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# Mixed Force and Displacement Control For Testing of Base-isolation Bearings in Real-Time Hybrid Simulation

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## ABSTRACT

This study presents a real-time hybrid simulation of a base-isolated building. In this study, the base isolation layer is experimentally tested while the entire structure is computationally simulated. To impose the earthquake induced lateral displacement as well as the vertical gravitational force, a mixed force and displacement control strategy is developed and implemented in the experimental system. The mixed force and displacement control strategy in this study is a decentralized approach that consists of a loop shaping and the conventional PID controllers. Following a thorough experimental verification of the mixed control, hybrid simulation of a base isolated building was performed using a series of recorded earthquake ground motions. The experimental results showed that the mixed control provided accurate loading in both lateral and vertical directions. This study presents the implementation of the mixed force and displacement control as well as the results in real-time hybrid simulation.

**KEYWORDS:** *Real-Time Hybrid Simulation, Mixed Force and Displacement Control, Base Isolation*

## 1. INTRODUCTION

Base isolation has become a favorable approach for the design of buildings and bridges in seismically active regions. The idea behind the base isolation is to make the fundamental frequencies of the structure lower than the predominant frequency of the ground motion so that not much vibration energy is transmitted to the structures from the ground (Kelly, 1986). In addition to the design of new structures, the base isolation technique has been adopted in the retrofit of existing structures in recent years, such as Salt Lake City and County Building and Los Angeles City Hall. The base isolation technique has been recognized as one of the most effective strategies to achieve performance goals in the performance-based earthquake engineering design framework.

Behavior of the base isolated structures is slightly different from structures with fixed base. Unlike the fixed-base structures where the earthquake loads are mostly resisted by the stiffness and energy dissipation of the entire structure, the base isolated structures have large deformation concentrated in the isolation layer and the structures behave more or less like a rigid body. While the structures remain/are designed to be linear elastic during ground motion, base isolation bearings and sliders typically exhibit complex nonlinear behaviors such as friction, slippage, and hysteresis in the displacement-force relation. Furthermore, base isolation bearings have dependence on the level of axial loads, temperature as well as aging deterioration. Therefore, in the seismic simulation of the base isolated structures it is critical to accurately account for the behavior of the base isolation layer.

One can apply shake table tests for the seismic simulation and assessment of the base isolated structures. Kelly and Hodder (1982) conducted a series of shake table tests of base isolation systems with laminated neoprene bearings at the University of California, Berkeley. Sasaki *et al*. (2012) utilized the Japan's E-defense shake table for assessment of Friction Pendulum and Lead-Rubber Bearings Systems. Other researchers also reported shake table tests of base isolation buildings. While shake table tests are ideal experimental approaches because the entire structure including the base isolation layer are modeled experimentally and the responses are directly obtained through the physical measurement, they may not be always the feasible options due to funding issues, limited access to facility, etc.

One of the cost-effective alternative approaches for investigation of the base isolated structures is real-time hybrid simulation (RTHS). Because of the high concentration of nonlinear behaviour in the base isolation layer, only the isolation layer needs to be physically tested while the rest of the structure (i.e., building) can be modelled numerically. This highly concentrated nonlinear behaviour makes the base isolated structures ideal applications of RTHS. However, there are technical challenges in the testing of base isolation bearings. Because behaviors of the base isolation bearings, including lateral stiffness, damping, hysteresis, stability, yield stress, and creep, are highly dependent on the axial load, the vertical force on the base isolation bearings has to be accurately imposed during hybrid simulation.

To address the need of such accurate vertical force control with lateral loading, this study proposes a mixed force and displacement control strategy. The proposed control strategy is a decentralized approach that consists of a loop-shaping controller for the force-controlled actuator and a PID controller for the displacement-controlled actuator. To verify the feasibility of the proposed mixed-mode control, a series of verification tests under various loading are performed. Furthermore, the mixed-mode control is also implemented in a RTHS framework for the simulation of a base isolated building. This paper presents experimental setup, verification tests, and RTHS of the base isolation building with the mixed force and displacement control.

## 2. EXPERIMENTAL SETUP

This study utilizes an experimental setup for testing of base isolation bearings developed at the Johns Hopkins University. The experimental setup consists of a loading frame, base isolation bearings, and control, instrumentation and data acquisition systems that are described herein.

### 2.1. Loading Frame and Base Isolation Bearings

A schematic of the loading frame and base isolation bearings is shown in Figure 1: (a) drawing and (b) photo. The loading frame is constructed with four steel W-Shapes: Three W8x40 sections make up both the vertical and top members, and a W12x58 section is used as the bottom support beam. The rubber bearings are bolted by end plates on the bottom of the frame, and they are spaced 22 inches from center to center. The rubber bearings are connected on top by a 34-inch long W8x40 section. The horizontal actuator is connected from one end of the loading frame to a bookend on top of the W8x40 section. The vertical actuator is bolted directly in the center of the two rubber bearings on the other end of the W8x40.

The bearings tested in this study are laminated elastomeric bearings (see Figure 1). Each bearing is composed of three layers of square 152mm x 152 mm ultra-strength neoprene rubber sheet and aluminum plates (Alloy 1100). The aluminum layers are 3.2 mm thick and the neoprene rubber layers are 25.4 mm thick. The aluminum and rubber are connected at each layer and to the end plates by epoxy. It should be noted that these bearings are specifically designed for proof-of-concept real-time hybrid simulation of base-isolated buildings using mixed force and displacement control that is developed and verified in this study.

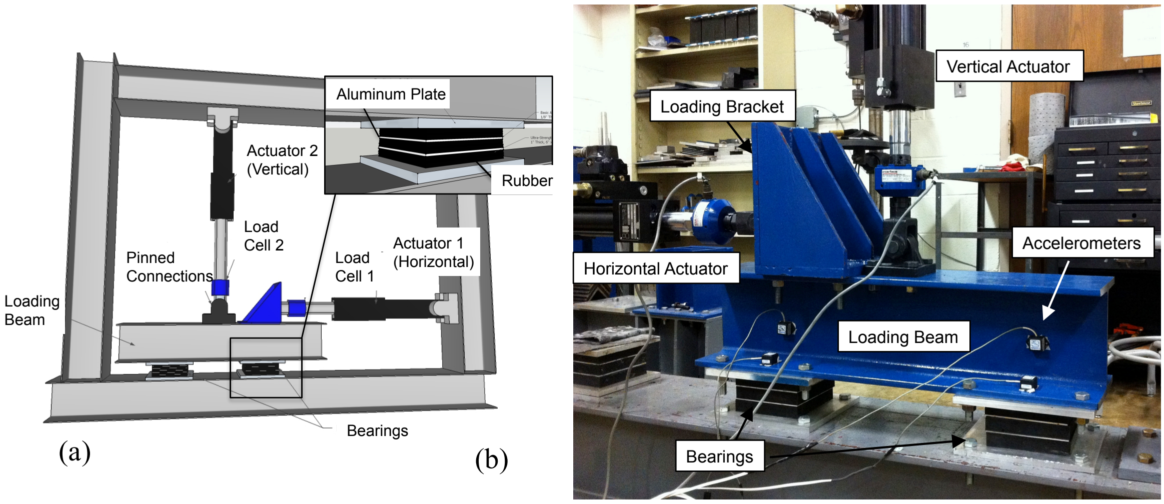

Figure 1. Loading system and base-isolation bearings: (a) drawing and (b) photo.

## 2.2. Control, Instrumentation and Data Acquisition Systems

Two identical actuators, 911D series manufactured by Shore Western Inc., are utilized in the test setup: one is in the horizontal direction and the other is in the vertical direction. Those actuators are equipped with a G761 series servo valve by Moog, Inc., a 22.2 kN load cell by Interface, Inc., and a 152mm DC operated linear variable differential transducer (LVDT). Maximum stroke and dynamic force capacity of the actuator are 152 mm and 24.5 kN, respectively. The hydraulic power is supplied by a 114 litter-per-second Whisper Pak Model 160 from Shore Western, Inc. The hydraulic pressure is rated at 3000psi, and 3.8-litter accumulators are placed in both pressure and return lines to reduce the pressure drop. In addition to the LVDTs and load cells for the actuators, four accelerometers are attached to the loading beam to measure horizontal and vertical accelerations of the base isolation bearings.

For the control of the hydraulic actuators and data acquisition of the sensor signals, a National Instruments PXI Express system is employed in this study. An embedded real-time controller used in the setup, PXI-8031, allows analog-to-digital and digital-to-analog signal conversions at a sampling rate of 4 kHz. LabVIEW Real-Time is used as a software platform for the implementation of mixed force and displacement control strategies in this study. For more details of hardware and software systems at the Smart Structures and Hybrid Testing Laboratory, refer to Nakata (2012).

# 3. PRELIMINARY INVESTIGATION OF THE BEARING BEHAVIOR

Prior to the development of mixed force and displacement control strategies, fundamental behaviors of the base isolation bearings are investigated. The preliminary experimental investigations of the bearings are conducted under displacement control.

A series of harmonic displacement are imposed in the lateral direction of the base isolation bearings. In this series, the vertical displacement is kept constant to investigate the effect of the lateral displacement on the vertical force. Figure 2 shows results of a test case where the lateral displacement is 0.1 Hz sinusoidal input with the peak displacement of 2.54 mm. As can be seen in Figure 2 (a) and (b), displacements in both lateral and vertical displacements are accurately controlled, showing good agreements between the reference and the measured. The time history of the lateral force shown in Figure 2 (c) is approximately a harmonic shape that is expected from the harmonic displacement input. On the other hand, the vertical force in Figure 2 (d) shows noticeable variation despite the constant vertical displacement. This variation has the same frequency as in the lateral displacement and is due to the influence of the lateral deformation that indications interaction between the lateral and vertical axes. Furthermore, it can be observed that the vertical force level decreases over time even after few cycles: 18.1 kN and 17.9 kN before and after the test, respectively. This reduction of the vertical force can be due to the wear of the bearing caused by the lateral deformation. Although not shown here due to the space limitation, the other test cases with different input frequency and amplitude show the similar trend in the vertical force of the base isolation bearings.

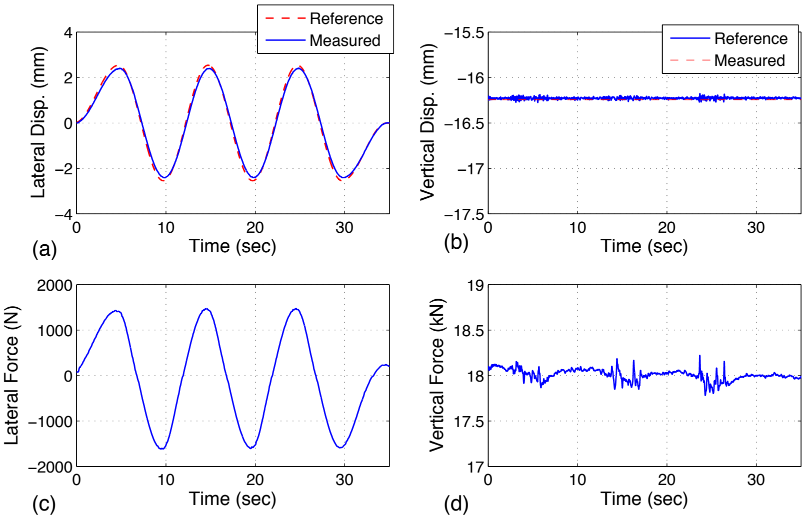

Figure 2. Time histories under displacement control in both lateral and vertical directions: lateral input is a 0.1 Hz 2.54 mm harmonic signal whereas the vertical input is constant.

Next, the influence of the axial force on the lateral stiffness of the base-isolation bearings is examined. Figure 3 (a) shows displacement-force hysteresis of the base isolation bearings at two different levels of axial force: nominal forces at 0.5 kN and 19.2 kN. The nominal force is the initial force in the vertical direction at the zero lateral displacement. As shown in the previous figure 2, the vertical force fluctuates as the lateral displacement is increased despite the constant displacement in the vertical actuator. As can be seen in figure 3 (a), the stiffness, slope of the hysteresis, of the base-isolation bearings is higher at the nominal force level of 19.2 kN than that of 0.5 kN. Furthermore, judged from the fatness of the hysteresis, the base isolation bearings have higher energy dissipation capability at the higher axial force level. The stiffness evaluation test is performed at more nominal force levels and the lateral stiffness estimated from hysteresis using the least square method is plotted against the nominal vertical force in figure 3 (b). It can be clearly seen that the lateral stiffness of the base isolation bearings is highly influenced by the axial force.

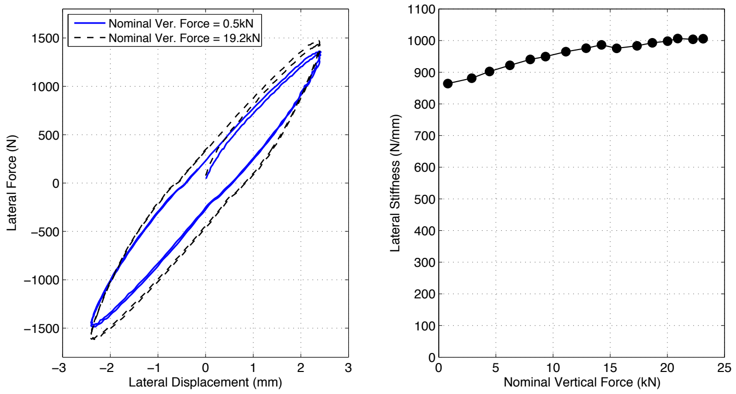

Figure 3. Effect of the vertical force on the lateral behavior of the base isolation bearings: (a) displacement and force hystereses; and (b) lateral stiffness.

The results in these preliminary experimental investigations demonstrate that the lateral behavior of the base isolation bearings is highly influenced by the axial force. Therefore, the axial force and its influence need to be carefully and accurately accounted in both numerical and experimental simulations of base isolated structures. Ignoring the effect of the axial force may cause non-negligible errors in the simulations.

## 4. MIXED FORCE AND DISPLACEMENT CONTROL DESIGN

Motivated by the need of the axial force control in the base isolation bearing tests, this study investigates actuator control strategies that enable challenging structural experiments. Specifically, mixed force and displacement control strategies are speculated. The mixed force and displacement control is often desired in testing of components that exhibit dependence of axial force on lateral and bending behaviors such as base isolation bearings and bridge piers. However, successful implementations of the mixed force and displacement control strategies are limited (Nakashima and Peng, Nakata et al.).

Figure 4 shows a general block diagram of the inner-loop servo controller for the actuators with mixed force and displacement control. In this diagram, two actuators are considered without loss of generality; in the mixed force and displacement control, at least one actuator has to be in displacement control and at least one actuator has to be in force control. If more than two actuators are used, they have to be added into the block diagram. In this diagram, actuator 1 is set in the displacement control while actuator 2 is in the force control.

The goal of the mixed force and displacement control is to produce accurate tracking in controlled displacement and force axes simultaneously. It should be noted that the mixed force and displacement controller is a multi-input and multi-output system. Therefore, if necessary, the controller has to take into account system dynamics and coupling between the two axes, dependent on the level of coupling and control demands. Design of the controller is essentially a development of algorithm that generates the actuator valve commands from the error signals to meet the control requirements.

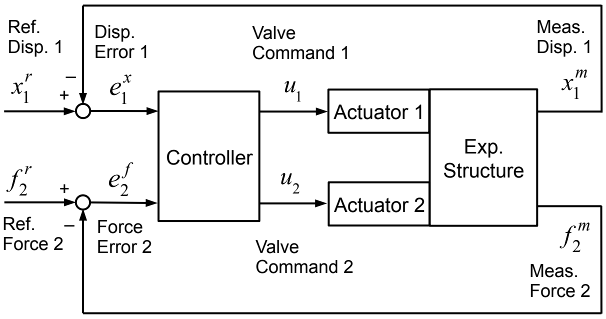

Figure 4. A generalized block diagram for mixed force and displacement control inner servo loops.

### 4.1. Decentralized Control Approach with Loop Shaping in the Vertical Actuator

Multi-actuator experimental systems in structural testing are generally configured with individual serve control loops for actuators if all of the actuators are displacement controlled. However, previous studies (Nakata et al.) showed that a centralized control approach is necessary if one or more actuators are force controlled and significant coupling between actuators exists. For example, a decoupling centralized controller is essential in multi-degrees-of-freedom force control testing where multiple actuators are force controlled (Nakata et al.). In a substructure shake table testing, a centralized controller is crucial for force the controlled actuator while an independent controller is satisfactory for the displacement controlled actuator. Thus, if force control is included in the experimental system, careful control design is needed to successfully perform intended experiments.

In this study, a decentralized control approach is explored because of the orthogonal configuration of the actuators. Figure 5 shows the servo control loop design for the mixed force and displacement control in the base isolation bearing tests. In this configuration, a proportional-integral-differential (PID) control is adopted for the displacement control in the lateral actuator, and a loop-shaping control is employed for the force control in the vertical actuator.

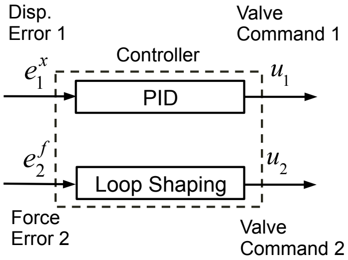

Figure 5. Decentralized control approach with loop shaping for the force controlled actuator and PID for the displacement controlled actuator.

### 4.2. Loop-Shaping Controller Design for the Force Controlled Actuator

The loop-shaping controller is a model-based control approach that can provide high performance and robustness. However, unlike the PID controller, it requires a dynamic model of the control plant, which in this case is the valve to force relation in the vertical actuator. To enable the loop-shaping control design for the force controlled actuator, a system identification test is conducted using a random excitation to the vertical actuator. During the system identification process, the horizontal actuator remains steady.

Figure 6 (a) shows the frequency domain response of the valve to force relation in the vertical actuator. It can be seen that the magnitude of the force decays as the frequency increases. An analytical model shown in Figure 6 (a) is developed using a curve-fitting technique, and the loop-shaping controller is designed such that the loop transfer function, a product of the plant and controller, has following two desired frequency domain characteristics: (i) high gain in a low frequency range and (ii) low gain in a high frequency range.

The frequency at which the magnitude passes 1.0 is called the crossover frequency and is designed to be around 30 Hz in this study. In general, the loop-shaping controller provides tracking performance at frequency less than the crossover frequency and robustness at frequency higher than the crossover frequency. The overall closed-loop transfer function in the force-controlled vertical actuator is shown in Figure 6 (c). It can be seen that the designed loop-shaping force feedback controller provides tracking performance in a low frequency range and robustness in a high frequency range beyond 20 Hz.

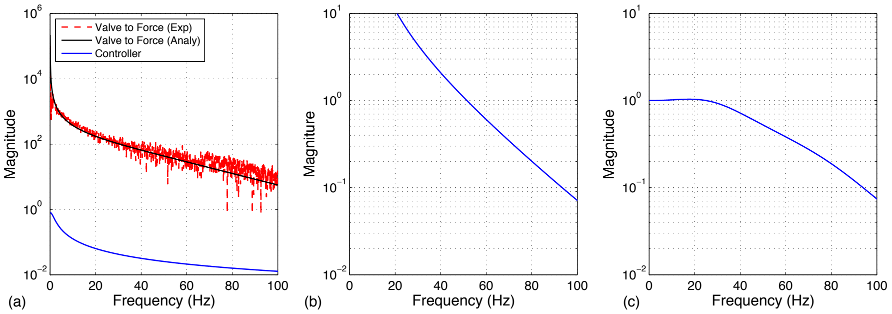

Figure 6. Transfer functions for the loop shaping: (a) transfer function of the control plant and controller; (b) loop transfer function; and (c) the overall closed-loop transfer function of the force.

## 5. EXPERIMENTAL VERIFICATION OF MIXED-MODE CONTROL

Prior to applications in real-time hybrid simulation, the mixed force and displacement control using the decentralized control approach is verified under various conditions and loadings. This section presents results of the verification tests and discusses capabilities and limitations of the mixed force and displacement control strategy.

### 5.1. Verification of Constant Vertical Force Control under Harmonic Lateral Loading

The first verification presented here is a constant vertical force control test under harmonic lateral loading. Figure 7 shows time histories of the displacements and forces in both lateral and vertical axes as well as the hysteresis and the trajectory in the loading plane. As shown in the figure, the lateral loading is a 0.5Hz continuous sinusoidal, and the bearings exhibit hysteresis showing energy dissipation. The vertical force time history in Figure 7 (d) shows that the force fluctuation is approximately within 1.5% of the reference constant force of 13kN. Although not clearly seen, the variations of the vertical displacement in Figure 7 (b) and (d) are the result of the vertical force control. More verification tests with different loading frequencies and amplitudes are also performed. Though not presented here, they show similar results with the same level of fluctuation in the vertical force.

### 5.2. Verification of Varying Vertical Force Control under Earthquake Lateral Loading

The next verification presented here is a varying vertical force control test under earthquake lateral loading. Similar to Figure 7, Figure 8 shows time histories of the displacements and forces in both lateral and vertical axes as well as the hysteresis and the trajectory in the loading plane. The lateral loading is a simulated displacement using the 1995 Kobe earthquake KJM record. The force that is proportional to this lateral displacement is used as the reference force in the vertical direction. Although this lateral displacement and vertical force combination needs to be further investigated, it gives a little more realistic loading to the bearing such as rocking than the constant vertical force.

As seen in the red dotted line in Figure 8 (d), the reference vertical force is dynamically changing in this test. While there is a discrepancy between the reference and measured forces, the measured force shows a reasonable tracking to capture the variation in the vertical force. As the result of the vertical force control, the vertical displacement changes accordingly. It is interesting to note that while the vertical force levels before and after the loading are almost the same (12.5kN), the vertical displacement drops after the loading. This change may imply a shrinkage of the rubber bearings due to thermal effect generated by the lateral loading.

The series of experimental verification tests show that the proposed mixed force and displacement control strategy provides accurate force tracking in vertical direction under lateral loading. With the accomplished level of accuracy, the proposed mixed-mode control algorithm is considered feasible for the implementation in real-time hybrid simulation.

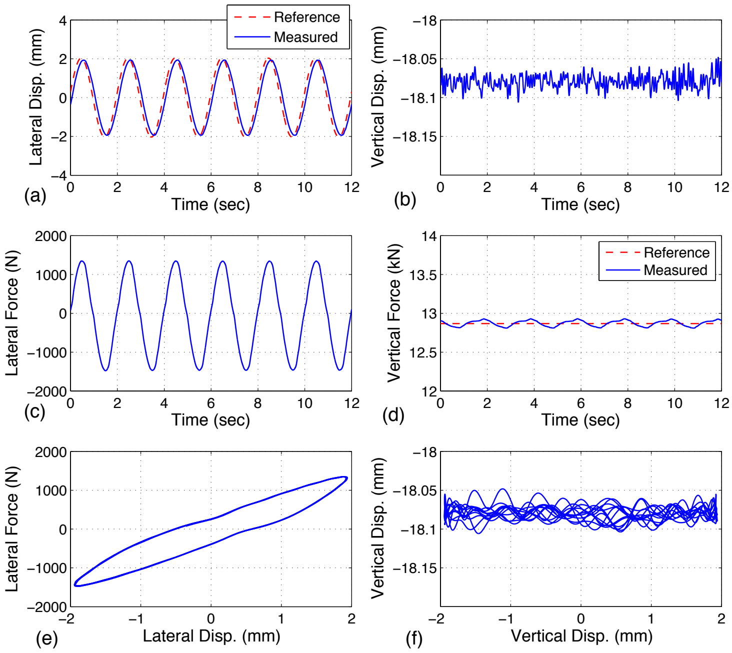

Figure 6. Results of a constant vertical force control under harmonic lateral loading: (a) lateral displacement; (b) vertical displacement; (c) lateral force; (d) vertical force; (d) hysteresis; and (f) loading trajectory.

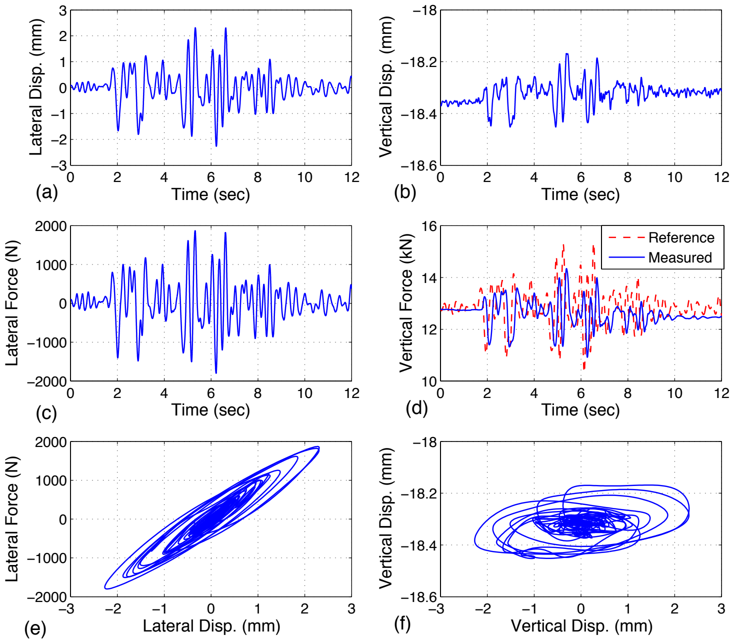

Figure 7. Results of a varying vertical force control under earthquake lateral loading: (a) lateral displacement; (b) vertical displacement; (c) lateral force; (d) vertical force; (d) hysteresis; and (f) loading trajectory.

## 5. REAL-TIME HYBRID SIMULAITON OF BASE ISOLATION BEARINGS

Feasibility of the developed mixed force and displacement control strategy is evaluated in a real time hybrid simulation framework. The considered structural model is a base isolated building where the building is numerically modeled and the base isolation layer is experimental tested. The building model is a rigid block with 5306kg mass and the experimental bearing component is assumed to be a ¼ of the entire base isolation layer. The estimated natural frequency of the structure is approximately 4.0 Hz.

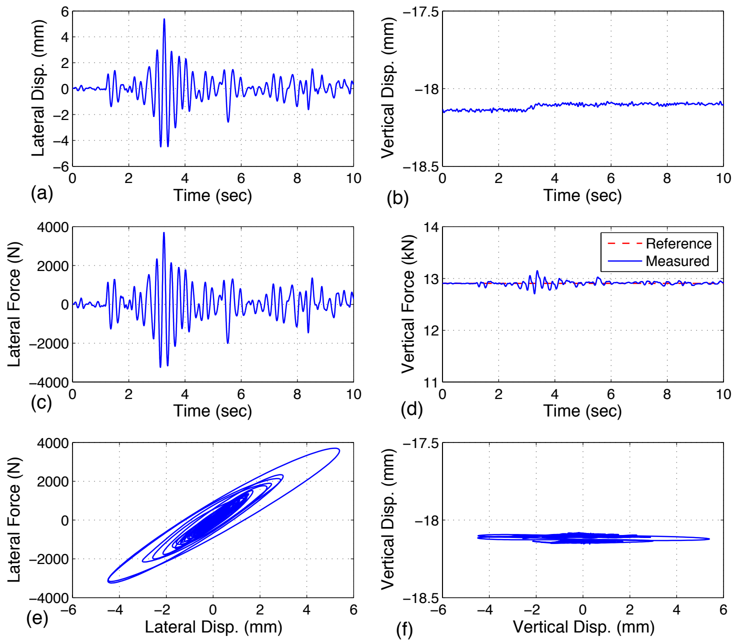

Figure 8. Real-time hybrid simulation with the mixed force and displacement control: (a) lateral displacement; (b) vertical displacement; (c) lateral force; (d) vertical force; (d) hysteresis; and (f) loading trajectory.

Figure 8 shows results of a real-time hybrid simulation. In this simulation, the input lateral ground motion is the 1995 Kobe earthquake record and the reference vertical force is the constant gravitational force of 13kN (=5306 x 9.8/4). As seen in the figure, despite a large variation in the lateral displacement and force (a) and (c), the vertical force is maintained at the reference level almost all the time during the simulation. The peak force error to the reference force is about 1.53%. As in the previous verification test, the change in the vertical displacement after the simulation is observed even for the constant force level. It should be noted that such observation cannot be made with the displacement control approach in the vertical direction.

## 5. CONCLUSIONS

This study presented a mixed force and displacement control strategy for testing of base isolation bearings in hybrid simulation. The controller strategy is a decentralized approach that consists of a loop-shaping controller for the force-controlled actuator and a PID controller for the displacement-controlled actuator. A series of experimental verifications were conducted and their results showed that the proposed mixed-mode control strategy provided acceptable tracking performance in the vertical force during lateral loading. Furthermore, the mixed-mode control was successfully verified in the real-time hybrid simulation of a base isolated building.

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