The 2017 World Congress on
Advances in Structural Engineering and Mechanics (ASEM17)
28 August - 1 September, 2017, Ilsan(Seoul), Korea

Effect of Time Delay on Real-Time Hybrid Simulation of Structural Response Under Strong Ground Motions

Selim Günay[1)], Khalid M. Mosalam[1)] and Tae-Hyung Lee[2)*]

[1]Department of Civil and Environmental Engineering, University of California Berkeley, Berkeley, CA 94720, USA
[2]Department of Civil Engineering, Konkuk University, Seoul, Republic of Korea

ABSTRACT

Actuator time delay, defined as the time difference between the time when a displacement is commanded to an actuator and the time when the actuator actually realizes this displacement, is not a critical factor in conventional structural testing, including shake table tests. However, due to the inherent dependence of real-time hybrid simulation (RTHS) on accurate control, it should be kept at a minimum level in RTHS tests. Otherwise, it can significantly affect the accuracy of RTHS and can even lead to instability. This paper investigates the effect of actuator time delay on the accuracy of RTHS conceptually, analytically and experimentally. Obtained results indicate that the effect of time delay on the accuracy of RTHS is dependent on the period and independent of stiffness for the same period. Furthermore, it is observed that the effect of actuator time delay is most significant in the linear elastic range and diminishes for inelastic response as long as the inelastic response is a softening response, which is defined with a reduction in post yield stiffness.

1 INTRODUCTION

Structural testing, including shaking table tests and hybrid simulations, is generally conducted by using an actuation system, which consists of servo-hydraulic actuators and controllers. Due to the inherent dynamics of the actuation system, there is a difference between the time when a displacement is commanded to an actuator and the time when the actuator actually realizes this displacement, which can be termed as the actuator time delay. This time delay is not a critical factor in conventional structural testing, including shake table tests. On the other hand, real-time hybrid simulation (RTHS), where the test specimen is loaded with a rate equal to the computed velocity, strongly relies on accurate control, i.e. the accurate displacement tracking of the actuators. Therefore, time delay is an important factor that affects the accuracy of RTHS and can even lead to instability.

The effect of actuator delay on real-time hybrid simulation has been studied by a number of researchers. For example, Mercan and Ricles [1] performed stability analysis of RTHS of a single-degree-of-freedom (SDOF) linear elastic system using a delay differential equation to model the effects of actuator delay in the experimental substructure. These studies show that actuator delay introduces negative damping into the system, which, if not compensated properly, can destabilize a RTHS. Various compensation methods have been proposed to minimize the effect of actuator delay for real-time testing [e.g. 2]. However, these methods may not be applicable to all RTHS tests and they may not be effective in some of the cases. Therefore, before conducting a RTHS, it is extremely informative to quantify the effect of time delay on the particular RTHS results. This is essential for evaluating the possibility of a specific set of equipment in a laboratory. This paper investigates the effect of actuator time delay on the accuracy of RTHS conceptually, analytically and experimentally. First, the consequences of time delay is conceptually demonstrated using a linear elastic force displacement relation. Then, the same concept is demonstrated experimentally from RTHS results. Finally, using a custom MATLAB code, a parametric study is conducted analytically to study the effect of time delay on SDOF systems with different periods. Work is currently ongoing for implementation of time delay in OpenSees for generalization of such investigations.

2 CONCEPTUAL INVESTIGATION

Effect of time delay on the results of hybrid simulation is conceptually demonstrated in Figure 1. In this figure, a specimen with a linear elastic force displacement relationship is considered. In a hybrid simulation, the numerical integrator observes the experimental specimen behavior as the computed displacement versus the measured force. In the case of overshooting of the computed displacement, as shown in the upper left figure, a larger restoring force is measured from the specimen, therefore a point that is defined as the pair of computed displacement and true force corresponding to the computed displacement (point 1 in Figure 1) is observed as the pair of computed displacement and the measured force corresponding to the applied displacement (point 2 in Figure 1). Similarly, any other point in the loading path deviates upwards from the linear relationship, while any point in the unloading path deviates downwards, resulting in the oval-shaped hysteresis shown in the upper right figure. Therefore, the specimen that actually has a linear elastic behavior is observed as a specimen with the oval hysteresis response by the hybrid simulation. Needless to say that such phenomenon will lead to incorrect HS results, it can be interpreted as unintendedly increased damping in the dynamic response of the hybrid system. In the case of undershooting or time delay, a similar phenomenon occurs, only with the difference of a reversal in the direction of the hysteresis, as shown in Figure 2. Such situation corresponds to energy added to the system, introducing negative damping. Depending on the value of the error and the amount of introduced negative damping, the hybrid simulation solution may even go unstable.

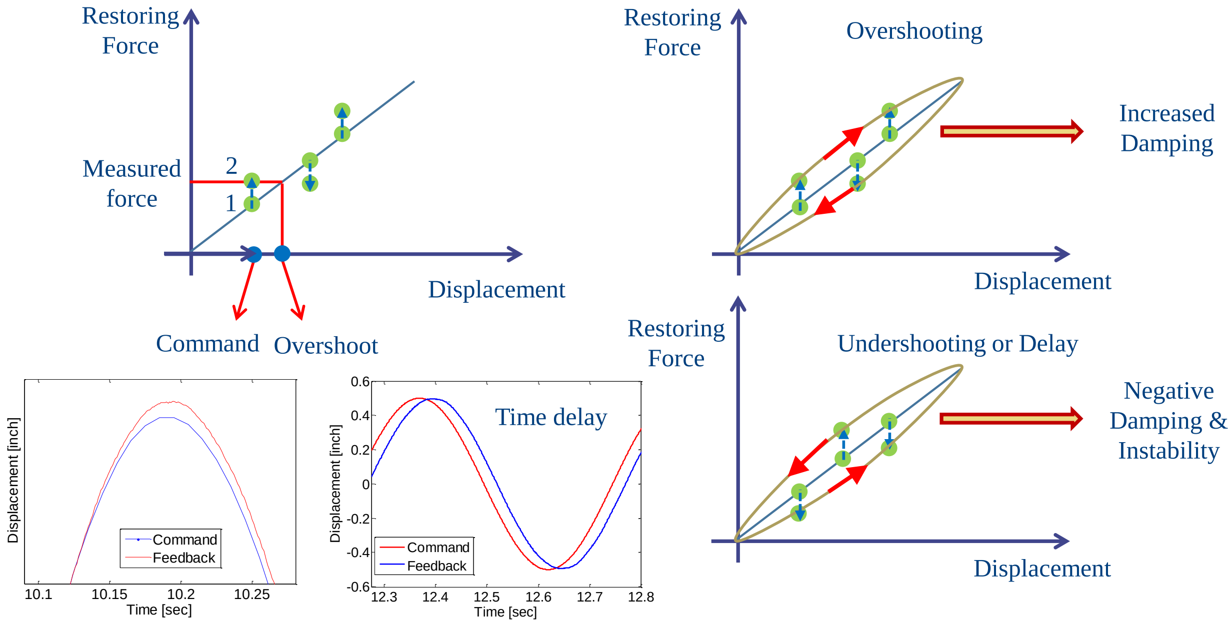
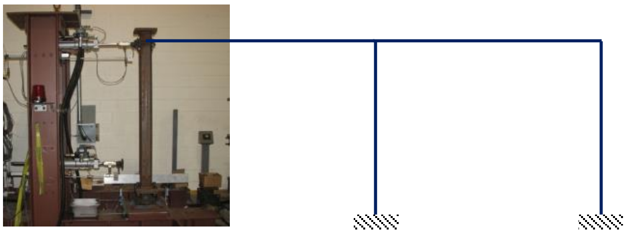


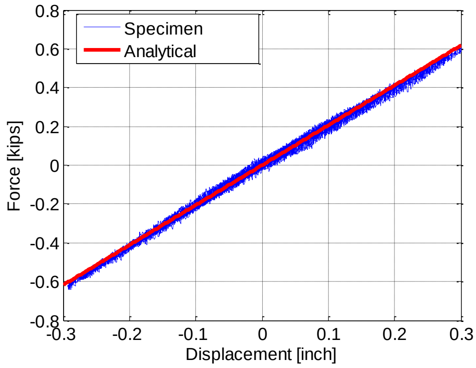
Figure 1. Conceptual demonstration of the effect of time delay on hybrid simulation

3 EXPERIMENTAL INVESTIGATION

To demonstrate the described conceptual investigation in a real experimental setting, a hybrid system setup of a one story, two bay frame is devised in the PEER structural laboratory as shown in Figure 2a. As shown in this figure, the left column is simulated as the experimental substructure, while the remaining elements are all modeled as the analytical substructure. The experimental substructure response is defined by the measured linear elastic response shown in Figure 2b. To demonstrate the effect of time delay, the experimental substructure is first replaced by an analytical element with stiffness of the experimental substructure. Mass is adjusted to result in a period of 0.5 sec. and the damping ratio is chosen to be 5%. A time history analysis of this completely analytical structure is conducted with the El Centro ground motion of the 1979 Imperial Valley Earthquake and the resulting response is recorded as the reference response. Then, a RTHS is conducted on the hybrid system using the same ground motion with close to zero time delay in the control, Figure 3a. As can be seen in this figure, results of this RTHS and the reference analytical simulation are fairly close. To observe the effect of time delay on RTHS, a time delay of 14 milliseconds is introduced by adjusting the PID control settings, Figure 3b, and a RTHS test is conducted on the hybrid system with this time delay. As shown in this figure, the RTHS results are completely incorrect in this case. Furthermore, the computed displacement is larger in RTHS due to the introduced negative damping.



(a)



(b)

Figure 2. (a) Hybrid system employed in the experimental investigation, (b) Force-displacement relation of the experimental substructure

4 ANALYTICAL INVESTIGATION

In order to study the effect of time delay for a larger variety of cases, time delay is introduced in the numerical integration of a linear elastic single degree of freedom system with different spring stiffnesses and periods. The error in displacement is proportional to both the velocity and the time delay, therefore the error term due to the time delay is defined in Equation 1, where *i* is the integration time step, $u_{comp,i}$ and $u_{real,i}$ are the computed and realized displacements respectively, vel_i is the computed velocity and *delay* is the time delay, which is a constant value as observed from Figure 1. Explicit Newmark, which is the most suitable method for RTHS if the stability criterion is satisfied, is used as the time integrator. In the conducted investigations, the solution with no time delay is accepted as the reference and the solutions with several values of the time delay are compared with the reference solution. Root mean square error (RMSE), defined by Equation 2, is employed as the parameter to quantify the differences between the reference solution with no time delay and the solution with delay. In Equation 2, *i* is the integration time step, *N* is the total number of steps, u_{ref} is the reference displacement history computed without the delay, and u_{app} is the displacement history computed with the delay.

$$u_{real,i} = u_{comp,i} + vel_i \times delay \tag{1}$$

$$RMSE = \frac{\sqrt{\sum_i \left(abs\left(u_{app,i} - u_{ref,i}\right)\right)^2 \Big/ N}}{median\left(abs\left(u_{ref}\right)\right)} \tag{2}$$

The effect of various time delay values are investigated on SDOF systems with different periods and stiffnesses using different integration time steps. It is observed that stiffness does not have any influence on the results for the same period. However, there is a clear influence of the period as indicated in Figure 4. It is observed that the error decreases with the period exponentially and there is significant level of error for periods of 0.5 sec and below. This shows the necessity of evaluating the time delay effect on the RTHS results properly before the test. The decrease of the error for long periods indicate that the effect of actuator time delay is most significant in the linear elastic range and diminishes for softening inelastic response. Work is currently ongoing for implementation of time delay in OpenSees for generalization of such investigations and to be able to simulate the RTHS with delays before the actual test.

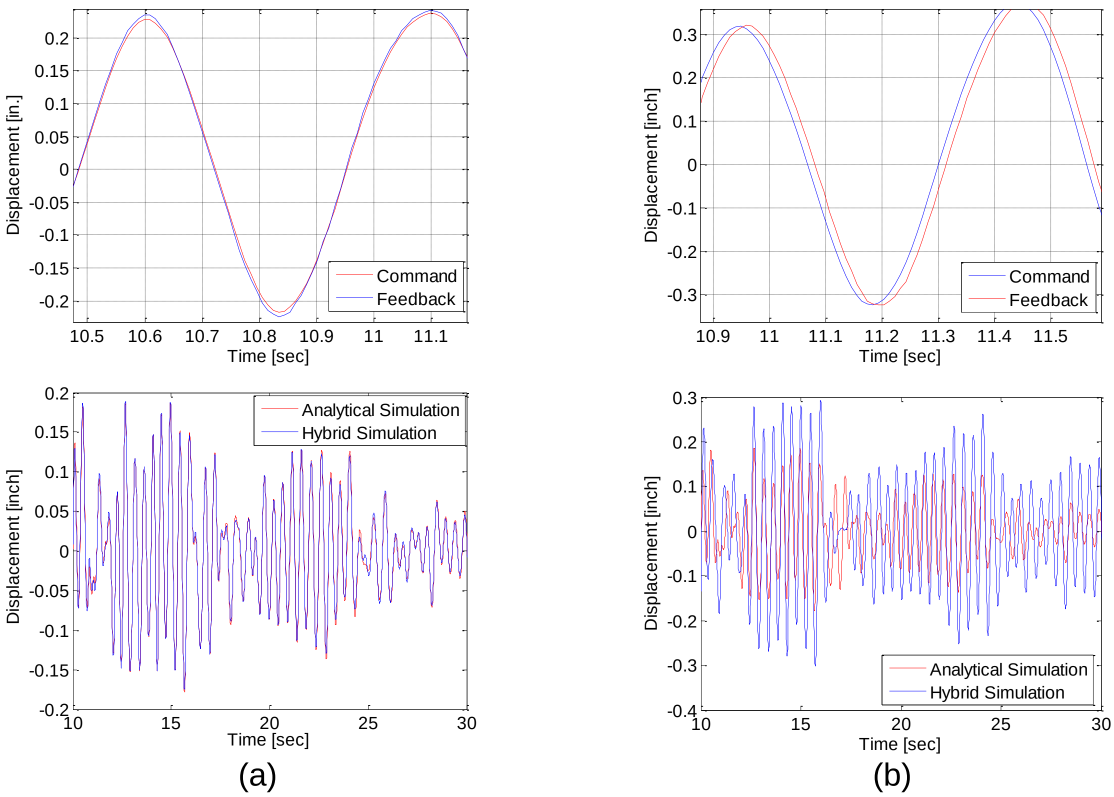


Figure 3. Comparison of RTHS (a) with, (b) without time delay and the reference solution

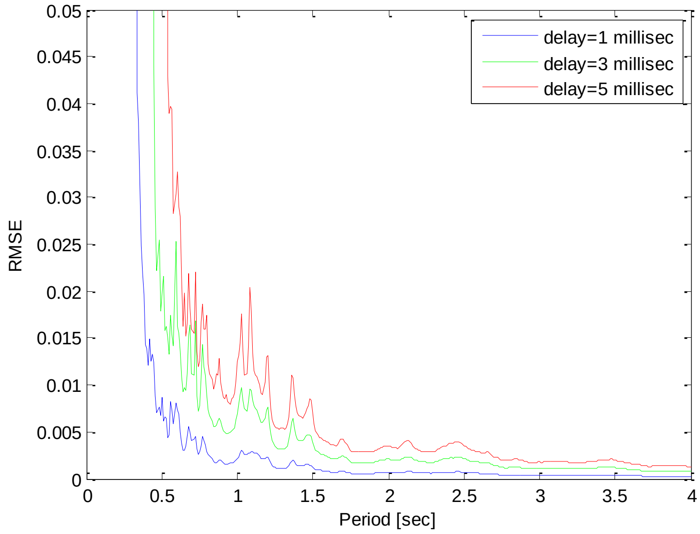


Figure 4. Effect of time delay in RTHS of SDOF systems with different periods

5 REFERENCES

1. Mercan, O., and Ricles, J. M. (2007). Stability and accuracy analysis of outer loop dynamics in real-time pseudodynamic testing of SDOF systems. *Earthquake Engineering and Structural Dynamics*, 36(11): 1523-1543.
2. Horiuchi, T., & Konno, T. (2001). A new method for compensating actuator delay in real–time hybrid experiments. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, 359(1786): 1893-1909.