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Real-time hybrid simulation of a shear building with a uni-axial shake table

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ABSTRACT

Recent investments in earthquake engineering research have produced an array of experimental equipment and testing capabilities worldwide. Laboratories are often equipped with shake tables, ranging from uni-axial tables to six-degree-of-freedom tables to multiple table arrays. These tables are capable of providing interface boundary conditions for substructure real-time hybrid simulation (RTHS). In the simplest case, the lower stories of a shear building are simulated numerically while the upper stories tested experimentally. Even this simple case reveals the challenges of RTHS using shake tables. Shake tables are highly nonlinear devices, making modeling and control a challenging task. Furthermore, the mass of the test specimen is typically large relative to the capacity of the table, leading to substantial coupling of the table and specimen dynamics. These challenges are exacerbated by the loop of action and reaction between numerical and experimental components in RTHS. Any delay or lag in the realization of the desired table trajectory and measurement of the base shear can introduce inaccuracies and instabilities into the loop. This research investigates the challenges of RTHS using shake tables through a simple uni-axial shake table and shear building specimen. A model-based shake table control approach is successfully implemented for online acceleration tracking. A Kalman filter is used to reduce measurement noise in the RTHS loop without introducing phase lag. Numerical and experimental substructures with low damping are selected to demonstrate the robustness of the proposed framework for a challenging RTHS scenario. Even for shake tables with large control-structure interaction and structures with low damping, the proposed framework is robust, reliable, and uses readily available equipment, providing a new experimental tool for laboratories with modest experimental testing capabilities.

1. Introduction

Real-time hybrid simulation (RTHS) is increasingly recognized as a powerful experiment technique to evaluate the performance of structural components subjected to earthquake loads. In RTHS, the combined numerical and experimental evaluation of the total structural performance is executed in real time, offering the capability to test rate-dependent specimens such as dampers [1–3]. The numerical simulation, which runs in parallel to the experimental testing, is executed with a small enough time step to ensure continuous real-time motion of the specimen. RTHS provides an attractive alternative to traditional shake table testing for earthquake engineering studies [4] by combining experimental testing and numerical simulation in an efficient and cost-effective framework. Structural components for which the response is well understood are modeled numerically, greatly reducing the required laboratory space and equipment. Because only the less understood, critical structural components are physically tested, they can be large or full-scale representations of the actual components, reducing size effects. In this way, even small laboratories can conduct accurate experiments of complex structures. The loop of action and reaction between experimental and numerical components is executed in real-time, ensuring accurate representation of both the local and global dynamic behavior of the structure.

One of the challenges for RTHS is that it requires a fixed, small sampling time in the execution of each testing cycle. Moreover, unless properly compensated, time delays and time lags introduced by the experimental equipment may lead to stability and accuracy problems [5]. Lin et al. [6] systematically studied the influence of system dynamics, substructuring, and time delays on RHTS stability. This study provided an example system with a ratio of numerical to experimental stiffness of 0.69 and critical damping ratio of 1.4% which exhibited unstable behavior when the time delay exceeded 15 ms. One of the most effective approaches to

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mitigate the effect of time delays and time lags is through actuator control strategies designed to compensate for the modeled dynamics of the servo-hydraulic system [7,8]. Shake tables present an opportunity in the area of RTHS because the equipment is widely available and the creation of substructure boundary conditions is straightforward. The shake table base plate can serve as the interface between numerical and experimental substructures, a convenient convention for certain structural systems. When used in dynamic substructuring [9], where there is significant vibrating mass in the experimental substructure, the shake table must track absolute accelerations at the interface boundary such that that the inertial forces of the specimen are accurately represented. Acceleration tracking strategies have been developed for decades to track desired ground motions for earthquake studies. Acceleration-based shake table control strategies can be repurposed for shake table RTHS if the strategy accepts an acceleration generated in real time.

Shake tables are inherently nonlinear devices due to nonlinearities in actuator behavior, friction in the table [10], and control-structure interaction (CSI) [11,12]. Therefore, it is difficult to reproduce a desired acceleration record over a wide range of frequencies. In addition to the challenges due to the physical shake table system, challenges are also induced by the desired tracking signal. Shake table testing is unique in that the desired trajectory is an acceleration signal, however, for stability, servo-hydraulic actuators still operate in displacement feedback through an inner-loop PID controller. Many shake table controllers are developed as outer-loop controllers built around inner-loop displacement feedback controller. With this understanding, the most basic approach to achieve the desired acceleration record is to first integrate twice to determine a compatible displacement record. Simova and Mamucevski [13] present this offline method, whereby the resulting displacement record is tracked by the shake table using displacement feedback. With this approach, shake table dynamics lead to difficulties matching the desired accelerations, especially at higher frequencies and around frequencies influenced by CSI.

Fletcher [14] presents a transfer function iteration method used by many commercial shake tables, later applied to a small-scale shake table in Spencer and Yang [15]. This approach is based on a linearized model of the shake table commands to measured acceleration. An inverse of this model is used to generate a command signal history from the acceleration record, taking into account the modeled table behavior. However, nonlinearities lead to error between desired and measured accelerations. These errors are used offline to iteratively modify the command signal to reduce errors in subsequent iterations.

Nakata [16] proposed an acceleration tracking control in which a linearized model of the shake table is used to develop the feedforward controller, joined by a displacement feedback controller to provide stability to the shake table and avoid excessive drift. In this approach, commands are sent directly to the servo-valve (no inner-loop controller is used). Phillips et al. [17] developed a feedforward–feedback approach based on a linearized model of the shake table dynamics and included both acceleration and displacement feedback though the use of LQG control. This method was demonstrated to be effective for evaluating nonlinear specimens in traditional shake table testing.

To address uncertainties in actuator control, Gao et al. [18] proposed a robust actuator controller for RTHS based on H_∞ control theory, balancing tracking performance and stability. This method was enhanced by Ou et al. [19] who proposed a robust integrated actuator control to reduce the influence of noise and achieve better performance. The controllers proposed by Ou et al. and others incorporate a Kalman filter to reduce noise in the measurement signals used for feedback control [8,17,19,20]. Some of these studies on uncertainty were conducted for displacement tracking [8,19,20] while others applied to acceleration tracking [17].

Unlike traditional shake table testing, in RTHS the acceleration trajectory is not known prior to testing (i.e., the acceleration is calculated online). Therefore, shake table control strategies in the literature requiring offline calculations and configuration (e.g., [13–15]) cannot be used for real-time testing. In contrast, some recently developed acceleration-tracking shake table control strategies (e.g., [16,21]) do not require the desired acceleration to be predefined and can potentially be employed in RTHS. In this study, a simple model-based control strategy consisting of both feedforward and feedback links proposed by Phillips et al. [17] is selected to provide the required real-time acceleration control.

There are a few examples in the literature of successful RTHS using a shake table to enforce substructure boundary conditions. Nakata and Stehman [22] presented a model-based actuator delay compensation and a force correction technique to achieve desired interface acceleration tracking. Shao et al. [23] investigated a more complex RTHS configuration with the experimental substructure taken as the middle floor of a building by using both a shake table and actuators. In these examples, the structures investigated are highly damped, resulting in a system that is less representative of a realistic structure but easier to control and achieve stability in RTHS. The damping ratios of the total structure in Nakata and Stehman [22] are 8%, 11%, and 19% for the first three modes and in Shao et al. [23] are 11%, 19%, and 7% for the first three modes. In addition, the numerical substructures are large relative to the experimental substructures, another favorable condition for RTHS stability and accuracy. In this paper, a lightly damped structure (2.6%, 3.5%, and 9.4% for the first three modes of the total structure) with relatively large experimental substructure is investigated to demonstrate the stability of the proposed framework.

This paper presents a simple framework with broad applications for substructure shake table RTHS. Online tracking of the desired acceleration is provided by adapting a model-based acceleration tracking control strategy for RTHS [17]. In the model-based controller, the feedforward controller compensates for the linearized shake table dynamics while the feedback controller accounts for any uncertainties or nonlinearities in the shake table performance. An adjustment to the feedforward controller is proposed to avoid introducing high-frequency commands to the RTHS loop. In addition, a Kalman filter is added to the RTHS loop to remove noise from the measurements before feeding back to the numerical substructure, avoiding introducing phase lag associated with other filters types which could lead to RTHS instability. In this study, a total of two Kalman filters are used, one for the feedback control of the shake table and another for the feedback loop of RTHS. The former improves acceleration tracking performance and the latter reduces measurement noise in the RTHS loop. The proposed shake table RTHS framework was verified through a uni-axial shake table and a two-story shear building specimen. The numerical substructure, experimental substructure, and total structure all had low damping. Two total structures were compared to show the influence of damping on shake table RTHS when the damping is low. This versatile shake table RTHS framework is reliable and uses readily available equipment, providing a new experimental tool to laboratories worldwide for assessing the responses of structures with realistic dynamic properties through RTHS.

2. Substructure shake table RTHS

For a simple illustration of the use of a shake table in RTHS, a linear 3DOF shear building is considered (see Fig. 1(a)). The equations of motion governing the dynamic response of the structure subjected to an input ground motion are represented as follows: