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Active vibration control for seismic excited building structures under actuator saturation, measurement stochastic noise and quantisation

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ABSTRACT

This paper investigates the active vibration control for seismic excited building structures in presenting of actuator saturation, stochastic measurement noise and quantisation. The active vibration controllers are placed in some storeys, meanwhile, some active tuned mass dampers (ATMDs) are also installed at the top floor and oscillating under their control forces. All of the control forces are generated by actuators which are only capable of providing limited outputs. Since the system states are difficult or barely impossible to be accurately measured, an observer based control law is proposed to guarantee system stability, meanwhile, an H_2/H_∞ index is employed for further improving the control performance. By the proposed control strategy, the mean square exponentially stability of close-looped system can be guaranteed almost surely while the desired H_2/H_∞ performance can be achieved simultaneously. In addition, the convergence rate of system state can be pre-scheduled. By regulating the different locations of sensors and controllers, the vibration response can be mitigated in different level. Numerical examples are provided to demonstrate the effectiveness of the proposed method.

1. Introduction

Building structures are usually vulnerable to seismic hazard, it is essential to protect these structures and human occupants from the seismic threat by reducing excessive structural vibration response. For mitigating this undesirable behavior, the effective approach is to alter the dynamic characteristic of the building by introducing energy absorption to avoid building response far exceed its elastic strength capacity [1].

Usually, the structural vibration can be mitigated by two kinds of techniques, i.e., the passive vibration control (PVC) and the active vibration control (AVC). One of typical PVC devices is known as the tuned mass damper (TMD), it is a device consisting of a mass attached to a building structure such that it oscillates at the same frequency of the structure. By designing appropriate TMD system, the vibration response of building structures can be alleviated [2,3]. However, concerning to high rise building structures or high magnitude earthquakes, the PVC schemes show weakness even ineffective to guarantee the structural stability and solidity [4,5].

Compared with the PVC, the AVC schemes attract more attestations in the past decades due to their superiorities. Typical AVC devices are known as the active mass damper (AMD) and active tuned mass damper (ATMD). An AMD or ATMD is created by adding an active control mechanism into the classic TMD. The positive factor of AVC is that an exogenous energy source is introduced in a building structure by the controller thus the vibration response may be controlled and alleviated. However, the negative effect is that the stability of building structure may be endangered since extra energy is entered. Therefore, so far as an AVC is concerned, the stability becomes a considerable issue. For example, a traditional proportional-derivative (PD) and proportional-integral-derivative (PID) control are proposed in [6]. Considering measurement signal time-varying transmission, an H_∞ AVC scheme is advocated in [7]. A genetic algorithm based optimal H_∞ AVC law is proposed in [8]. A distributed mass damper based AVC law is proposed [9]. Considering the control and actuator faults, an robust finite frequency H_∞ AVC law is designed in [10].

Usually, the electric or magnetic fields are mainly employed to control the PVC devices. For reducing cost and energy consumption of the external energy source, some semi-active vibration control (SAVC) strategies are gradually proposed. For example, by a magneto rheological elastomer based isolator, a fuzzy SAVC strategy is proposed to enhance the performance of the isolator in suppressing structural vibrations in [11]. A similar magneto rheological elastomer base isolator is employed and an optimal linear quadratic regulator SAVC law is proposed in [12]. Based on a magneto rheological damper, a multi-objective optimal fuzzy SAVC law is investigated for high rise building

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in [13]. The commonly used semi-active control device is known as the semi-active controllable electro rheological or magneto rheological damper, which has special liquid or elastomer whose property can be modified by applying electro or magneto field [1]. The advantage of SAVC is that it enables high authority control and flexibility due to less energy requirement and moving mechanical part. However, because the system status can only be indirectly achieved by adjusting the stiffness or damping, more significantly, the electro rheological and magneto rheological isolators usually appear nonlinear and hysteretic by nature, the adequate semi-active controller is still difficult to be designed and real-timely controlled.

The aforementioned works provide some fundamental AVC schemes to mitigate dynamic behaviors of seismic exited building structures. However, the above AVC will easily loss effectiveness because some important practical issues are not be fully considered. For completing the theoretical research and easy-implementation, the following real issues will be addressed in detail.

Form the control viewpoint, the structural responses are firstly measured by different kinds of sensors, then the control forces are calculated according to some pre-scheduled control laws to drive the actuators for suppressing the unwanted vibrations. However, due to some practical reasons, for example, sensor precision, online data acquisition method of sensors, data filtering and processing procedures, etc; the sensor outputs become noise-perturbed values instead of accurate measurements. Many literatures show that the measurement noise can severely degrade the control performance and sometimes even make the system unstable [7,8,14].

After the measurement signals are acquired, they will be transmitted to the controller and employed to calculate the control signals. In this sense, the controller is commonly capable of digital calculation and implemented through hardware. Therefore, the analog signals measured by sensors will be encoded to digital ones then transmitted to the controller for decoding and further calculating. The above en- and decoding processes inevitably introduce data errors in the measurement signals. Due to the strong nonlinear characteristics brought by quantization, the system performance may be lead to a very large degradation or even instability [15,16].

When the control commands are calculated, they will be transmitted to the actuators for performing real-time control of building structures. Unfortunately, the physical actuators can only accept limited input signals and produce restricted outputs in practice. Therefore, if the required control forces exceed its limit, the actuator can only perform its maximum output. Such a phenomena is known as the actuator saturation, and if the actuator saturation is not properly taken into consideration in the controller design, the system performance may be degraded and even system stability can be deteriorated as well [17,18].

With the motivations mentioned above, this paper further investigates an effective AVC scheme for mitigating vibration response of seismic excited building structures while tolerating system uncertainties including measurement noise, quantisation and actuator saturation. The contributions of this work are listed as follows. (i) By integrating the aforementioned uncertainties, an observer-based feedback AVC law is proposed. Since the observe state is not influenced by seismic excitation and measurement noise, the proposed control law contributes to improve system robustness. (ii) By the proposed method, not only system mean square stability can be guaranteed almost surely but also an hybrid H_2/H_∞ performance can be simultaneously achieved. In addition, the convergence rate of close-looped system can be pre-scheduled. (iii) The structural responses can be reduced in different level by regulating sensor and controller locations.

The remainder of the paper is organized as follows. Problem is formulated in Section 2. Main result is presented in Section 3. Section 4 gives some simulation examples. Conclusion remarks are outlined in Section 5.

The following notations are given which will be used throughout the literature. Let $\mathscr{R}$ and $\mathscr{N}$ denote the real numbers and the integer numbers, respectively. The notations $\mathscr{R}^+,\mathscr{R}^n$ and $\mathscr{R}^{n_1\times n_2}$ are the set of positive real numbers, n-dimensional Euclidean space and the set of $n_1\times n_2$ real matrices, respectively. For a given matrix A,A^T and A_i denote its transpose and i^{th} row. The function $sym(A) = A + A^T$. For a given vector $v\in\mathscr{R}^m$,v_i is the i^{th} element. The script '$*$' denotes the corresponding transposed matrix item. The notation I_n denotes a n dimensional identity matrix. For simplicity, the number 0 denotes an appropriate dimensional zero matrix.

2. Problem formulation

In this section, the structural dynamic equation of building structure is given at first and the seismic excitation is described as an energy-bounded disturbance. For enclosing a close-looped control, a feedback signal is chosen while the stochastic measurement noise and measurement quantisation are simultaneously considered. At last, an observer based control strategy is proposed meanwhile an H_∞ performance is employed to improve system control performance.

2.1. Structural dynamic equation

In [19–21], it has been demonstrated that the active vibration controllers are capable of providing better effectiveness and improved control performances. In this regard, for a $n\in\mathscr{N}$ degree-of-freedoms building structure under seismic excitation, an AVC strategy is appropriate to mitigate the undesirable vibration. The overall building structure is shown as Fig. 1.

In Fig. 1, $\ddot{x}_g(t)$ is the ground acceleration; m_i,k_i,c_i,$x_i(t)$ and $u_{Si}(t)$ are the mass, stiffness, damping, relative drift and control input of each storey, $i = 1,2,\dots n$;m_{Tj},k_{Tj},c_{Tj},$x_{Tj}(t)$ and $u_{Tj}(t)$ are the mass, stiffness, damping, relative drift and control of each ATMD with respect to top storey, $j = 1,2,\dots,s$.

Since the reaction force of current storey influences the dynamics of all of its upper storeys, the dynamics of $n-1$ storeys except the top one can be described as:

$$m_i\sum_{k=1}^{i}\ddot{x}_k(t) + c_i\dot{x}_i(t)-c_{i+1}\dot{x}_{i+1}(t) + k_ix_i(t)-k_{i+1}x_{i+1}(t) = u_{Si}(t)-m_i\ddot{x}_g(t),\tag{1}$$

where $i = 1,2,\dots,n-1$.

From Eq. (1), one can find that high rise storeys suffer more external force than the lower storeys. As a result, the relative displacement of high rise storeys vary in larger regions. In this sense, it is appropriate to set up multiple active tuned mass dampers (MATMDs) at top storey of buildings for mitigating the vibration. Since the control forces of s MATMDs are directly applied on the top storey, the dynamic of top storey is given as:

$$m_n\sum_{k=1}^{n}\ddot{x}_k(t) + c_n\dot{x}_n(t) + k_nx_n(t) = u_{Sn}(t)-m_n\ddot{x}_g(t)-\sum_{j=1}^{s}m_{Tj}(\ddot{x}_{Tj}(t) + \ddot{x}_g(t)).\tag{2}$$

For each ATMD, its dynamic can be represented as:

$$m_{Tj}\ddot{x}_{Tj}(t) + c_{Tj}\dot{x}_{Tj}(t) + k_{Tj}x_{Tj}(t) = u_{Tj}(t) + c_{Tj}\sum_{k=1}^{n}\dot{x}_k(t) + k_{Tj}\sum_{k=1}^{n}x_k(t)-m_{Tj}\ddot{x}_g(t),\tag{3}$$

where $j = 1,2,\dots,s$.

Define $x(t) = (x_1(t),x_2(t),\dots,x_n(t))^T$,$x_T(t) = (x_{T1}(t),x_{T2}(t),\dots,x_{Ts}(t))^T$,$u_S(t) = (u_{S1}^T(t),u_{S2}^T(t),\dots,u_{S(n-1)}^T(t),0)^T$ and $u_T(t) = (u_{T1}^T(t),u_{T2}^T(t),\dots,u_{Ts}^T(t))^T$, by Eqs. (1)–(3) gives: