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Experimental implementation of predictive indicators for configuring a real-time hybrid simulation

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ABSTRACT

Real-time hybrid simulation (RTHS) is gaining acceptance as an efficient and cost-effective method for realistic structural evaluation. Advances in real-time computing and control methods have enabled research in the development of this novel methodology to progress rapidly. However, to explore effectiveness and accuracy, and thus build broader confidence in the use of this method as an alternative to shake table testing, there is a need to better understand and address the key features that determine the success of an RTHS. Here we discuss the design and analysis of a SDOF RTHS case study conducted in Purdue University's Intelligent Infrastructure Systems Lab (IISL). We examine the key factors that determine the success, through configuration of the test using predictive indicators, design of an appropriately effective actuator controller, and a thorough comparison with shake table testing. The reference structure chosen for this case study is a single story, moment resisting frame structure. This particular specimen is of lab scale and well-known component properties, making it a suitable choice for such an investigation. However, noise, control–structure interaction and damping introduce numerous challenges typically faced in establishing an effective RTHS configuration. We investigate two key issues that lead to the design of a successful RTHS, specifically the partitioning between numerical and physical substructure for stability and performance, and the actuator motion control algorithm. Predictive indicators are demonstrated to be particularly helpful for properly configuring an RTHS experiment to meet a researcher's specified objectives. Furthermore a direct comparison is conducted to examine the ability of RTHS to replicate a shake table test. The results demonstrate that with proper partitioning and actuator control design, successful RTHS can be implemented despite unfavorable transfer system properties.

1. Introduction

Hybrid simulation, which combines physical testing and numerical simulation, provides an efficient alternative to full-scale dynamic testing [1]. In conventional hybrid simulation that is conducted at an extended time scale, the critical components are tested physically, while the rest of the structure is represented with a numerical simulation. During each time step, the responses of the system under a dynamic disturbance are obtained using numerical integration. Then the calculated displacements are imposed on the physical substructure at the interface using hydraulic actuators (also known as the transfer system). Measured forces are fed back into the numerical simulation for the calculation of structure responses for the next time step. In response to the interest shown in this approach, the NEES Task Force on Hybrid Simulation recently developed a hybrid simulation primer and dictionary which provides a general introduction for users new to hybrid simulation and terminology used in this emerging field of study [2]. Implementations of hybrid simulation in various NEES projects are introduced in [3].

Advances in hardware with real-time computing capabilities have enabled and accelerated the development of real-time hybrid simulation (RTHS) methods [4]. In RTHS, each communication loop between the numerical and physical substructures must be executed at real time and within one single time step. Therefore, this approach preserves rate dependent behavior that may play a role in the tested physical components. Compared to shake table testing, other advantages of RTHS are that it is more cost efficient, occupies less space and requires smaller loading capacity, while allowing researchers to focus on a particular portion of the system

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that may not be well understood. Moreover, one may use a single test specimen to facilitate the evaluation of a broad set of structures under a wide range of structural configuration and operating conditions. Fig. 1 illustrates a typical RTHS setup with dampers.

One of the challenges in conducting RTHS is the ability to accurately reproduce the boundary conditions between the numerical and physical components, i.e. compensate for the time delays and lags introduced by communication, computational hardware and hydraulic actuators. Failure to do so can lead to errors and even system instabilities [5]. Horiuchi et al. [5] demonstrated that the actuator response dynamics have an effect equivalent to introducing negative damping into the system. A polynomial extrapolation method was developed to reduce the time delay [5]. This method was implemented with a multi-degree-of-freedom system [6] and further improved to establish adaptive online estimation of time delay [7]. An adaptive phase lag compensation method, based on online system identification, has been developed [8,9]. First order transfer functions have been used to approximate servo-hydraulic dynamics [10,11]. Including a controller that represents an inverse of such a model over a certain frequency bandwidth may accommodate time delays present in the system. Higher order models have also been adopted and inverted to account for the dynamics over a broader frequency range [12–14]. Recently, controllers based on H_∞ algorithm have also been developed and successfully implemented for RTHS [15,16].

In addition to synchronizing numerical-physical boundary conditions, the overall dynamics of the reference structure, the fidelity of the numerical model, and the numerical-physical partitioning choice are primary factors that impact the fundamental stability and performance characteristics of an RTHS. Several researchers have investigated the impact of these properties on the stability and performance of simulations [7,15,17–21]. Moreover, to support the design of an appropriate RTHS experiment, predictive stability indicators (PSI) and predictive performance indicators (PPI) have been developed. PPI and PSI were established to provide researchers with the tools to assess the impact of partitioning choices on the stability and performance of a global RTHS system [22]. They facilitate a quantitative examination of the sensitivity of an RTHS configuration to any phase discrepancy arising from time delays and lags in the system, thus assisting the researcher to design an effective experiment. Also, Maghareh et al. [23] developed a stability switch criterion for effective RTHS implementation and specified minimum requirements of the transfer system and actuator controller, minimum required sampling frequency, and effective methods to stabilize an unstable simulation due to the limitations of the available transfer system. The experimental data used for verifying these indicators is publically available [24].

Different sources of error may occur in RTHS that those adopting this testing approach should consider in designing a test. For instance, errors introduced by structural modeling, numerical integration and experimental setup [22,25]. Model idealization is present in the numerical substructure model which is built to approximate actual continuous structure. The integration scheme and time step selection also influence the accuracy of an RTHS, with various explicit and implicit integration methods having been developed and implemented for real-time hybrid simulation [11,25–28]. Computational frameworks have been developed within various software environments to facilitate RTHS [29–31]. Recently, an open-source computational tool RT-Framce2D was developed for dynamic analysis of steel buildings, which offers real-time execution capabilities and various modeling options [32]. An emerging technique adopted from structural mechanics, known as multi-rate RTHS, is also being developed for computationally demanding numerical substructures. Here larger computational models are enabled by executing the numerical and physical substructures at different rates [33–35]. Finally, various random and systematic experimental errors exist in RTHS. For example, measurement noise and analog-to-digital truncations in electrical signals belong to random errors. Communication and computational delays, servo-hydraulic dynamics and calibration errors may also introduce systematic errors. Numerical errors are present in all hybrid testings and may be minimized with proper techniques, which are not within the scope of this manuscript. The focus of this study is mainly on systematic experimental errors.

RTHS has recently been applied to various types of civil engineering structures, to evaluate novel structural components and systems, and to establish design guidelines and codes [for a sample of such projects, see: 11,12,14,15,24,36–40]. However, it is important to recognize that researchers choose to employ RTHS for conducting tests having one or more specific goals in mind. Key features that determine the success of an RTHS toward those goals need to be addressed and understood. Thus, herein we focus on the question of how the researcher can, in advance, best design and configure an RTHS experiment to best meet those goals. By considering those goals in the configuration of the experiment, e.g., by selecting the partitioning scheme and understanding the stability and performance capabilities of the particular configuration selected, one can most effectively harness the power of RTHS to conduct successful tests and make significant advances.

The focus of this study is to demonstrate the use of the predictive indicators for an RTHS case study, and experimentally verify the effectiveness and accuracy of the approach, providing insight into the configuration of the RTHS. First, an RTHS experiment using a single story steel frame as the physical substructure is introduced. This particular test structure is of lab scale and well known component properties, and yet RTHS with this structure proved to be quite challenging due to low damping and our objective to utilize a straightforward actuator controller. However, with a good understanding of this SDOF system, the performance can be evaluated by comparing with shake table testing and pure simulation. A baseline shake table test is conducted so that a direct evaluation between RTHS and shake table test is available. As mentioned

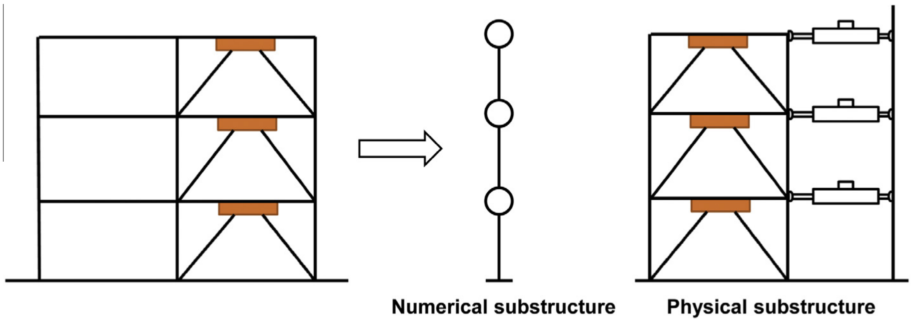

Fig. 1. Real-time hybrid simulation of a large scale steel structure with dampers.