Substructure Effective Force Testing: A Force-Based Real-Time Hybrid Simulation

N. Nakata & S. Combs
Johns Hopkins University, USA

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SUMMARY:
This paper presents a force-based real-time hybrid simulation called substructure effective force testing. The method divides test structures into load-resisting members and mass components where the load-resisting members are experimentally tested under force control and the mass components are computationally simulated. Inertial forces of the mass components are integrated into the reference forces to the load-resisting members. A preliminary experimental investigation of the proposed substructure EFT method was performed using a mass-spring-actuator system at the Johns Hopkins University. This paper discusses the experimental results, sources of errors in the method and required compensation techniques to make the proposed method feasible for performance assessment of structures.

Keywords: Hybrid simulation, effective force testing, substructure technique, delay compensation

1. INTRODUCTION

Force-based experimental methods aim to impose prescribed controlled force on test structures. Unlike the conventional displacement-based methods, the force-based methods allow for structural displacement, velocity and acceleration to be evaluated from the experiment; displacement-based methods enable evaluation of structural force by imposing a prescribed displacement that in turn controls velocity and acceleration. Because true loading paths to structures during earthquakes are governed by force equilibrium, force-based experimental methods are expected to provide more realistic dynamic phenomenon in the evaluation of structural performance.

The idea of force-based experimental methods was first proposed by Thewalt and Mahin (1987), but it was not until 1999 that an experimental study of dynamic force control was first published in literature on the effective force test (EFT) method by Dimig et al (1999). Dimig et al presented experimental results to demonstrate that hydraulic actuators do not have the ability to apply force at the natural frequencies of test structures. This challenge is known as control-structure interaction and a relevant topic can be found in the study of structural control (1995). The work by Dimig et al was further expanded by Zhao et al (2005) incorporating velocity feedback to compensate for the control structure interaction. While force control with the velocity feedback compensation technique was successfully implemented, controllable frequency ranges were limited to 10 Hz.

Nakata recently reported effective force tests using a loop shaping force feedback controller (2012). The loop shaping controller was proven not only to expand controllable frequency ranges to 25 Hz, but also to enable compensation of the control-structure interaction without velocity feedback. Furthermore, the loop shaping controller provides excellent force tracking capabilities as well as robustness to reduce the effects of oil-column resonance of hydraulic actuators for linear and nonlinear test structures. With such robust and high-performance force feedback controllers, force-based experimental methods have to be further explored to provide new means of evaluating structural performance under earthquake loadings.

This paper proposes a new force-based experimental method called substructure effective force test as an expansion of the conventional effective force test method. As opposed to the conventional effective force testing where the entire structure is tested experimentally, the proposed method can evaluate the entire structural performance by only testing the load-resisting members. Using a test setup at the Johns Hopkins University, a preliminary experiment was performed to investigate the feasibility of the proposed method. Experimental results revealed that delay compensation techniques are required in the proposed substructure EFT method. This paper presents the concepts of the method including potential structures to which the substructure EFT can be applied; experimental setup and preliminary experimental results of the substructure EFT; a numerical investigation of experimental errors; and the effects of a compensation technique in the substructure EFT method.

2. SUBSTRUCTURE EFFECTIVE FORCE TESTING

A new force-based experimental method proposed in this paper is an expansion of effective force testing (EFT). This section presents the basic concepts of the proposed substructure effective force test method in comparison with shake table tests and effective force tests.

Consider an earthquake simulation of a structural system that consists of distinct mass components and load-resisting members. A schematic of such a structure is shown in Figure 1 (a). Structures such as water towers and highway bridges can be categorized in this type; in bridge systems, decks are primary mass components and piers are load-resisting members. The equation of motion of such a structure can be expressed as:

$$\left(1+\alpha\right)m\ddot{x}+c\dot{x}+kx=-\left(1+\alpha\right)m\ddot{x}_g \tag{2.1}$$

where m, c and k are the mass, damping, and stiffness of the load resisting member, respectively; α is the mass ratio of the mass component with respect to the load resisting member; x is the displacement of the structural system; and $\ddot{x}_g$ is the ground acceleration due to an earthquake. Note that the contribution of the mass components in the dynamic equilibrium is only through inertial force and the restoring forces are solely from the load resisting members. If an earthquake simulation is performed using a shake table (see Figure 1(a)), the input in the experimental system is ground acceleration.

The EFT method evaluates response of structures due to the impact of earthquakes in terms of force. Instead of shaking entire test structures from their foundation, actuators are attached to the test structure and a prescribed force is dynamically applied at structural nodes. A schematic of the EFT method for the same structure is shown in Figure 1 (b). The equation of motion and the input force in EFT are expressed as follows:

$$\left(1+\alpha\right)m\ddot{x}+c\dot{x}+kx=f_r \tag{2.2}$$

$$f_r=-\left(1+\alpha\right)m\ddot{x}_g \tag{2.3}$$

Applied forces in the EFT method are equivalent to the inertial forces during earthquakes and can be defined prior to the experimental simulation. In comparison to shake table tests, the left side of the equation of motion (Eq (2.2)) is experimentally evaluated in the EFT method. While the EFT method requires dynamic force control using hydraulic actuators, it has some advantages over shake table tests. For example, because the entire structure does not need to be shaken, the EFT method can be performed with smaller actuators than those required in shake table tests. For more detailed description of the EFT method, refer to Dimig et al (1999).

The EFT method can be further refined to incorporate a substructure technique by reformulating the equation of motion and altering the experimental structure. If the mass components do not provide restoring forces as assumed above, the equation of motion can be written with respect to the load-resisting member.

$$m\ddot{x} + c\dot{x} + kx = \bar{f}_r \tag{2.4}$$

where $\bar{f}_r$ is written as.

$$\bar{f}_r = -(1+\alpha)m\ddot{x}_g - \alpha m\ddot{x} \tag{2.5}$$

Eq (2.4) can be evaluated from effective force tests of the load resisting members with reference force $\bar{f}_r$. One difference between the proposed method and the conventional effective force test is that the reference force in Eq (2.5) includes an inertial force term from the mass components, $-\alpha m\ddot{x}$. However, acceleration of the mass components is the same as that of the load resisting members. Therefore, by feeding the measured acceleration of the load resisting members from the effective force tests in real time, the reference force can be updated to incorporate the inertial force term from the mass components. Thus, the set of equations in Eq (2.4-5) implies that the performance of the entire structure can be evaluated with the EFT method applied to the load-resisting members in Eq (2.4) and the updated reference force command from the acceleration feedback in Eq (2.5).

An illustration of the proposed substructure EFT is shown in Figure 1 (c). The substructure EFT method allows for a force-based evaluation of structural response by performing effective force tests of only load-resisting members. Contribution of the mass components is computationally incorporated in the updated reference force with measured acceleration of the load-resisting members. While the proposed substructure EFT method includes real-time computational processes that are not required in the conventional EFT method, such processes can be implemented into commercially available real-time operating systems. It should be mentioned that because nonlinear response of the test structures, if any, are within the load resisting members and experimentally modeled, the proposed substructure EFT method allows for evaluation of nonlinear test structures.

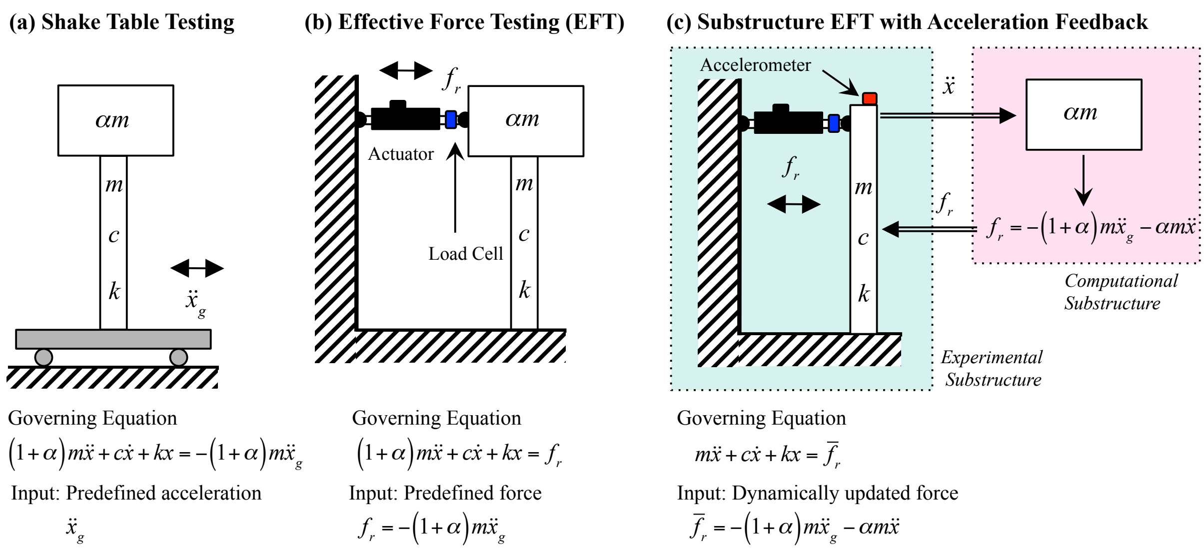

Figure 1. Schematics of various experimental methods: (a) shake table test; (b) effective force test; and (c) substructure effective force test.

3. EXPERIMENTAL SYSTEM FOR SUBSTRUCTURE EFT

To assess the feasibility of the substructure EFT method, a preliminary experimental investigation is performed at the Johns Hopkins University. An experimental setup that was previously used for the development of EFT (2012) was adopted in this study. The experimental setup consists of a mass-spring-actuator loading system and a high-performance integrated data acquisition and digital control system. A loop shaping force feedback controller is employed for dynamic force control using hydraulic actuators.

3.1. Loading system

The loading system includes a 52.7kg mass and a 2.11 x 10^5 N/m linear spring. Two linear bearings and guides are placed under the mass to support gravity of the mass as well as to provide smooth motion of the mass. Figure 2 shows an overview of the loading system. The mass-spring system is treated as a load-resisting member while mass components are computationally simulated as an additional mass. The natural frequency of the mass-spring system without additional mass is 10.1 Hz.

A fatigue rated actuator manufactured by Shore Western, Inc. (Model number: 911D) is attached to the mass-spring model. The 911D actuator has a total stroke of 152 mm and a maximum dynamic loading capability of 24.5 kN. An MTS 252 series servo valve is used to drive the 911D actuator. For the measurement of actuator force and acceleration, a 22.2 kN load cell from Interface, Inc. and a 4g general purpose accelerometer from Omega, Inc. are employed in the test system. National Instruments PXI system and LabVIEW Real-time are deployed for digital signal processing including data acquisition and control. Detailed information about the control system used in this study can be found in Nakata (2011).

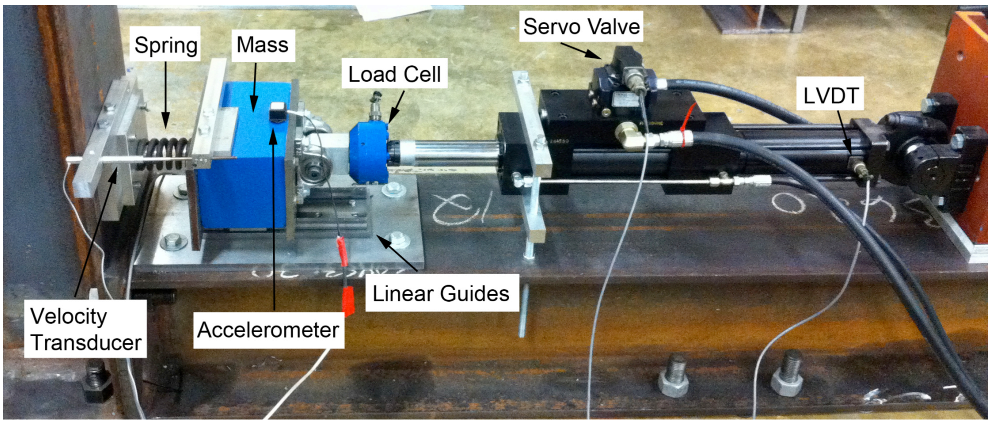

Figure 2. The mass-spring-actuator system for EFT at JHU.

3.2. Loop shaping controller

A dynamic force feedback controller has been already developed, implemented and validated in the study of effective force tests with the test setup used in this study. This study adopts a loop shaping controller that was proven to provide excellent force tracking capabilities as well as robustness for force control. This section presents an overview of the loop shaping force feedback controller.

The loop shaping is a frequency domain technique for design of feedback control system. Controllers can be designed by changing gains and adding poles and zeros until the loop transfer function has a desired shape (Astrom 2006). With a proper controller design, the loop shaping can address two primary challenges in dynamic force control using hydraulic actuators: compensation of control-structure interaction and robustness for the oil-column resonance.

Figure 3 (a) shows the experimental and analytical frequency response functions from the actuator valve command to the restoring force of the mass-spring system, H_{fu}. The experimental function is obtained through spectral system identification techniques. It can be seen that the valve-to-force frequency response function has a zero at 10 Hz and a pole around 90 Hz. This frequency of 10Hz corresponds to the natural frequency of the mass-spring model and the zero is a result from the control-structure interaction (Dyke et al 1995). The pole at 90 Hz is an oil-column resonance of the actuator. The analytical function in a rational polynomial form is obtained to capture characteristics of the experimental frequency response function using curve fitting techniques. Based on the analytical function in Figure 3 (a), the loop shaping controller, C_f, is developed to compensate for the control-structure interaction as well as to provide robustness for the oil-column resonance (see Figure 3 (b)). The continuous form of the controller is expressed as:

$$C_f = \frac{37}{s^2 + 17.14s + 4002} \tag{3.1}$$

A resulting loop transfer function that is a product of the controller and the plant is shown in Figure 3 (c). The loop transfer function displays desirable characteristics for closed-loop control: higher at the low frequency range, lower gain at the high frequency range, and smooth transition over the entire frequency range of interest. The crossover frequency of the controller is 12 Hz.

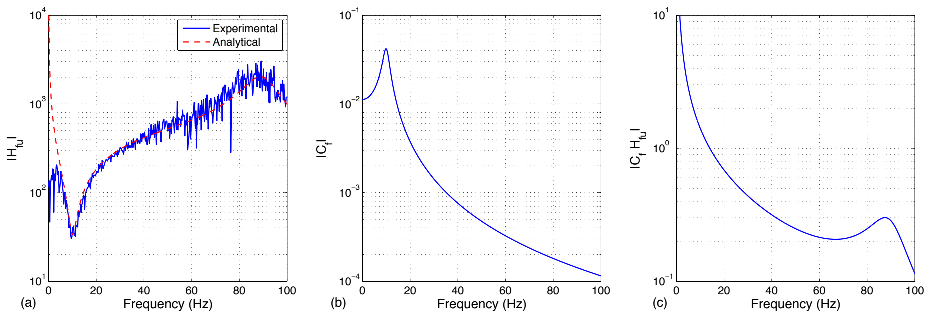

Figure 3. Open-loop transfer functions: (a) transfer function from valve voltage to actuator force; (b) controller transfer function; and (c) loop transfer function.

Figure 4 shows magnitude and phase of the frequency response curve from the reference force to the measured force The magnitude plot shows excellent force control performance over a wide frequency range, particularly up to 25 Hz. While a small dip can be found at the natural frequency of the mass-spring system in the magnitude plot, the control-structure interaction is sufficiently compensated by the application of the loop shaping controller. This imperfection in the compensation is due to an estimation error of the natural frequency of the system. Both the magnitude and phase plots from the experiment exhibit good agreement with analytical ones proving successful implementation of the controller.

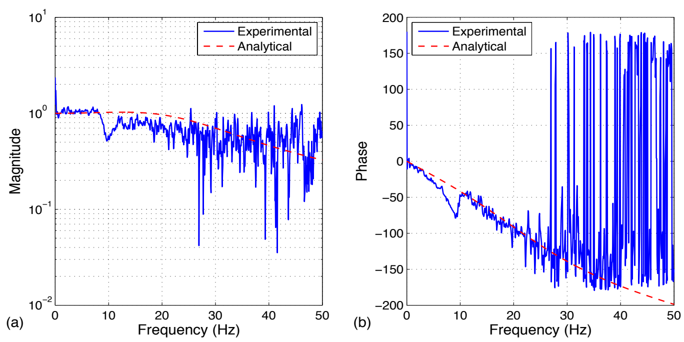

Figure 4. Closed-loop transfer function of actuator force: (a) magnitude and (b) phase.

3.3. Implementation of the substructure EFT

The proposed substructure EFT method requires a real-time update of the reference force with measured acceleration during experiment. An acceleration feedback loop is added in the real-time digital controller to incorporate the effect of the inertial force of the mass components with parameter α. A block diagram for the proposed substructure EFT method is shown in Figure 5. From the implementation point of view, the substructure EFT method consists of two feedback loops. The acceleration feedback is to refine the earthquake loading and determine the reference force input to the actuator servo loop. The actuator servo loop consists of force feedback to achieve the reference dynamic force. In the following experimental studies, the mass ratio of the computational substructure will be changed in the acceleration feedback loop while the experimental substructure, the load-resisting system, remains the same.

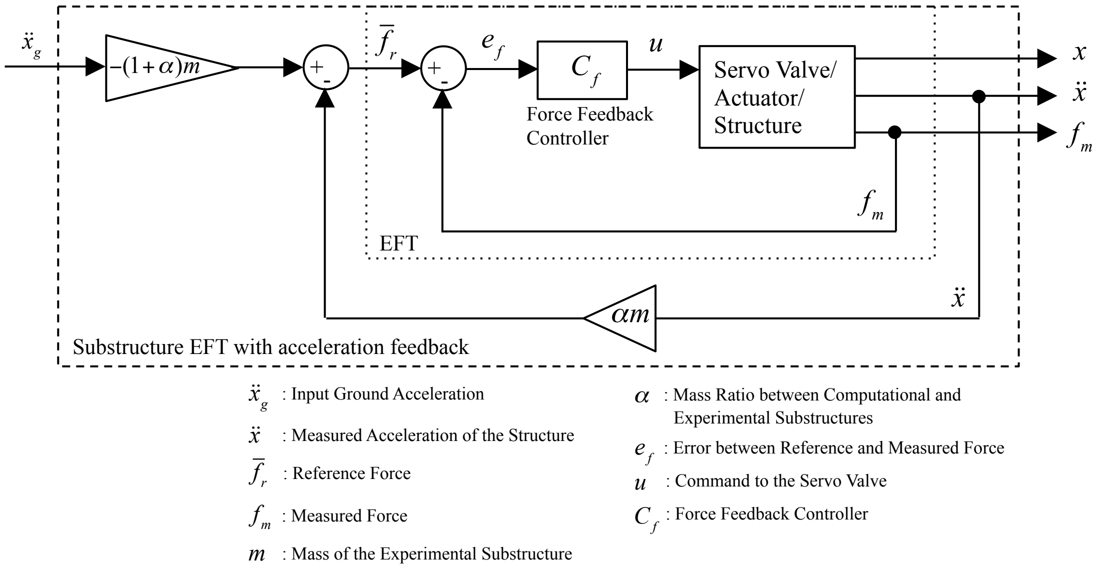

Figure 5. A block diagram of the substructure effective force test method incorporating acceleration feedback for simulated inertial force.

4. PRELIMINARY EXPERIMENTAL RESULTS

Preliminary tests of the substructure EFT method were performed using a series of earthquake and random excitations with different mass ratios. In this section, experimental results are presented along with analytical results where the entire structural system, including mass components and load-resisting members, is computationally simulated. The computational analysis serves as a reference to validate the feasibility of the substructure EFT in this study; because the test system is a linear elastic single-degree-of-freedom system, response can be accurately modeled in a computational analysis. Differences between the experimental and analytical results for different mass ratios are discussed.

Figure 6 shows displacement, force, and acceleration time histories under the 1995 Kobe earthquake at α=0, 0.5, and 1.0. The amplitude and time scale factors of the earthquake input are 1000 N and 0.5, respectively. It should be mentioned α= 0 means zero computational mass, and thus acceleration is not fed back in the simulation (same as the conventional EFT); α= 1 means that the computational mass is the same as the experimental one (i.e., 52.7 kg) and the total mass of the simulation model is 105.4 kg.

As shown in Figure 6 (a,d, and g), the experimental results agree well with the reference analytical results at α= 0. This fact implies that dynamic force control was achieved with reasonable accuracy. However, discrepancies show up at α= 0.5 (see Figure 6 b, e, and h); peak force and acceleration responses in the experiment are smaller than those in computational analysis. Furthermore, the discrepancies between the experimental and analytical results become larger at α = 1.0 (see Figure 6 c, f, and i). Also, the magnitude and the phase in the experiment do not match those in the analysis. Most notably, undesirable high frequency forces and acceleration responses appear in the experiment at α = 1.0. Though not presented in this paper, a test was performed with α = 1.5 and the system became unstable. Because the level of high frequency vibration increases with the mass ratio α, this undesirable high frequency vibration is considered to be induced by acceleration feedback. These results do not verify that the proposed EFT method is suitable for response assessment of the substructure system for earthquake excitations.

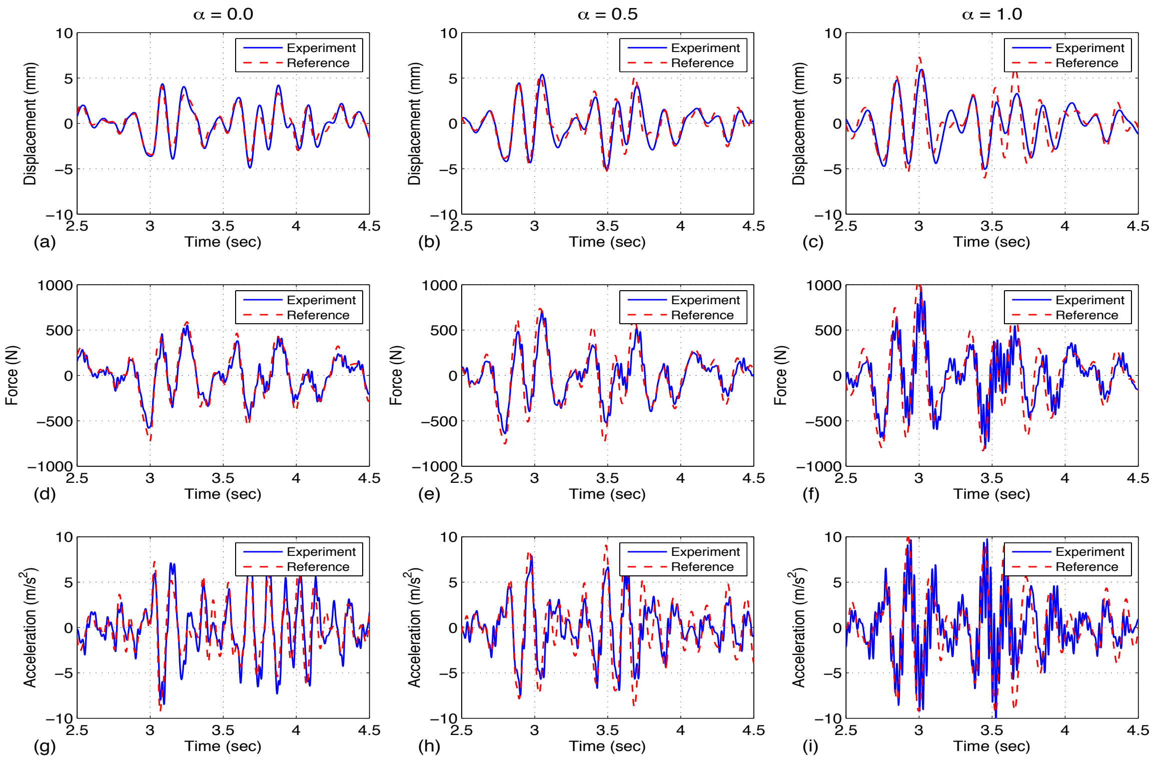

Figure 6. Time histories under the 1995 Kobe earthquake; (a), (b), and (c) displacement time histories for α = 0, 0.5 and 1.0, respectively; (d), (e), and (f) force time histories for α = 0, 0.5 and 1.0, respectively; and (g), (h), and (i) acceleration time histories for α = 0, 0.5 and 1.0, respectively.

5. INVESTIGATION OF THE EXPERIMENTAL ERRORS

While the concept of the proposed substructure EFT method is simple, the experimental results revealed infeasibility of the method due to substantial errors. In order to make the method applicable to the assessment of structural performance, the sources of errors need to be identified and appropriate measures, if possible, have to be developed. This section investigates the sources of errors in the substructure EFT method.

5.1. Incompatibility in Acceleration Time Steps

Because of a high-level of errors with the nonzero mass ratios, primary errors are considered to be due to acceleration feedback in the reference force. To investigate the impact of the acceleration feedback, detailed steps and causality in the experimental process are examined. Measured acceleration at time t is a result of the force imposed by the actuator, and it satisfies the following equation of motion:

$$m\ddot{x}_m(t) + c\dot{x}_m(t) + kx_m(t) = f_m(t) \tag{5.1}$$

where the subscript m denotes measured values of each physical property. Hydraulic actuators are electro-mechanical-hydrodynamic devices that have an inherent time constant, known as the time delay. Because of this delay, the measured force is delayed from the reference force:

$$f_m(t) = \bar{f}_r(t-\tau) \tag{5.2}$$

where τ is the linearized time delay of the actuator. In the proposed substructure EFT method, the reference force at time t is formulated with the input ground acceleration at time t and the measured acceleration at the previous time step:

$$\bar{f}_r(t) = -(1+\alpha)m\ddot{x}_g(t) - \alpha m\ddot{x}_m(t-\Delta t) \tag{5.3}$$

where Δt is the sampling period of the digital controller.

By combining Eqs (7-9), the equation of motion in the substructure EFT method yields:

$$\alpha m\ddot{x}_m(t-\tau-\Delta t) + m\ddot{x}_m(t) + c\dot{x}_m(t) + kx_m(t) = -(1+\alpha)m\ddot{x}_g(t-\tau) \tag{5.4}$$

The above equation shows that the acceleration time steps are incompatible between the experimental and computational masses due to the actuator dynamics.

5.2. Numerical Investigation of Acceleration Incompatibility

To verify the effects of the acceleration incompatibility in the substructure EFT method, numerical simulations are performed using structural properties of the experimental system. In the numerical simulations, a sampling period of 0.002 seconds and the experimentally identified actuator time delay of 0.01 seconds are used.

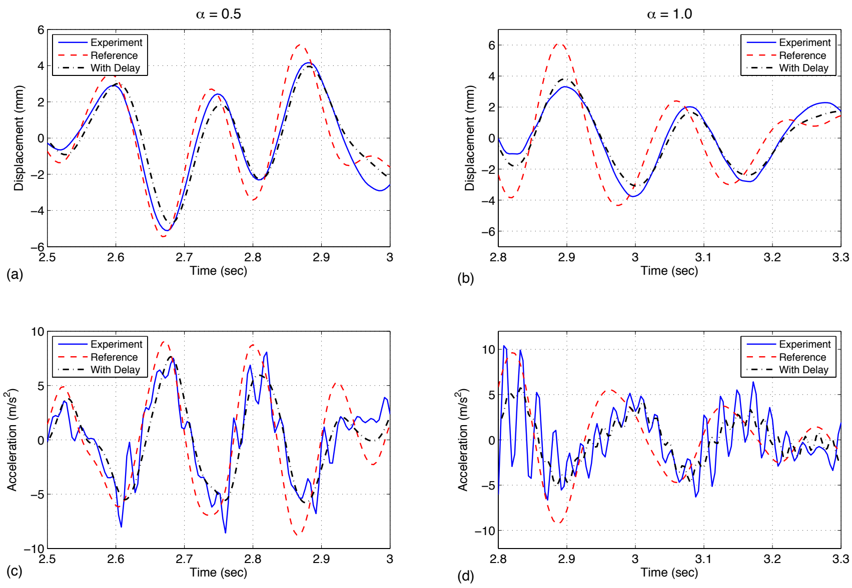

Figure 7. Comparison of time histories among reference, experiment and numerical simulations with actuator delay: (a) displacement at $\alpha = 0.5$; (b) displacement at $\alpha = 1.0$; (c) acceleration at $\alpha = 0.5$; (d) acceleration at $\alpha = 1.0$.

Figure 7 shows time histories of the numerical simulations with the actuator delay in comparison with the experimental results for α = 0.5 and 1.0. Displacement time histories in the numerical simulations with actuator delay match the experimental results very well for both α = 0.5 and 1.0 (a and b). While the level of high frequency vibration is smaller in the numerical simulations, acceleration time histories in the numerical simulations with delay also agree well with the experimental results (c-f).

Judging from a high level of agreement between the experiment and the numerical simulations with actuator delay, it can be concluded that the major sources of error in the proposed substructure EFT method is the incompatible acceleration. To make the substructure EFT method feasible as an experimental method, the incompatibility in acceleration has to be resolved.

6. DELAY COMPENSATION OF MEASURED ACCELERATION

A number of techniques to compensate for delay induced by actuator dynamics can be found in the study of control and real-time hybrid simulation. This paper presents an application of a model-based delay compensation technique by Carrion and Spencer (2007) to the substructure EFT method.

The model-based delay compensation technique is based on a prediction of response with known or estimated structural properties. In this study, the measured structural responses at the beginning of each time step are used as the initial conditions, and the future response at time $\tau(=0.01)$ are then computed using the central difference numerical integration method.

The effect of the model-based delay compensation technique in the substructure EFT method is numerically investigated. Figure 8 shows comparisons of the reference, experiment and numerical simulations with the delay compensation. It can be seen in each of the plots that response with delay compensation shows good agreement with the reference. Furthermore, undesirable high frequency vibrations observed in the experiment and numerical simulations with delay do not appear in the responses with delay compensation. Overall, the results in Figure 9 demonstrated that the substructure EFT method is able to provide an accurate response of test structures with delay compensation techniques for the acceleration feedback in the updated reference force.

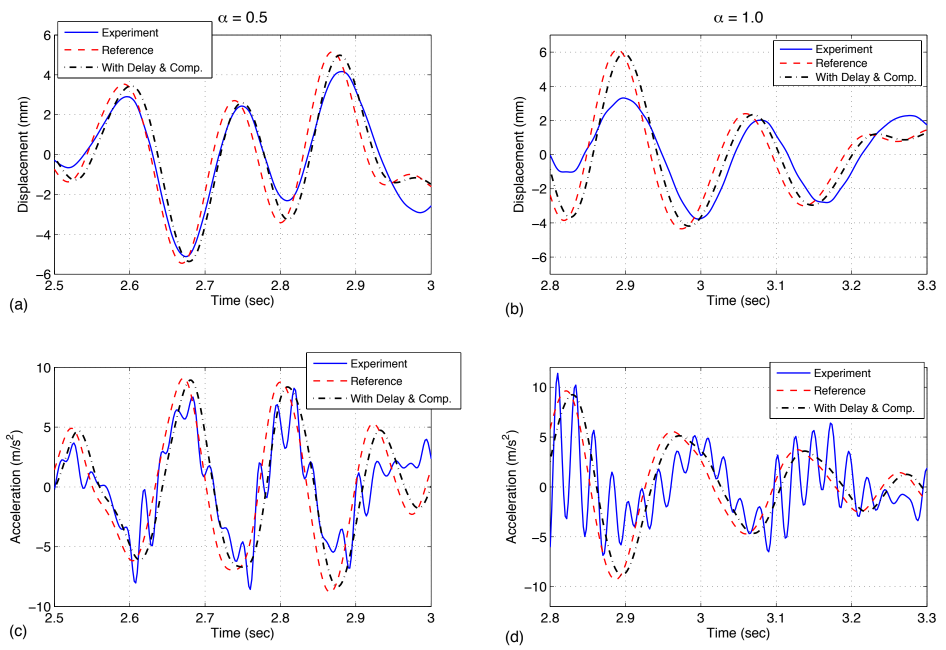

Figure 7. Comparison of time histories among reference, experiment and numerical simulations with delay compensation: (a) displacement at α = 0.5; (b) displacement at α = 1.0; (c) acceleration at α = 0.5; (d) acceleration at α = 1.0.

7. CONCLUSIONS

This paper presented a new force-based experimental method called substructure effective force testing. As opposed to the conventional effective force testing where the entire structure is tested experimentally, the proposed method can evaluate the entire structural performance by only testing the load-resisting members. Using a mass-spring-actuator system and a loop shaping force feedback controller, a preliminary experimental investigation was performed at the Johns Hopkins University. However, experimental results did not verify the feasibility of the substructure EFT method due to substantial errors and a high level of high frequency vibrations with the increase in mass ratio.

To investigate sources of error, numerical simulations of the substructure EFT method were carried out incorporating delays in measurement due to actuator dynamics. The numerical simulation results show that the major source of errors in the proposed method is acceleration incompatibility induced by the feedback of measured acceleration. A model-based delay prediction technique is employed to compensate for the acceleration incompatibility in the updated reference force. Numerical simulations with the delay compensation demonstrated that the proposed substructure EFT method is able to provide accurate response of test structures with proper delay compensation techniques for the acceleration feedback in the updated reference force. The experimental validation of the substructure EFT method with delay compensation is currently underway at the Johns Hopkins University.

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