.M., Sivaselvan, M.V., Weinreber, S., and Shao, X. (2004). "A novel approach to dynamic force control." *Third European conference on structural control*, Vienna, Austria.
- [6.] Zhao, J., French, C., Shield, C., and Posbergh, T., "Considerations for the development of real-time dynamic testing using servo-hydraulic actuation." *Earthquake Engineering & Structural Dynamics*, 2003. **32**(11): 1773-1794.