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Evaluation of a real-time hybrid simulation system for performance evaluation of structures with rate dependent devices subjected to seismic loading

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ABSTRACT

Real-time hybrid simulation is a viable experiment technique to evaluate the performance of structural systems subjected to earthquake loads. This paper presents details of the real-time hybrid simulation system developed at Lehigh University, including the hydraulic actuators, the IT control architecture, an integration algorithm and actuator delay compensation. An explicit integration algorithm provides a robust and accurate solution to the equations of motion while an adaptive inverse compensation method ensures the accurate application of the command displacements to experimental substructure(s) by servo-hydraulic actuators. Experiments of a steel moment resisting frame with magneto-rheological fluid dampers in passive-on mode were conducted using the real-time hybrid simulation system to evaluate the ability for the simulation method to evaluate the nonlinear seismic response of steel frame systems with dampers that are intended to enhance the response of the structure. The comparison with numerical simulation results demonstrates that the real-time hybrid simulation system produces accurate and reliable experimental results and therefore shows great potential for structural performance evaluation in earthquake engineering research.

1. Introduction

Real-time hybrid simulation, also known as real-time substructure testing, is a real-time extension of conventional hybrid simulation. It divides a structural system into experimental substructure(s) and analytical substructure(s), and enables the complete structural system to be considered during the simulation [1,2]. Therefore, real-time hybrid simulation provides an economic yet viable technique for investigating the dynamic response of structural systems, especially for structures with rate-dependent devices. During a real-time hybrid simulation, the coupling between the experimental and analytical substructures is achieved by maintaining the compatibility and equilibrium at the interfaces between these substructures. The displacement response of the structural system is calculated using an integration algorithm that solves the equations of motion based on restoring forces from the substructures developed under the imposed displacement response. Unlike conventional hybrid simulation [3], real-time hybrid simulation is conducted in a real-time manner, which requires the command displacements be imposed at a real-time scale by servo-hydraulic actuator(s) onto the experimental substructure(s). The experimental and analytical substructures, the integration algorithm, and the servo-hydraulic actuator(s) are integrated together through an IT control architecture to form the real-time hybrid simulation system. A successful real-time hybrid simulation requires that the integration algorithm be robust and accurate; the servo-hydraulic control system must enable the actuators to accurately impose command displacements onto the structure in real-time; and the communication between the integration algorithm, servo-hydraulic control system, and analytical substructure needs to be synchronized and have minimal delay.

Explicit integration algorithms are usually preferred for real-time hybrid simulation since the structural response are calculated based on the information from previous time steps [4–6]. Explicit integration algorithms therefore do not involve iterations within the time step and require less computational effort than implicit integration algorithms. However, commonly used explicit integration algorithms such as the central difference method are only conditionally stable and restrictions on the time step size exist due to numerical stability. Implicit integration algorithms have also been investigated for real-time testing. Nakashima et al. [7] developed the operator-splitting technique for real-time testing. Shing developed a procedure that uses a fixed number of iterations for the implicit Hilber–Hughes–Taylor (HHT) α-method [8], which was

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Nomenclature

AIC	adaptive inverse compensation
CR	Chen-Ricles
DBE	design basis earthquake
HHT	Hilber–Hughes–Taylor
MCE	maximum considered earthquake
MNS	maxwell nonlinear slider
MR	Magnetorheological
MRF	moment resisting frame
RMS	root-mean-square
RTMD	real-time multi-directional
TI	tracking indicator

applied for fast hybrid simulation at the University of Colorado [9,10]. Recently, several innovative integration algorithms have been developed by researchers, including the explicit integration algorithms by Chang [11], Lamarche et al. [12], and Chen and Ricles [13].

After the integration algorithm solves the equations of motion, servo-hydraulic actuators are used to impose the transformed structural response to the experimental substructure(s). Due to servo-hydraulic dynamics, a time delay will be introduced in the actuator response; this time delay is often referred to as *actuator delay*. The effect of actuator delay on real-time hybrid simulation has been investigated by numerous researchers [14–16]. Their research shows that actuator delay will lead to a de-synchronization between the measured restoring force(s) from the experimental substructure(s) and the integration algorithm, which can destabilize a real-time hybrid simulation if not compensated properly.

Actuator delay compensation is often used to minimize the detrimental effect of actuator delay so as to achieve accurate actuator control for real-time testing. The underlying theory for actuator delay compensation methods is to send predicted displacements to the servo-hydraulic actuator so that the actuator would reach the desirable displacements at the desired time points. Horiuchi et al. [17,18] proposed two compensation schemes for actuator control based on polynomial extrapolation and a linear acceleration assumption, respectively. Chen [19] proposed a simplified model for servo-hydraulic actuator response using a first-order discrete transfer function, and applied its inverse to compensate for actuator delay in a real-time hybrid simulation. Methods originating from control engineering theory have also been applied to real-time testing, such as the derivative feed-forward compensation method [9,10]. These compensation methods assume a constant actuator delay throughout the simulation. Chen and Ricles [20] showed that the performance of these compensation methods can be analyzed through frequency response analysis of the equivalent discrete transfer function.

An accurate estimate of actuator delay is often difficult to acquire before the test. Moreover, variable actuator delay might exist during a real-time hybrid simulation due to the nonlinearities in the servo-hydraulic system and the experimental substructures. Compensation methods based on adaptive control theory have been investigated by a number of researchers. Darby et al. [21] proposed an online procedure to estimate and compensate for actuator delay during a real-time hybrid simulation. Bonnet et al. [22] applied model reference adaptive minimal control synthesis (MCS) to real-time testing. Carrion and Spencer [23] used a feedforward-feedback controller in conjunction with inverse modeling to compensate for variable actuator delay. Chen and Ricles [24] developed an adaptive inverse compensation method based on the inverse compensation to minimize the effect of inaccurately estimated and variable actuator delay for a real-time hybrid simulation.

The Lehigh real-time multi-directional (RTMD) Facility, an equipment site of the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES), has focused on the development of the real-time hybrid simulation method for earthquake engineering research. This effort has resulted in the development of a large-scale real-time hybrid simulation system. This system uses the unconditionally stable explicit CR integration algorithm develop by Chen and Ricles [13] for solving the equations of motion and the adaptive inverse compensation for actuator delay compensation [24]. The real-time hybrid simulation system is described in detail in this paper and its performance is evaluated through real-time hybrid simulations of a two-story, four-bay steel moment resisting frame with rate-dependent MR fluid dampers in passive-on mode subjected to selected ground motions.

2. Integration algorithm for RTMD real-time hybrid simulation system

For a typical structural system subject to predefined external excitation, the time-discretized equations of motion can be written as

$$\mathbf{M}\cdot\ddot{\mathbf{X}}(t)+\mathbf{C}\cdot\dot{\mathbf{X}}(t)+\mathbf{r}(t)=\mathbf{F}(t) \tag{1}$$

where $\boldsymbol{M}$ and $\boldsymbol{C}$ are the mass and viscous damping matrices of the structural system, respectively; $\dot{\mathbf{X}}(t)$ and $\ddot{\mathbf{X}}(t)$ are the velocity and acceleration response vectors, respectively; $\boldsymbol{F}(t)$ is the external excitation force vector; and $\boldsymbol{r}(t)$ is the restoring force vector of the structure. For a linear elastic structure, the restoring force $\boldsymbol{r}(t)$ can be calculated using the linear elastic stiffness matrix $\boldsymbol{K}$ and the displacement response vector $\boldsymbol{X}(t)$ of the structure.

The Lehigh RTMD real-time hybrid simulation system utilizes an unconditionally stable explicit CR integration algorithm developed by Chen and Ricles [13], of which the variation of displacement and velocity over the time step are defined as

$$\dot{\mathbf{x}}_{i+1}=\dot{\mathbf{x}}_i+\Delta t\cdot\boldsymbol{\alpha}_1\cdot\ddot{\mathbf{x}}_i \tag{2a}$$

$$\mathbf{x}_{i+1}=\mathbf{x}_i+\Delta t\cdot\dot{\mathbf{x}}_i+\Delta t^2\cdot\boldsymbol{\alpha}_2\cdot\ddot{\mathbf{x}}_i \tag{2b}$$

where Δt is the integration time step; α_1 and α_2 are integration parameter matrices. Eqs. (2a) and (2b) indicate that the CR integration algorithm is explicit for both displacement and velocity. It can also be observed from Eq. (3) that integration parameters of the explicit CR algorithm are dependent on properties of the structure. To attain unconditional stability for the CR integration algorithm for a linear elastic structure, the integration parameters α_1 and α_2 are defined as

$$\boldsymbol{\alpha}_1=\boldsymbol{\alpha}_2=4\cdot(4\cdot\mathbf{M}+2\cdot\Delta t\cdot\mathbf{C}+\Delta t^2\cdot\mathbf{K})\cdot\mathbf{M}^{-1} \tag{3}$$

Fig. 1 show the properties (equivalent damping associated with the numerical damping and period elongation for the algorithm) of the explicit CR algorithm for a linear elastic single-degree-of-freedom system with 2% inherent viscous damping. Also presented in Fig. 1 for the purpose of comparison are properties of the Newmark explicit method, Newmark method with constant average acceleration, and HHT α-method ($\alpha = -1/12$). It can be observed that the explicit CR integration algorithm has the same accuracy (i.e., the same equivalent damping and period elongation) as the Newmark method with constant average acceleration.