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Structural control and health monitoring of building structures with unknown ground excitations: Experimental investigation

Jia He [a,b,*], You-Lin Xu [a], Sheng Zhan [a], Qin Huang [c]

[a] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China
[b] College of Civil Engineering, Hunan University, Changsha, Hunan, China
[c] Shenzhen Graduate School, Harbin Institute of Technology, Shenzhen, China

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ABSTRACT

When health monitoring system and vibration control system both are required for a building structure, it will be beneficial and cost-effective to integrate these two systems together for creating a smart building structure. Recently, on the basis of extended Kalman filter (EKF), a time-domain integrated approach was proposed for the identification of structural parameters of the controlled buildings with unknown ground excitations. The identified physical parameters and structural state vectors were then utilized to determine the control force for vibration suppression. In this paper, the possibility of establishing such a smart building structure with the function of simultaneous damage detection and vibration suppression was explored experimentally. A five-story shear building structure equipped with three magneto-rheological (MR) dampers was built. Four additional columns were added to the building model, and several damage scenarios were then simulated by symmetrically cutting off these columns in certain stories. Two sets of earthquakes, i.e. Kobe earthquake and Northridge earthquake, were considered as seismic input and assumed to be unknown during the tests. The structural parameters and the unknown ground excitations were identified during the tests by using the proposed identification method with the measured control forces. Based on the identified structural parameters and system states, a switching control law was employed to adjust the current applied to the MR dampers for the purpose of vibration attenuation. The experimental results show that the presented approach is capable of satisfactorily identifying structural damages and unknown excitations on one hand and significantly mitigating the structural vibration on the other hand.

1. Introduction

Research on vibration control and health monitoring of civil structures has been actively conducted in the past decades, and many state-of-the-art reviews on these two areas are available [1–4]. A number of experiments have also been carried out for investigating the efficiency of control systems or validating the accuracy of damage detection algorithms. In

* Corresponding author at: College of Civil Engineering, Hunan University, Changsha, Hunan, China
E-mail address: hj19830507@126.com (J. He).

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consideration that the MR dampers are employed for vibration control and the EKF-based approach is used for damage detection in this experimental study, some experiments focusing on the investigation of the above two aspects are briefly introduced herein. For example, on the usage of clipped-optimal control strategy, a series of experiments was conducted by Dyke et al. [5] to investigate the efficiency of MR dampers for seismic response reduction. With two MR dampers installed on the first and second floor of a six-story building structure, the experimental studies were conducted to demonstrate the capabilities of multiple MR devices for seismic control of civil structures [6]. By using a logic control algorithm to adjust the properties of multiple MR dampers, an experimental investigation was carried out by Chen et al. [7] for seismic response control of a complex building structure. For the damage detection on the basis of EKF, Zhou et al. [8] presented experimental studies to validate the reliability of the adaptive EKF approach [9] for online identification of structural damage in a small-scale three-story building structure. Moreover, the capability of various adaptive approaches, including adaptive least-square estimation (ALSE), adaptive EKF, quadratic sum-squares error (QSSE), and the sequential non-linear least-square estimation (SNLSE), in tracking structural damage were compared and demonstrated using experimental data [10]. Experimental studies were also performed by Yin et al. [11] for the verification of the capability of the adaptive EKF approach for identifying and tracking damages in nonlinear building structures. By using the mutual information as a measure for nonlinear signal cross correlation, a vibration-based health monitoring technique was recently developed by Trendafilova et al. [12] and experimentally validated via a composite beam.

However, in most previous investigations, vibration control system and health monitoring system are treated separately according to their individual primary objective pursued. Since sensors, data acquisition, transmission and processing devices are required in both vibration control system and health monitoring system, integrating both systems together will be cost-effective by sharing the same hardware devices and beneficial for creating a smart building structure where the function of damage detection and vibration control can be simultaneously fulfilled. In recent years, increasing attentions have been paid on the development of such smart civil structures. For example, with the aid of semi-active friction dampers, an integrated system was developed for the purpose of vibration control and health monitoring on the basis of the variations of natural frequencies and mode shapes [13,14]. Chen et al. [15] also proposed an integrated method in the time-domain for damage detection and seismic response control of building structures equipped with semi-active friction dampers. More recently, based on the adaptive structural control law, Lin et al. [16] presented a hybrid health monitoring system by combining the global damage detection method with local damage identification method using infrared imaging technique. An integrated semi-active control and health monitoring method was developed by Karami and Amini [17] to improve the control performance on one hand, and to reduce the damage of frame structure caused by strong seismic excitations on the other hand. Lei et al. [18] proposed an integrated algorithm for decentralized vibration control of tall shear building structures and for identification of unknown earthquake-induced ground motion. On the basis of EKF and error tracking techniques, an on-line integration technique was also presented by Lei et al. [19] for health monitoring and active control of the undamaged/damaged structures. Amini et al. [20] proposed an integrated damage detection and semi-active control algorithm to locate and characterize the damage in base-isolated structures and to suppress the excessive vibration of buildings caused by seismic excitation. Based on recursive LSE, Xu et al. [21] proposed a real-time integrated procedure for accurately identifying time-varying structural parameters and unknown excitations, as well as optimally mitigate excessive vibration of building structure.

Although much progress has been made on the integration of vibration control system and health monitoring system, the effectiveness of most aforementioned methodologies are examined through numerical examples. The experimental investigation of integrated structural vibration control and health monitoring systems is limited. By using smart tuned mass dampers, a time-frequency algorithm for system identification and response control of MDOF systems was developed and experimentally investigated by Nagarajaiah [22]. Yang et al. [23] presented a hybrid real-time health monitoring and control system for the building structures under seismic excitations and experimentally validated via a three-story aluminum frame structure. Based on frequency response functions, a new method for system identification and damage detection of the controlled buildings equipped with semi-active friction dampers was proposed and experimentally validated via a complex building structure with a twelve-story main building and a three-story podium structure [24,25]. The authors [26] recently proposed an integrated approach for simultaneously identifying structural damage and suppressing excessive vibration of building structure, and verified the reliability and accuracy of the proposed approach through a numerical example. A significant difference between the proposed approach and other existing EKF-UI (Extended Kalman Filter with Unknown Input) based approaches is that the damage detection and vibration control are integrated and both are considered collectively in the proposed approach while other EKF-UI approaches consider damage detection (system identification) only. In the proposed approach, the control forces can be used not only for attenuating the structural vibration but also for aiding the identification of structural parameters and excitations. Moreover, the projection matrix is presented and used to transform the multiple regression equation into a simple regression equation. The closest solution of the unknown excitations is obtained via the least-square estimation.

In this study, the possibility of establishing such a smart building structure was explored experimentally. First, the time-domain integrated vibration control and health monitoring approach was briefly introduced. Then, a five-story shear-type building structure equipped with three MR dampers was designed and introduced. Four additional columns were added to the building model and several damage scenarios were then simulated by symmetrically cutting off these columns in certain stories. The static tests and hammer tests were carried out to determine the dynamic properties of the building model when the MR dampers were removed. Finally, the shaking table tests of the five-story building model equipped with MR dampers