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A new active control performance index for vibration control of three-dimensional structures

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ABSTRACT

Remarkable results have been reported about conventional active control algorithms during the last 30 years, but nearly all the existing literature considers 2-dimensional in plane structures to implement and verify the active control algorithms. To simulate the behavior of real buildings more accurately, more realistic and complex models should be used in the performance evaluation and design of controllers and their control algorithms. This paper presents a new performance index for active vibration control of three-dimensional structures. To analytically validate the proposed performance index, a six story three-dimensional structure is considered as an example with a fully active tendon controller system implemented in one direction of the building. Tier building formulation is used for three-dimensional dynamic analysis. The building is modeled as a structure composed of members connected by a rigid floor diaphragm such that it has three degrees of freedom at each floor, i.e., lateral displacements in two perpendicular directions and a rotation with respect to a vertical axis for the third dimension. The performance of the building with the active tendons controlled using a classical linear optimal control algorithm is compared to the performance of the proposed control algorithm under several far-fault and near-fault earthquakes using several performance measures. Comparison between the computational results shows that the proposed algorithm outperforms the performance of the classical linear optimal control algorithm for the actively controlled building.

1. Introduction

Vibration control of civil engineering structures has drawn much attention during the last two decades. It will continue to be a vigorous area of research because of the need to protect structures against earthquakes and strong winds. The various vibration control strategies, used to prevent structural damage in structure subjected to dynamic loads can be classified as active, passive, hybrid and semi-active control. To mitigate undesirable building motion under strong earthquakes and wind gusts, different structural control systems have been proposed and investigated [1–3]. With remarkable advances in the technology of structural control there has been increasing progress and development with these systems [4–7].

Active control methods are effective for a wide frequency range as well as for transient vibrations. Active control devices are always integrated with a power supply, real time controllers and sensors placed on the structure. One of the most important active control devices is active tendon controllers [8–14]. The numerical example of this study also considers them. Active tendon control systems consist of diagonal prestressed steel cables, pulleys, actuators, controller devices, and sensors. In the active tendon control of structures, the damping of the vibrations is sustained by controlling the force on diagonal prestressed tendons connected to actuators placed on the sides of the structure. While applying active control to structures with active tendon controllers or other active devices an appropriate active control algorithm must be selected. There are several categories of control algorithms i.e. classical linear optimal control [15,16], H_2 and $H\infty$ control [17], fuzzy control [18,19], adaptive control [20], decentralized control [17], frequency domain techniques [21] and instantaneous optimal control algorithms [22,23].

In research studies and practical applications, various control algorithms have been proposed to obtain the optimal active control force. A new performance index which minimizes the mechanical, control and the seismic energies of the structure simultaneously in the minimization procedure was proposed and validated for shear frame structures with active tendon controllers in [11]. A modified predictive control algorithm for active control of structures in

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discrete-time and illustrated control effectiveness with active tendon controlled single degree of freedom and multiple degree of freedom structures was developed in [12]. An energy-based technique to find gain matrices in classical linear optimal control was developed in [13]. In order to improve the performance of active isolation systems (AISs) for acceleration sensitive equipment or structures, two optimal control laws that utilize performance indices associated with system absolute energy were proposed in [23]. A new active control algorithm for the suboptimal solution of the optimal closed-open-loop control based on the prediction of earthquake excitation using the Taylor series and the Kalman filter was proposed in [24]. A neuro genetic algorithm for active control of high rise building was proposed in [25]. A novel wavelet-hybrid feedback-Linear Mean Square (LMS) algorithm for robust control of large civil structure was proposed in [26]. A simple integral-type quadratic functional as the performance index was proposed in [27]. This simple active control algorithm was validated numerically by using an eight story shear frame incorporating active tendon controllers. An optimal $H\infty$ control algorithm for time delayed active tendon control systems were developed in [28]. Neural networks have also been used for improving controller behavior [29]. A direct adaptive active control method to control the seismic behavior of an undamaged and a damaged structure using active hydraulic actuators was proposed in [30]. A new method uses three algorithms: discrete wavelet transform (DWT), particle swarm optimization (PSO), and linear quadratic regulator (LQR) was presented to find the optimal control forces for active tuned mass damper in [31]. An improved multi-input multi-output filtered-X least mean square-based vibration control algorithm was proposed to solve the reference signal extraction problem for active vibration control system in [32].

Although there is some promising development, research efforts regarding active control, usually consider two-dimensional plane frame structures or shear frames [10–19,22–24,27,28,30,31]. Therefore, it limits the applicability of this method into simple and symmetrical structures. Some researchers have considered three-dimensional structures as building models in structural control and dynamics studies [33–38,40–43]. They mentioned the benefits of using three-dimensional buildings as example structures [33,36,38,43,45]. A procedure was developed to analyze three-dimensional buildings utilizing active and passive control devices [33]. In their study they suggested that as buildings are three-dimensional in geometry, it is necessary to carry out the research in three dimensions rather than two dimensions. They also added that this can represent buildings in a more natural pattern and reflect its true behavior. An irregular three-dimensional structure incorporating active tendon controllers was investigated in [36]. In this study they discussed that in active control, controllers may be also configured for reduction of torsional effects. They also noted that all civil structures are torsionally irregular because of accidental torsion so it must be taken into consideration in structural designs. Active tendon controlled torsionally irregular structures considering soil–structure interaction effects were numerically analyzed in [38]. In this study it has been presented that in previous structural control studies, many researchers assumed that a controlled structure is a planar structure built on a fixed base. They also presented that, it is generally recognized that a real building is actually asymmetric to some degree even with a nominally symmetric plan. A semi-active control strategy was implemented into a two story three-dimensional building in [43]. The authors of this study discussed that, the effectiveness of a control strategy, depends upon the possibility of achieving reliable modeling of both the uncontrolled and controlled structures.

Another lack about active control studies is that most of the studies about active control in the literature [13,15,16,21,24,31] are based on the classical active control algorithms, which are the applications of the regulator problem in which the performance index is defined as the integration of a quadratic expression with respect to the state and the control vectors. This performance index has two contributions; the first one reflects the desire of bringing the controlled variable to zero while the second one that of keeping the control input as small as possible. But, only classical closed-loop control can be applied to structures. However, since the nonlinear matrix Riccati equation is obtained by ignoring the earthquake excitation term classical closed-loop control is approximately optimal and does not satisfy the optimality condition. On the other hand, while the classical closed open loop control and open loop algorithms are superior to the closed-loop control, they are not applicable to earthquake-excited structures, because the whole earthquake ground acceleration history is not known a priori. Therefore, it is almost impossible to find the optimal control exactly for the structures under earthquake forces.

This study proposes a new performance index for three-dimensional structures so that the resulting control scheme does not require a priori knowledge of seismic input and the solution of the nonlinear matrix Riccati equation to apply the control forces. The proposed study introduces the seismic energy term into the performance index so that the mechanical energy of the structure, the control and the seismic energies are considered simultaneously in the minimization procedure, which yields cross terms in the performance index. The effectiveness of the proposed control is investigated by applying the algorithm to a three-dimensional building incorporating an active tendon control system under bidirectional ground motion. For example a six story 2D typical steel structure is converted to a three-dimensional six story building to consider and compare the behavior of the proposed active control performance index with classical optimal active control (CLOC). This typical steel building plan is inspired by a structure which is developed for the SAC project for the Los Angeles, California region [39]. Tier building formulation is used while converting the 2D building to a three dimensional structure. The three-dimensional building model and analysis have been implemented by some researchers [40–43]. This paper utilizes the model similar to the one in Weaver and Nelson [40,41]. The idealized three-dimensional tier building is excited bidirectionally by fault normal and fault parallel components of several near fault and far-ground motions. Rotational and translational behavior of the building in two directions is analyzed for three control cases; (1) uncontrolled, (2) with a tendon controller system under the proposed active control performance index, and (3) with a tendon controller system under the classical linear optimal control law. Moreover, energy-based comparisons are made by defining some performance indices.

2. Mathematical model of the building

A tier building is one in which each story is treated as a rigid body with 3 degrees of freedom (DOF) per floor. In this study a 3 dimensional n story tier building is used to evaluate and compare the efficiency of the new active control performance index with classical linear optimal control (CLOC). Tier building formulation is defined by Weaver and Nelson [40,41] and recently implemented by Gattuli et al. [43].

2.1. 3D tier building formulation

To integrate our performance function into a multi-DOF multi-story structural model, we propose the use of the well-developed and relatively simple matrix formulation of the tier buildings and incorporate it into the active controller. This would enable inclusion of the lateral–torsional response of a prototypical frame