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Real time hybrid simulation with online model updating: An analysis of accuracy

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ABSTRACT

In conventional hybrid simulation (HS) and real time hybrid simulation (RTHS) applications, the information exchanged between the experimental substructure and numerical substructure is typically restricted to the interface boundary conditions (force, displacement, acceleration, etc.). With additional demands being placed on RTHS and recent advances in recursive system identification techniques, an opportunity arises to improve the fidelity by extracting information from the experimental substructure. Online model updating algorithms enable the numerical model of components (herein named the target model), that are similar to the physical specimen to be modified accordingly. This manuscript demonstrates the power of integrating a model updating algorithm into RTHS (RTHSMU) and explores the possible challenges of this approach through a practical simulation. Two Bouc–Wen models with varying levels of complexity are used as target models to validate the concept and evaluate the performance of this approach. The constrained unscented Kalman filter (CUKF) is selected for using in the model updating algorithm. The accuracy of RTHSMU is evaluated through an estimation output error indicator, a model updating output error indicator, and a system identification error indicator. The results illustrate that, under applicable constraints, by integrating model updating into RTHS, the global response accuracy can be improved when the target model is unknown. A discussion on model updating parameter sensitivity to updating accuracy is also presented to provide guidance for potential users.

1. Introduction

In contrast to conventional testing methods and pure numerical simulation, in hybrid simulation (also known as pseudo-dynamic testing or dynamic sub-structuring) the structural system is decomposed into two substructures, namely the numerical substructure (which is usually well understood) and the experimental substructure (whose behavior is to be studied). For simulation, the two substructures of HS are linked by a transfer system (hydraulic actuator, shake table, electric motors etc.) to enforce continuity of the solution at the interface. Both the local performance (specimen level) and the global performance (structural level) can be observed and evaluated, and thus HS is considered to be a cost/space/time efficient approach compared to traditional shake table testing [38,27].

For several decades, HS were exclusively implemented using extended time, thus neglecting any rate-dependent effects

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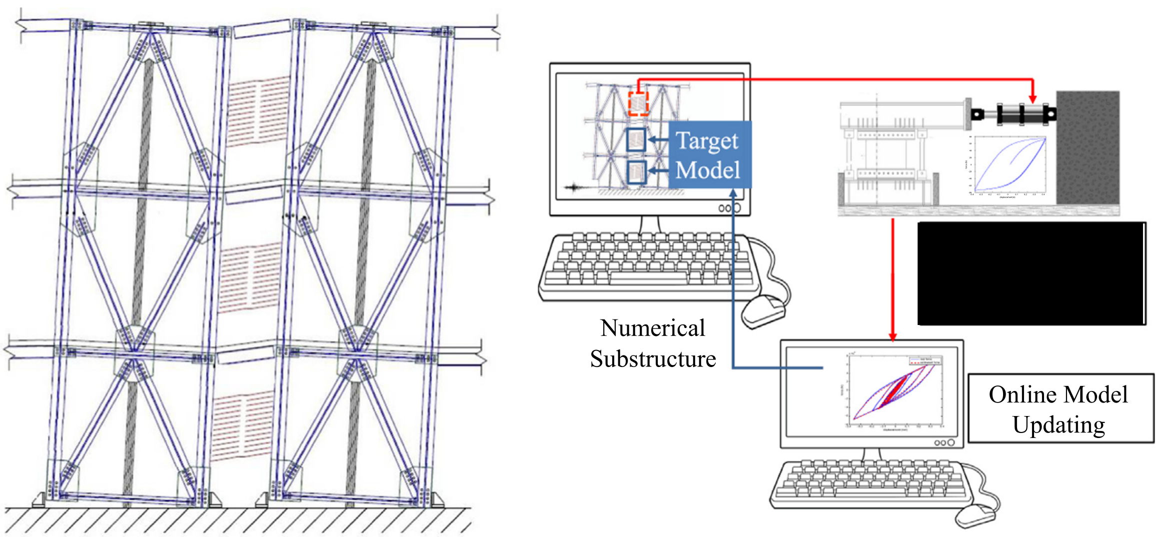
associated with structural components [24,39,32]. Recent advances have encouraged the development of HS methods that are executed at a real time scale, named real time hybrid simulation (RTHS) [6,7,15].

One benefit of RTHS is that only the critical component must be fabricated and tested, the remainder of the structure can be numerically modeled. Therefore it is intuitive to choose auxiliary devices (MR dampers, base isolation, etc.) as the experimental substructure, because the functionality of those devices (normally for vibration control purposes) is unique and quite distinguishable from the structural components. However, for evaluating structures in which a given component (column, bridge pier, structural connection) may be used in multiple instances in the structure, one might take the approach of using a limited number of the repeated components as the critical physical specimens and leave the rest in the simulation. Therefore, the modeling error of these similar components may contribute significantly to the global response, and affect the fidelity of a RTHS. Thus, estimation of the numerical model of those nonlinear components during HS can preserve the fidelity of the experiment.

This opportunity has recently been recognized by researchers developing novel testing approaches. Rather than only exchanging information at the interface (displacement, acceleration or restoring force), information to improve the numerical substructure can also be extracted from the response of the experimental substructure. It can then be used to improve the representation of similar components in the numerical model. Kwon et al. [22] first introduced the concept of representing an entire structure with several key physical components, and modifying their numerical models using the physical response in real-time. The numerical model used in simulation consisted of a collection of Bouc–Wen models with predetermined parameters. During HS, a weighting factor was identified for each Bouc–Wen model until the summation of their weighted responses matched the measured physical response. Thus, the accuracy of this approach highly depends on the chosen initial collection of Bouc–Wen models. In the subsequent two years, several techniques to apply model updating in HS have been developed, mostly in the unscented Kalman filter family. Those approaches include using the constrained unscented Kalman filter (CUKF) in RTHS [42,45] and the unscented Kalman filter (UKF) algorithm in HS [16] and RTHS [26] to identify Bouc–Wen model parameters. Experimental results in the aforementioned work demonstrate the feasibility of model updating in HS and the associated improvement in testing accuracy.

Although HS with model updating (HSMU) has been experimentally validated, an evaluation of the limitations of HSMU has not been performed. For both HSMU and RTHSMU, online model updating algorithms require knowledge of the excitation to the experimental substructure as well as its response to identify the model parameters. This excitation normally takes the form of a structural response which is already filtered (the structure itself is a filter) and likely contains limited frequency information, especially on examining the dynamic system where specimen response is rate dependent. In HS, the identification information is more related to amplitude where the loading does not contain frequency content with low speed execution. While in RTHS, the information maybe related to both amplitude and frequency. For system identification, this filtered excitation may be insufficient or provide limited useful information. Other possible limitations relate to the varying level of complexity of the nonlinear models to be identified. In addition, parameter convergence in model updating may affect the behavior of other numerical components which receives model updating parameters in real time. Clearly, the performance of the chosen model updating algorithm with respect to such challenges should be carefully examined prior to implementing model updating in hybrid simulation.

Here, RTHSMU is validated and evaluated through simulation of RTHSMU, representing a practical design shown in Fig. 1



(a) Rocking Frame with Connection Plates (b) Concept of HSMU

Fig. 1. Simulation Case Study. (a) Rocking Frame with Connection Plates [9]. (b) Concept of HSMU.