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# Experimental and Numerical Studies of a Newly Developed Semi-active Outrigger Damper System

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## Abstract

Outrigger system is commonly used in resisting lateral loads induced by earthquakes and winds for high-rise buildings. The structural form of outrigger system consists of a central core, exterior columns, and horizontal cantilever outriggers connecting the core to the exterior columns. This efficient structural system increases the lateral stiffness of the structure, thus ensuring the stability and serviceability of the structure. Recently, damped outrigger system incorporating passive fluid-viscous dampers installed between outriggers and exterior columns was introduced and its effectiveness in increasing structural damping was verified through the application of them to a high rise building in Philippine.
This paper presents a newly developed semi-active outrigger damper system, in which exterior columns and horizontal cantilever outriggers are connected with a semi-active outrigger damper. The semi-active outrigger damper acts as an on-off locking device enabling the exterior columns and the outriggers to be engaged or disengaged through an appropriately designed control algorithm, Due to the necessity of controlling the device, the semi-active outrigger damper system consists of sensors and a controller. Numerical simulation results show that optimally selected switching between engagement and disengagement is shown to be effective in reducing structural responses. Performance test on a semi-active outrigger damper was carried out to verify its applicability as an on-off locking device. The developed device showed a stable performance under a harmonic loading.

**Keywords**: Outrigger Damper System, Semi-active, On-off locking device, Controller

## 1. Introduction

An outrigger system is an efficient structural system in resisting lateral loads induced by earthquakes and winds for high-rise buildings. It consists of a central core, exterior columns, and horizontal cantilever outriggers and increases its lateral stiffness, thus ensuring the stability and serviceability of the structure.
Recently, there's an effort to increase structural stability and serviceability of an outrigger system by installing passive and semi-active dampers between outriggers and exterior columns. Jeremlah (2006) introduced an outrigger damping system in which passive viscous dampers are installed between outriggers and exterior columns. It was shown to be effective in reducing structural responses under impulse-like loads such as wind gusts. Smith and Willford (2008) applied an outrigger damping system to a high-rise building in Philippine and proved it to be cost-effective by decreasing the demand for high stiffness and strength of the structure. Wang et al. (2010) developed a controllable outrigger damping system in which the semi-active control devices, magnetorheological (MR) dampers, are used to improve the control performance of the system and investigated the effectiveness of clipped-optimal algorithms with different control targets.
In this paper, a semi-active outrigger damper system in which the structural responses are controlled by changing the values of structural stiffness through an engagement and disengagement of a semi-active outrigger dampers installed between outriggers and exterior columns is proposed. The control performance of the proposed semi-active outrigger damper system is investigated numerically and the performance test on a newly developed semi-active outrigger damper is carried out to verify its applicability as a switching device.

## 2. Numerical simulation for a semi-active outrigger damper system

The semi-active outrigger damper system is another kind of an active variable stiffness (AVS) system proposed by Kamagata and Kobori (2000). In section 2.1, the AVS system is briefly described and, in section 2.2, the numerical simulation results of a semi-active outrigger damper system are presented.

2.1 AVS system

The purpose of the AVS system is to reduce structural vibrations induced by external loads such as earthquakes and winds by controlled switching between the engagement and disengagement of the variable-stiffness device (VSD), installed between the controlled structure and stand-by bracing as shown in Figure 1. The status of the VSD is controlled by switching control algorithms.

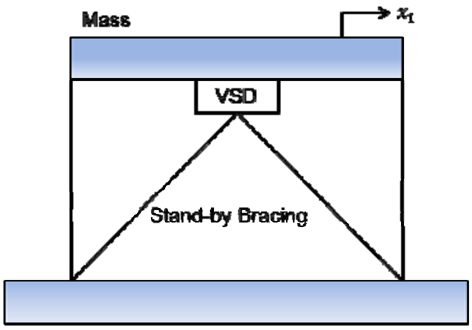


Figure 1. The illustrative picture of the AVS system

The equation of motion for the AVS system with a generic VSD is described as follows.

$$(1)\ m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1 x_1 = -u_{q(t)} \qquad \mathrm{q(t)} \in \{ON \quad OFF\}$$

$$(2)\ u_{q(t)} = \begin{cases} k_b\big(x_1(t) - x_r(t)\big) & if\ q(t) = ON \\ 0 & if\ q(t) = OFF \end{cases}$$

in which $x_1$ is the displacement of the structure, and $m_1, c_1, k_1, k_b$ are the mass, damping, stiffness of the structure and stiffness of the stand-by bracing. The reference position $x_{r(t)}$ is required to provide a zero force position. The control force $u_{q(t)}$ represents the force during the modes ON and OFF.

The switching signal q(t) is regulated by the switching control algorithms at every instant of switching time to decrease the structural responses. The activated mode must be maintained during the length of time between switching time, which is defined by the control sampling period T where $\mathrm{T} = t_{k+1} - t_k$.

An on-off switching algorithm deciding the status of the VSD was proposed by Kamagata and Kobori (1994). The on-off switching algorithm decides when the structure and stand-by bracing are engaged together or when they are disengaged separately as follows. They are engaged together when the mass crosses its zero equilibrium point and maintains the mode ON until it reaches a peak displacement position. They are disengaged as soon as the displacement of the structure reaches its peak position and then subsequently maintains the current status of disengagement until the mass reaches its zero equilibrium point.

A resetting control law was proposed by Yang et al. (2000). It activates the disengagement whenever the displacement of the structure reaches its peak position. As soon as the duration of the disengagement predetermined by the control sampling period is over, the engagement is activated and maintained until the displacement of the structure reaches its peak position again.

The resetting control law was shown to improve structural control performance compared with the on-off switching algorithm. The resetting control law descried within the comprehensive switching framework proposed by Joung et al. (2010) is presented in Table 1.

Table 1.The resetting control law for the AVS system within the comprehensive switching framework

| Switching decision | Switching condition |
|---|---|
| $\mathrm{q(t) = ON}$ | |
| Activation | $\dot{x}_1(t)\vert_{t=kT} \cdot \dot{x}_1(t)\vert_{t=(k-1)T} \leq 0$ |
| Deactivation | $\dot{x}_1(t)\vert_{t=kT} \cdot \dot{x}_1(t)\vert_{t=(k-1)T} > 0$ |

| $\mathrm{q(t)} = \mathrm{OFF}$ | |
|---|---|
| Activation | Right after predetermined control sampling period T is elapsed |
| Deactivation | Duration of the control sampling period T |

For above mentioned two switching control algorithms, numerical simulation is performed for free vibration and the results are shown in Figure 2. It is shown that the resetting control law enables the displacement of the AVS system to decay more rapidly than the on-off switching control algorithm does.

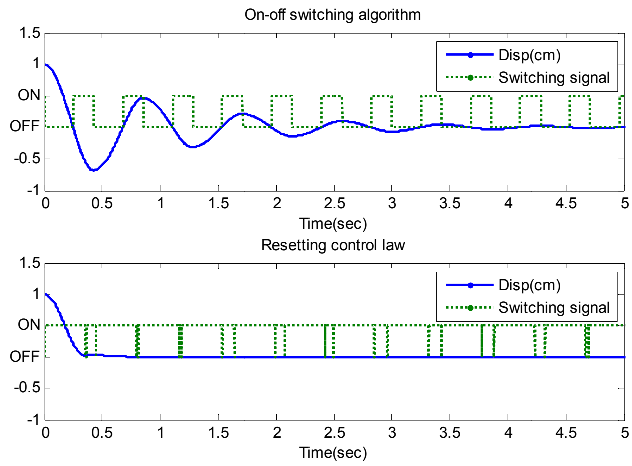


Figure 2. The displacement time histories and switching signal induced by an on-off switching algorithm and a resetting control law under free vibration

2.2 Semi-active outrigger damper system

The semi-active outrigger damper system reduces structural responses by active controlled switching between the engagement and disengagement of a semi-active outrigger dampers installed between outriggers and exterior columns. Figure 3 shows a conventional outrigger system and a semi-active outrigger damper system.

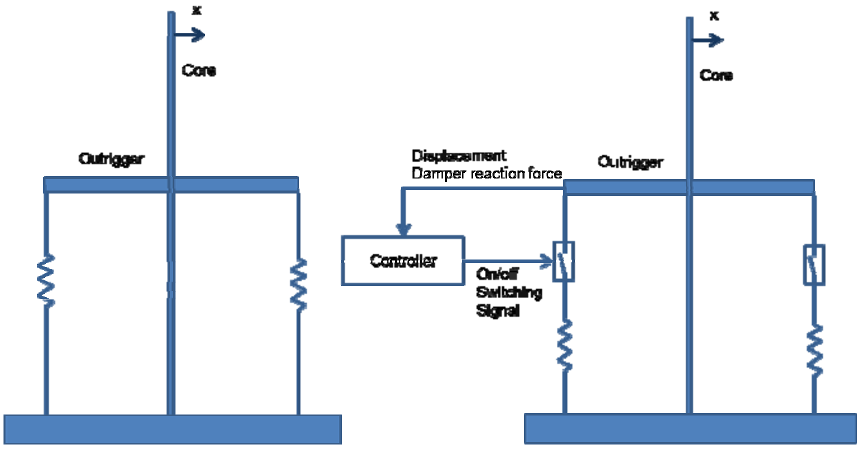


Figure 3. A conventional outrigger system and a semi-active outrigger damper system

The equation of motion for the semi-active outrigger damper system with a generic on-off locking device is described as follows.

$$m_o\ddot{x}_o + c_o\dot{x}_o + k_o x_o = -u_{q(t)} \qquad \mathrm{q(t)} \in \{ON \quad OFF\} \tag{3}$$

$$u_{q(t)} = \begin{cases} k_c\big(x_o(t) - x_{or}(t)\big) & if\ q(t) = ON \\ 0 & if\ q(t) = OFF \end{cases} \tag{4}$$

in which $x_o$ is the displacement of the structure, and $m_o, c_o, k_o, k_c$ are the mass, damping, stiffness of the structure and stiffness of the exterior columns. The reference position $x_{or(t)}$ is required to provide a zero force position. The control force $u_{q(t)}$ represents the force during the modes ON and OFF. The values of parameters are adopted from Jeremlah (2006) except for the damping ratio which is set to 0 % here. The control sampling period T is set to 0.1s and the fundamental period of the system is set to 5s. The forcing function adopted from Jeremlah (2006) represents two successive wind gusts as impulse-like loads of which periods are close to the fundamental period of the structure and is shown in Figure 4.

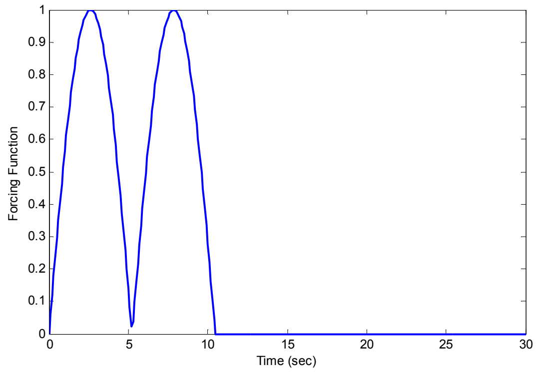


Figure 4.. Forcing function for a semi-active outrigger damper system

Numerical simulation results are shown in Figure 5 and Figure 6. It is shown that resetting control law outperforms on-off switching control law in reducing structural responses.

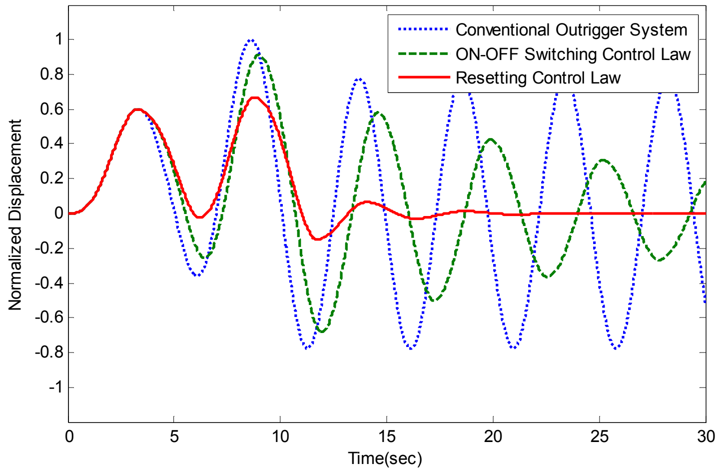


Figure 5. Normalized displacement time histories for without control, on-off switching control law, and resetting control law

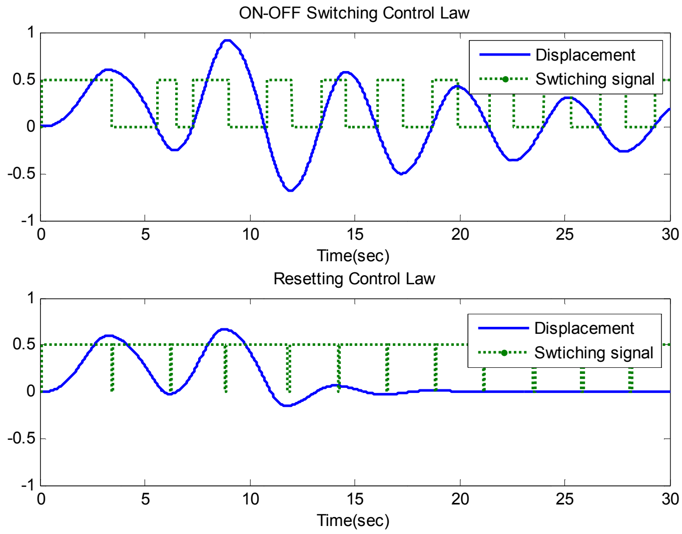


Figure 6. Normalized displacement and switching signal time histories for on-off switching control law and resetting control law

## 3. Performance test on a displacement-dependent semi-active outrigger damper

In this section, performance test on a displacement-dependent semi-active outrigger damper are carried out to verify its applicability as an on-off locking device. The test includes three different cases: when the damper generates high reaction force during the engagement, when the damper generates low reaction force during the disengagement, and when the damper generates high and low reaction forces alternately during the switching between the engagement and disengagement.

The reaction force generated by the damper can controlled by selecting appropriate timing for opening and closing of solenoid valves installed in the valve block which is connected to the damper. The timing for opening and closing of the solenoid valves are determined through appropriately designed control algorithms. The experimental semi-active outrigger damper control system consists of two hydraulic double-acting cylinders generating displacement-dependent reaction force, a valve block including solenoid valves and steel tubes connecting two cylinders together, and PXI controller from National Instruments connected to a laptop computer for controlling the switching signal and measuring pressures generated in the cylinders and piston displacement and is shown in Figure 7.

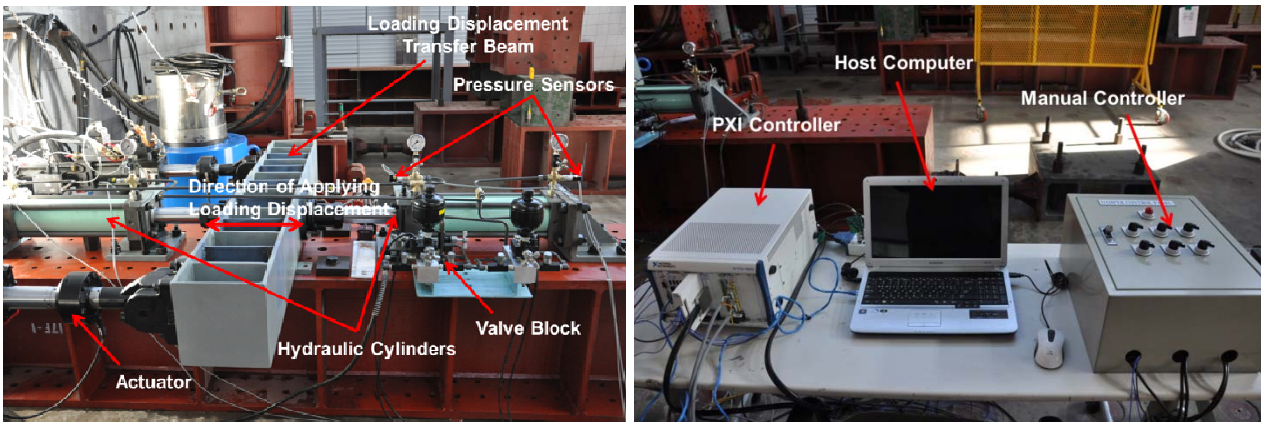


Figure 7. Experimental semi-active outrigger damper control system

The damper generates reaction force proportional to the piston displacement caused by displacement loading from actuators. The beam placed between two cylinders was used to transfer displacement loading from the end of beam attached to an actuator to the damper. In this performance test, the damper was designed to generate up to 20 ton. Four pressure sensors for each chamber and a LVDT (Linear Variable Differential Transformer) for measuring piston displacement were attached to the damper. The reaction force is calculated from measured pressures.

The performance test on the damper was carried out for three different cases: during the engagement, during the disengagement, during the switching between the engagement and disengagement. The control sampling period is set to 0.1s. To verify the relationship between the reaction force and initial pressures in the cylinders, four different initial pressures, 1 bar, 20 bar, 30 bar, and 50 bar were applied to the damper and corresponding reaction forces under linearly increasing loading displacement were measured. From Figure 8, it is shown that the reaction force reaches its maximum value more rapidly as initial pressure increases. The sinusoidal loading displacement with gradually increasing amplitude was applied to the damper. Figure 9 shows the reaction force time histories during the engagement and disengagement. Figure 10 shows the reaction force time history during the switching between the engagement and disengagement. It is shown that the damper generates high reaction force during the engagement and low reaction force during the disengagement as we expected. Furthermore, during the switching between the engagement and disengagement, the damper can switch high reaction force to low reaction force in a very short time, which is the most required property for an on-off locking device.

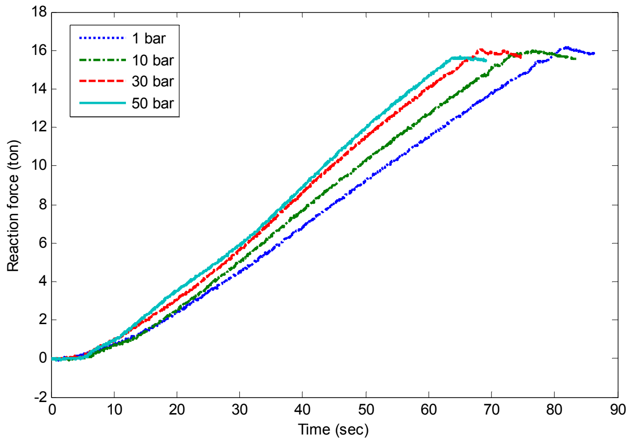


Figure 8. Reaction force time histories with four different initial pressures in the cylinders

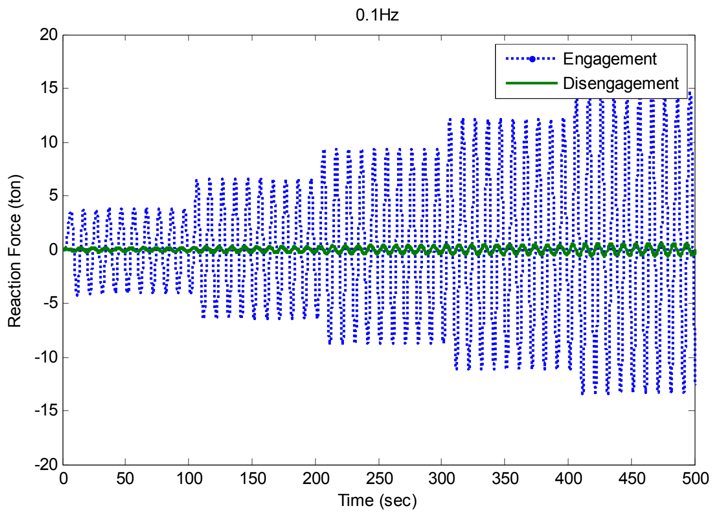


Figure 9. Reaction force time histories during the engagement and disengagement

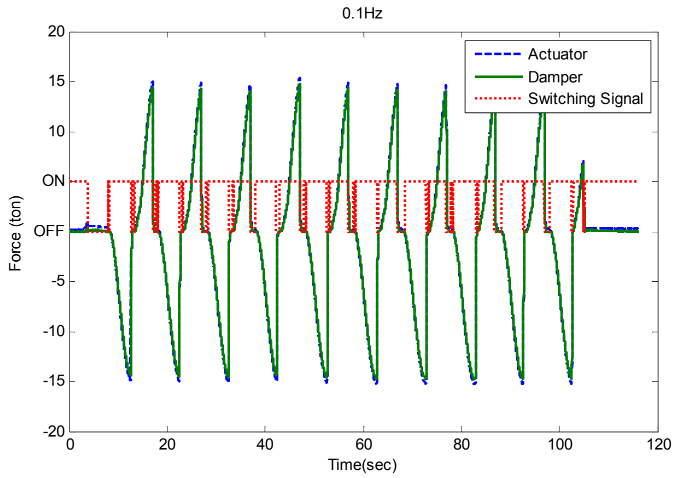


Figure 10. The force time histories generated from actuators and a damper and corresponding switching signal time histories

## 3. Conclusions

A newly developed semi-active outrigger damper system is proposed here and studied numerically and experimentally. It is shown that the semi-active outrigger damper system with appropriately designed switching control algorithms outperforms conventional outrigger system in reducing structural responses. From the experimental results, the damper is shown to switch high reaction force to low reaction force in a very short time, which is the most required property for an on-off locking device.

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