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Real-time hybrid simulation of a smart outrigger damping system for high-rise buildings

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ABSTRACT

Smart outrigger damping systems have been proposed as a novel energy dissipation system to protect high-rise buildings from severe earthquakes and strong winds. In these damping systems, devices such as magnetorheological (MR) dampers are installed vertically between the outrigger and perimeter columns to achieve large and adaptable energy dissipation. To complement the high performance shown in previous theoretical studies, this control approach needs to be experimentally verified. To examine a smart outrigger damping system experimentally, real-time hybrid simulation (RTHS) provides an alternative where the damping devices can be experimentally tested, while the remaining components in the structural system are simultaneously tested through numerical simulation. The focus of this study is to experimentally investigate and verify smart outrigger damping systems for high-rise buildings subject to scaled El Centro and Kobe earthquake records using RTHS. Through RTHS, the efficacy of the smart outrigger damping system is demonstrated for two historical earthquakes.

1. Introduction

The number of high-rise buildings in urban areas around the world has dramatically increased in the past two decades, spurred by the development of new materials and technologies. However, this achievement also generates new problems; specifically, how these buildings can be protected from strong winds and severe earthquakes. To protect these tall buildings from such severe loadings, researchers and engineers have considered various passive structural control strategies, such as viscous dampers, viscoelastic dampers, and tuned mass dampers [16,28]. However, interstory drifts of a size that is sufficient to dissipate large amounts of input energy are generally not available in high-rise buildings. To solve this problem, numerous response amplification systems have been proposed, e.g. toggle braces [7], scissor-jacks [23], gear-type systems [1], and the mega brace [29].

Smith and Salim [25], Charles [5], Smith and Willford [26] have proposed outrigger damper systems as an alternative response amplification method. This system employs vertical viscous dampers installed between outrigger walls and perimeter columns in a frame-core-tube structure to enhance structural dynamic performance. Willford et al. [32] reported on a real-world implementation in a high-rise building in the Philippines. While successful, this approach is a passive system, which is unable to adapt to structural changes, varying usage patterns, and loading conditions.

In recent years, semi-active control employing magnetorheological (MR) dampers has been shown to achieve high-level adaptive performance, while being able to run on battery power supplies [27]. Indeed the effectiveness of MR dampers has been demonstrated by many researchers [10,27,28,6,33,11]. In the outrigger damping system, Wang et al. [30] presented a numerical example in which outrigger systems was implemented using MR dampers, achieving superior performance over the corresponding passive system.

While these results are encouraging, the complex nonlinear behavior of an MR damper demands experimental verification of this smart outrigger damping system. For this type of structural system, shaking table testing may not be appropriate in terms of the cost and shaking table capacity. Instead, the real-time hybrid simulation (RTHS) method [12,20,14,21,13] enables the testing of the physical damper experimentally while simulating the high-rise building numerically.

RTHS is challenging because it requires execution of each testing cycle within a fixed, small increment of time (typically on the order of 1 ms). Furthermore, unless appropriate compensation for time delays (from communication and computing time) and actuator dynamics is implemented, stability and accuracy problems are likely to occur during the experiment. Horiuchi et al. [14] proposed the prediction method using polynomial extrapolation for time

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delay compensation. However, this technique performs well only when the prediction time is small as compared to the smallest fundamental period of the structure. So, for many RTHS studies of MDOF structures having high natural frequencies, substantial numerical damping must be added to the higher modes to achieve stable experiments, i.e., 10% damping to 2 modes in Darby et al. [8] and 5% damping to 2 modes in Blakeborough et al. [2]. This added damping compromises the accuracy of the RTHS. To solve this problem, an approach for RTHS has been developed that uses model-based methods to compensate for time delays and actuator dynamics and combines fast hardware and software (for high-speed computations and communication) with high performance hydraulic components [3,22].

The number of studies that use RTHS to evaluate structural control performance is very limited. In most cases, the structure considered is a simple shear building with only a few degrees of freedom. In this context, the effectiveness of RTHS for structurally controlled MDOF buildings should be verified.

This paper seeks to use RTHS to verify the efficacy of smart outrigger damping systems employing MR dampers for high-rise buildings subject to earthquake loading. The paper also investigates how magnitude and time delay errors in the input signals to the MR damper affect the accuracy of RTHS for a MODF structure. First, a smart outrigger damping system in a 60-story building is designed and the damper capacity is appropriately scaled for laboratory testing. Then, an MR damper with a servo-hydraulic actuator is assembled as the experimental component of RTHS. System identification is used to obtain an accurate model of the servo-hydraulic system. This model is used to apply model-based actuator control approaches for accurate and stable RTHS. In the experimental verification, a number of semi-active controllers are evaluated and compared with the results from pure simulation. The improvement in performance for the smart outrigger system is also demonstrated in this study.

2. Smart outrigger

In this section, the models for both the high-rise building and the MR damper are presented. Also, the semi-active control algorithm selected for the system is illustrated. In RTHS, a physical MR damper is used, while in numerical simulation, the MR damper model is used.

2.1. Problem formulation

Smart outrigger damping systems are an attractive method to achieve sufficient displacement for damping devices on high-rise buildings. According to Yang et al. [34], a high-rise building can be modeled as a cantilevered beam in which the structural deformations are derived from the behavior of the core. For a high-rise building with outrigger damping, the control devices (e.g., viscous dampers or MR dampers) are located between the outrigger walls and the perimeter columns. Assuming that the perimeter columns are axially very stiff and that the outrigger behaves as a rigid body, then the high-rise building with damped outriggers can be modeled as shown in Fig. 1. As can be seen, the forces from the control devices result in moments being applied to the core through the rigid outrigger. In essence, the damped outrigger acts as a point rotational damping device. The moment applied to the core by the outrigger system f_m can be written as

$$f_m = n_d o_e f \tag{1}$$

where f is the force from a single control device; n_d is the number of control devices; o_e is the distance from the control devices to the

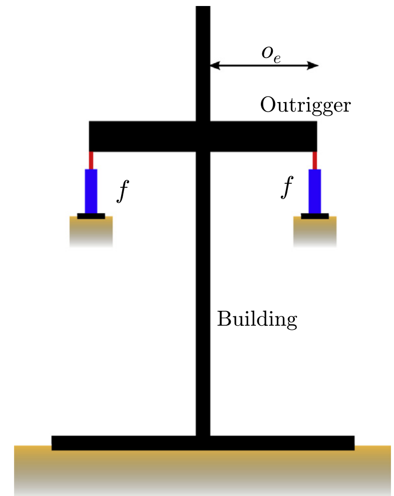

Fig. 1. Mechanism of outrigger systems.

center of the core (see Fig. 1). The equation of motion of the control problem can be written as

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{\Lambda} f_m - \mathbf{M}\mathbf{\Gamma}\ddot{x}_g \tag{2}$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ are the structural mass, damping, stiffness matrices, respectively; $\mathbf{u}$ is the structural deformation vector; $\mathbf{\Lambda}$ is an influence vector that applies the damper restoring force to the appropriate rotational degrees of freedom (DOF); $\mathbf{\Gamma}$ is a vector with entries equal to unity for translational DOFs and zero for others; and $\ddot{x}_g$ is the ground acceleration. The state space form of Eq. (2) is given by

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B} f_m + \mathbf{E}\ddot{x}_g \tag{3}$$

$$\mathbf{y} = \mathbf{C}_y\mathbf{x} + \mathbf{D}_y f_m + \mathbf{F}_y\ddot{x}_g + \mathbf{v} \tag{4}$$

$$\mathbf{z} = \mathbf{C}_z\mathbf{x} + \mathbf{D}_z f_m + \mathbf{F}_z\ddot{x}_g \tag{5}$$

where $\mathbf{y}$ presents the measured structural responses including the relative displacements, the relative velocities, and the absolute floor accelerations; $\mathbf{v}$ is the measurement noise; and $\mathbf{z}$ corresponds to the regulated structural responses. And $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}_y$, $\mathbf{C}_z$, $\mathbf{D}_y$, $\mathbf{D}_z$, $\mathbf{E}$, $\mathbf{F}_y$, and $\mathbf{F}_z$ are appropriately chosen matrices corresponding to the associated state space equations.

2.2. Building model

The building used in this study is the St. Francis Shangri-La Place in Philippines [32,15,4]. This 60-story building has a height of 210 m and has 12 perimeter columns which are 20 m from the building centerline. The concrete core is assumed to be 12 m × 12 m with 0.5 m thickness. The total mass of the building is 30,000 tons and the outrigger system installed consists of 16 viscous dampers, 8 of which control the response in each of the two orthogonal directions.

To create the model for evaluation, a vertical cantilever beam model based on the Bernoulli–Euler beam theory is applied. A finite element model is developed so that every story has one transitional and one rotational degree of freedoms. Therefore, the total number of degrees-of-freedom should be 120 (60 in translation and 60 in rotation). Hence, the reduced structural deformation vector up to mth mode, $\mathbf{u}_{\mathrm{red},m}$ can be represented by

$$\mathbf{u}_{\mathrm{red},m}(t) = \sum_{i=1}^{m}\phi_i q_i(t) = \mathbf{\Phi}_m\mathbf{q}_m(t) \tag{6}$$

where $\mathbf{\Phi}_m = [\,\phi_1 \quad \phi_2 \quad \cdots \quad \phi_m\,]$ is the mode shape matrix up to the mth mode and $\mathbf{q}_m = [\,q_1 \quad q_2 \quad \cdots \quad q_m\,]$ is the modal coordinate