The Application and Research Progress of Adjacent Structures Vibration Control

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Abstract: Over the past three decades, adjacent structures vibration research has steadily gained momentum from proposed research concepts to actual implementation. Numerous passive and active control strategies have been considered for low- to high-rise buildings. This paper contains a literature review of adjacent structures control, and reviews from the aspects including neural control method, laboratory test, and engineering application. The existing problem and the future developing in application are also summarized respectively.

Keywords: adjacent structures; passive control; active control; laboratory test; engineering application

1. Introduction

In modern cities, due to a high value of land space, limited availability of land preference to centralized services, there is a tendency to construct the buildings in close proximity without maintaining proper separation gaps. During an earthquake event, these structures vibrate vigorously and may become a cause for severe damage because of mutual pounding. The 1985 Mexico City and 1989 Loma Prieta earthquakes are the typical examples of the large-scale damage caused by structural pounding. Strong seismic events can cause severe inelastic behavior in civil structures, threatening the safety of occupants and resulting in potential human and material losses.

Civil structures are traditionally protected from large seismic events through redundancies. In recent years, medium and high-rise structures have begun employing control techniques such as active mass drivers (AMDs) to help mitigate responses. Ultrahigh-rise buildings, such as recent trends are producing, are relatively flexible and difficult to control with AMDs, due to long actuator strokes and large energy requirements. Adjacent structures have been shown to be a viable alternative for the protection of adjacent flexible structures (Seto, 1994a). Recently, adjacent structures control has received much attention in Japan and the U.S. as a number of researchers are studying various control strategies, and full-scale applications are beginning to appear.

2. Control Methods

In 1972, Klein, *et al.* (1972) first proposed the concept of coupling two tall buildings in the U.S. In 1976, Kunieda (1976) proposed coupling multiple structures in Japan. In the mid 1980's, Klein and Healy (1987) suggested a rudimentary semi-active approach, coupling two buildings with cables that could be released and tightened (when slack is available) to provide specified dissipative control forces. They observed that the structures being coupled with a single link must have different primary natural frequencies to insure controllability. They also proposed that the buildings be connected near the top as this is a region where the vibratory modes will have non-zero amplitudes.

In the 1990's, interest in coupling civil structures was renewed due to advancements in structural control and the apparent limits of existing technology (e.g., base isolators, AMDs, etc.). Graham (1994) coupled single-degree-of-freedom building models for both passive and active control strategies and concluded that, in addition to a passive control strategy, an active LQR control approach can effectively reduce the response of the two adjacent structures. Further studies would continue to show the effectiveness of passive and active control strategies for the adjacent structures problem.

Passive control strategies have been studied for both high- and low-rise buildings. Gurley, *et al.* (1994), Kamagata, *et al.* (1996), Fukuda, *et al.* (1996) and Sakai, *et al.* (1999) have each studied the case of coupling tall flexible structures with passive devices, while Luco, *et al.* (1994, 1998), Xu, *et al.* (1999a) and Ko, *et al.* (1999) have studied connecting low- to medium-rise structures with passive devices. Each of these papers reports positive results in mitigating the responses due to wind and seismic excitations. Additionally, Fukuda, *et al.* noted, as Klein and Healy had implied, that when a coupling link is placed at a node of a vibratory mode, that mode cannot be controlled by the link, reiterating the importance of the location of the coupling link along the height of the buildings.

Active control strategies have been studied extensively for flexible structures. Seto, *et al.* (1994a, 1994b, 1995, 1996, 1998), Haramoto, *et al.* (1999, 2000), Matsumoto, *et al.* (1999), Mitsuta and Seto (1992), Hori and Seto (1999) and Yamada, *et al.* (1994) have studied connecting tall flexible structures using active control techniques to control the long period motion, as well as the higher modes, with encouraging results. The higher modes of flexible structures may be more susceptible to seismic excitations and are a concern for this class of buildings. Seto, *et al.* have successfully controlled the first two modes of two and three adjacent flexible building models in simulation and experimentally. They intentionally placed coupling links at the vibration nodes of the first neglected mode, making it uncontrollable, to prevent spillover of the controller into this higher mode.

3. Laboratory Test

In addition to the numerous analytical studies actively coupling adjacent buildings for response mitigation, there has been significant experimental work. Mitsuta, *et al.* (1992) performed experimental tests on two adjacent single-degree-of-freedom (SDOF) building models and adjacent single- and 2-DOF building models. The building masses were coupled with an active control actuator, using absolute displacement sensors for the feedback measurement. Yamada, *et al.* (1994) coupled a pair of 2-story and 3-story building models at the second story with a negative stiffness active control device and was able to effectively reduce the displacements of these low-rise building models. A number of experiments have been conducted on coupling two continuous plates, representing flexible high-rise structures (Fukuda, *et al.* 1996, Hori and Seto, 1999, Kamagata, *et al.* 1996, Seto, 1996, 1998, Seto, *et al.* 1994a, 1994b, 1995). These active control experiments have used one and two control actuators. The active control strategies for these experimental tests employ displacement measurements for feedback.

The direct measurement of displacement on large-scale structures is difficult to achieve. Additionally, nearly all of the experimental tests performed to date have produced active control forces using electromagnetic actuators. The exception is Yamada, *et al.* (1994) who used a spring in series with a stepping motor of rack and pinion mechanism to realize their negative stiffness control strategy. The idealized actuators have little device dynamics, and thus control-structure interaction is not significant in the resulting experiments. Since control-structure interaction can have a significant effect on the ability of the control actuator to produce desired forces at the structures resonant frequencies, the inclusion of this phenomenon for actuators models more representative of full-scale devices is important (Dyke, *et al.* 1995).

Christenson put forward a pair of 2-dof flexible building models with an active control actuator is employed. Acceleration feedback is incorporated, using the acceleration measurements at the top floors of the building models. The accelerations at the top floors of each building are significantly reduced as observed in the reduction of the resonant peaks of the top floor transfer functions and in the transient response of the system to an initial displacement. A schematic of the experimental setup discussed in this paper is shown in Figure 1.

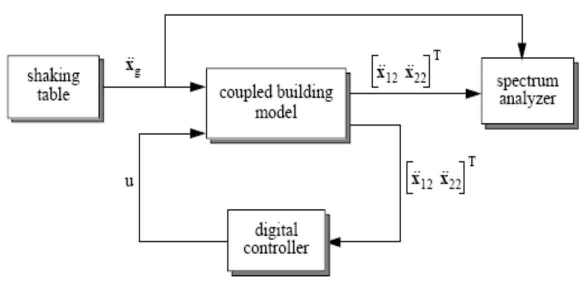

Figure 1. Schematic of adjacent structures experiment

The adjacent structures model consists of a pair of 2-dof building models, an active control actuator and accelerometers. The two 2-story building models were manufactured by Quanser Consulting Inc. The buildings are 305 by 108 mm in plan and 980mm tall. The height and stiffness of the buildings are similar with different floor masses. The

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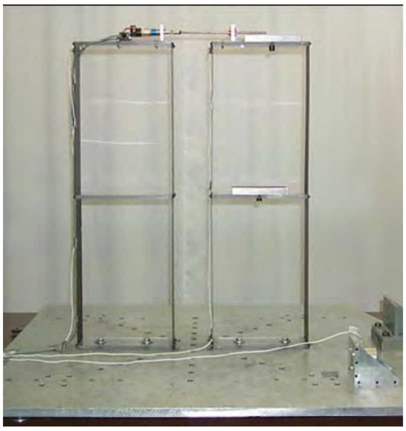

Figure 2. Adjacent structures model

buildings are tested along their weak axis (305mm). Additional masses have been added to the floors of building 1 to insure that the buildings are dynamically dissimilar. The buildings are tested along their weak axis (305mm). The natural frequencies of building 1 are 0.9Hz and 2.70Hz. The natural frequencies of building 2 are 1.85 Hz and 5.73 Hz. The potentiometer is used for the feedback control of the actuator itself. The adjacent structures model, as attached to the shaking table in the SDC/EEL, is shown in Figure 2.

4. Engineering Applications

In addition to these research activities, full-scale tests are being performed and full-scale applications are being realized. Three adjacent structures control applications, all located in Japan, are pictured in Figure 3. In 1989, the KI (Kajima Intelligent) Building complex was constructed in Tokyo, Japan. This complex coupled the 5-story and 9-story structures in a low-rise office complex with passive yielding elements connected at the 5th floor. The general contracting firm, Konoike, has implemented four substructure coupling projects in recent years and, in 1998, coupled four of their headquarter buildings, one 12-story and three 9-story buildings, in Osaka, Japan, with passive visco-elastic dampers. Iemura, *et al.* (1998) has studied passive and active control of two low-rise structures and is preparing full-scale tests to verify the concept at the Disaster Prevention Research Institute (DPRI) in Kyoto, Japan. Here they will connect 3- and 5-story building frames at the 3rd floor. The Triton Square office complex, located in Tokyo waterfront on Harumi Island, was completed in

Figure 3. Examples of full-scale adjacent structures implementations

March 2001. The complex is a cluster of three buildings, 195 m, 175 m, and 155 m tall. The 195 m and 175 m tall buildings are coupled at a height of 160 m. The 175 m and 155 m tall buildings are coupled at a height of 136 m. The three buildings are coupled with two 35-ton active control actuators for wind and seismic protection.

Experimental studies to verify active adjacent structures control have traditionally employed displacement feedback. The direct measurement of displacements on larger scale structures is difficult to achieve, thus acceleration feedback, as considered in this dissertation, is an appealing control strategy for adjacent structures control.

Active control strategies employing acceleration feedback have been shown in previous experiments to be effective for other civil structure applications, including an active bracing system (Spencer, *et al.* 1993), an active tendon system (Dyke, *et al.* 1994a, 1994b) and active mass driver systems (Dyke, *et al.* 1996b, Battaini, *et al.* 2000).

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