ARTICLE IN PRESS

ISA Transactions xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research article

Sampled-data-based vibration control for structural systems with finite-time state constraint and sensor outage

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ARTICLE INFO

Keywords:
Finite-time stability
Sensor outage
Structural systems
Vibration
Sampled-data

ABSTRACT

The problem of sampled-data-based vibration control for structural systems with finite-time state constraint and sensor outage is investigated in this paper. The objective of designing controllers is to guarantee the stability and anti-disturbance performance of the closed-loop systems while some sensor outages happen. Firstly, based on matrix transformation, the state-space model of structural systems with sensor outages and uncertainties appearing in the mass, damping and stiffness matrices is established. Secondly, by considering most of those earthquakes or strong winds happen in a very short time, and it is often the peak values make the structures damaged, the finite-time stability analysis method is introduced to constrain the state responses in a given time interval, and the H-infinity stability is adopted in the controller design to make sure that the closed-loop system has a prescribed level of disturbance attenuation performance during the whole control process. Furthermore, all stabilization conditions are expressed in the forms of linear matrix inequalities (LMIs), whose feasibility can be easily checked by using the LMI Toolbox. Finally, numerical examples are given to demonstrate the effectiveness of the proposed theorems.

1. Introduction

In recent years, because strong earthquakes and hurricanes happen frequently, vibration control for structural systems has received considerable attention, and many control methods were achieved for attenuating those vibrations resulted from seismic or wind excitations. Normally, those methods can be classified into three types: passive control, semi-active control and active control. Due to the virtues of low energy consumption and low cost, the passive and semi-active controls were ever researched heatedly [1,2]. However, with the structural systems built higher and higher, the stability and solidity of structural systems are challenged and cannot be guaranteed only by those passive and semi-active control methods. Thus, the active vibration control for structural systems has been heatedly discussed recently, and many control strategies, such as, classical H_∞ theories [3–5], energy-to-peak control [6–8], finite frequency control [9], sliding mode control [10,11], adaptive control [12], fuzzy control [13,14], model predictive control [15], optimal control [16], etc., have been utilized for protecting structures subjected to seismic or wind excitations. Moreover, many active control devices, such as, active mass damper (AMD) [17,18], active brace system (ABS) [19,20], etc., were also designed for applying those control algorithms.

However, most of the existing results are obtained on the basis of the assumption that the sensors can provide uninterrupted signal measurement. In practice, contingent failures are possible for all sensors in a system, which may result in substantial damage, and can even be hazardous to human and environmental security. Thus, sensor failure is an inevitable problem which needs to be considered in the active control devices and algorithms design. At least, the sensor failures include two major types: sensor outage and sensor performance degradation. Sensor outage means the sensor is completely broke down; and sensor performance degradation means the sensor can still work with lower performances, such as lower degree of precision, higher error rate, etc. During the last decades, some efforts have been made by scholars to obtain the results about sensor failures, and some achievements were reached. For example, based on linear matrix inequality (LMI) technique, the problem of sensor fault-tolerant vibration attenuation controller design for uncertain buildings structural systems was investigated in Ref. [21]. In terms of H_∞ theory, Ref. [22] discussed the problem of simultaneous design of reliable filter and fault detector for a class of linear continuous-time systems with bounded disturbances and nonzero constant reference inputs, and numerical example was given to illustrate the effectiveness of the proposed methods. The

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https://doi.org/10.1016/j.isatra.2018.04.021
Received 21 December 2015; Received in revised form 7 February 2018; Accepted 30 April 2018

existing results show robust analysis can solve some sensor performance degradations greatly, however, the results about sensor outage are still few, and it is not fully investigated, obviously.

On the other hand, with the advances in computer measurement and control technique, the analog signals are often replaced by digital signals to provide better performances [23]. Thus, sampled-data systems have attracted great attention, and many achievements have been reached during the last several decades. The corresponding results can be found in Refs. [24–27] and those references therein. Moreover, with recent focus on wireless monitoring and control of structural systems [28–31], research on sampled-data-based control for structural system is becoming significant. Classical solutions to this type of problem can be found in the literatures [8,32–34], where sampled-data control algorithms taking into account external excitations were given for structural systems, and numerical examples were given to show the validation of those methods. However, most of those existing results were obtained by using Lyapunov stability theory, which cases about asymptotic convergence of structural systems. It is well known that the structural systems are often damaged by the peak responses of displacements or accelerations, thus, obtaining some results with a constraint on the peak responses of displacements or accelerations will be much more practical, obviously. Very recently, the problem of finite-time stability of systems has received considerable attention. For example, by employing the Lyapunov-like function method, Ref. [35] addressed the problems of input-output finite-time stability analysis for linear time-delay systems and applied it to active vibration control for structural systems with input delay. In terms of a special Lyapunov functional, the finite-time vibration control of earthquake excited linear structures with input time-delay and saturation was concerned in Ref. [36], and numerical examples were given to illustrate the effectiveness of the developed theory. More achievements about this issue can also be found in Refs. [37,38] and the references therein.

This paper concerns the problem of sampled-data-based vibration controller design for structural systems with finite-time state constraint and sensor outage. Based on matrix transformation, the state-space model of structural systems, which contain sampled-data signals, sensor outage and uncertainties appearing in the mass, damping and stiffness matrices, is established. Then, in terms of the obtained model and finite-time stability technique, the LMIs-based conditions are established for the structural systems to be stabilizable with finite-time state constraint and sensor outage. By solving these LMIs, the desired controller can be obtained such that the state responses of the closed-loop system constrained by $\mathbf{x}^T(t)\overline{\mathbf{R}}\mathbf{x}(t) < c_3^2(\overline{\mathbf{R}} > 0)$ during the time interval $[0,T]$, and the influence of the external disturbances is constrained by $\|\mathbf{z}\|_2 < \gamma\|\boldsymbol{\omega}\|_2(\gamma>0)$ during the whole control process. Furthermore, when sensor outages happen, the control system can reconfigure the controllers according to the signals come from the sensor outage detector. In the end, numerical examples are given to show the effectiveness of the proposed theorems.

Notation. Throughout this paper, for real matrices $\mathbf{X}$ and $\mathbf{Y}$, the notation $\mathbf{X} \geq \mathbf{Y}$ (respectively $\mathbf{X} > \mathbf{Y}$) means that the matrix $\mathbf{X} - \mathbf{Y}$ is semi-positive definite (respectively, positive definite). $\mathbf{I}$ is the identity matrix with appropriate dimension, and a superscript "T" represents transpose. We define $\mathbf{M}^H = \mathbf{M}^T + \mathbf{M}$. For a symmetric matrix, $*$ denotes the symmetric terms. The symbol R^n stands for the n-dimensional Euclidean space, and $R^{n\times m}$ is the set of $n\times m$ real matrices.

2. Problem formulation and dynamic models

Consider an n degree-of-freedom structural system, which is depicted in Fig. 1. The structural model equation can be written as [5–9,21,35,36,38,39].

$$\mathbf{M}\ddot{\mathbf{x}}_m(t) + \mathbf{C}\dot{\mathbf{x}}_m(t) + \mathbf{K}\mathbf{x}_m(t) = \mathbf{H}_0\mathbf{u}(t) + \mathbf{H}_\omega\ddot{\mathbf{x}}_g(t), \tag{1}$$

where $\mathbf{x}_m(t) = [x_{m1}(t), x_{m2}(t), \cdots, x_{mn}(t)]^T$, $x_{mn}(t)$ is the relative drift of the

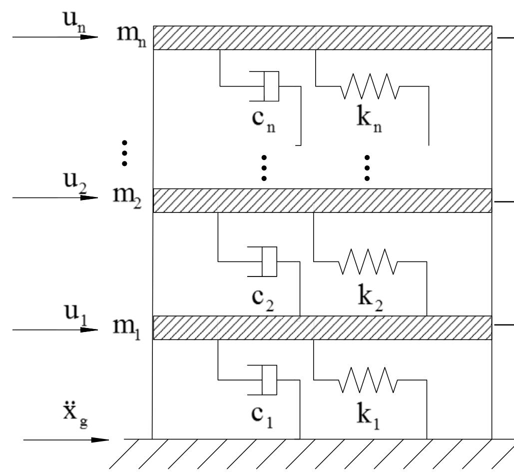

Fig. 1. n degree-of-freedom structural system.

nth storey to ground; $\mathbf{u}(t)$ is the control force input; $\ddot{\mathbf{x}}_g(t)$ is the ground acceleration, $\mathbf{H}_0 \in R^{n\times m}$ gives the locations of these controllers, $\mathbf{H}_\omega \in R^{n\times 1}$ is an vector denoting the influence of disturbance excitation, and $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K} \in R^{n\times n}$ are the mass, damping and stiffness matrices of the system, respectively. From Fig. 1, it is obtained that

$$\mathbf{M} = \mathrm{diag}\{m_1, \ m_2, \ \cdots, \ m_n\}, \ \mathbf{H}_\omega = -[m_1, \ m_2, \ \cdots, \ m_n]^T,$$

$$\mathbf{C} = \begin{bmatrix} c_1 + c_2 & -c_2 & \cdots & 0 \\ -c_2 & c_2 + c_3 & \cdots & \vdots \\ \vdots & \vdots & \cdots & -c_n \\ 0 & 0 & \cdots & c_n \end{bmatrix}, \quad \mathbf{K} = \begin{bmatrix} k_1 + k_2 & -k_2 & \cdots & 0 \\ -k_2 & k_2 + k_3 & \cdots & \vdots \\ \vdots & \vdots & \cdots & -k_n \\ 0 & 0 & \cdots & k_n \end{bmatrix},$$

Defining the state variables as $\mathbf{x}(t) = [\mathbf{x}_m(t)^T, \dot{\mathbf{x}}_m(t)^T]^T$, equation (1) can be written in the following state-space form:

$$\begin{aligned} \dot{\mathbf{x}}(t) &= \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{B}_\omega\omega(t), \\ \mathbf{z}(t) &= \mathbf{C}_z\mathbf{x}(t), \end{aligned} \tag{2}$$

where $\mathbf{C}_z$ is real constant matrix with appropriate dimensions, $\boldsymbol{\omega}(t) = \ddot{\mathbf{x}}_g(t)$, and

$$\mathbf{A} = \begin{bmatrix} \mathbf{I} & 0 \\ 0 & \widetilde{\mathbf{M}} \end{bmatrix}\mathbf{A}_0, \ \mathbf{B} = \begin{bmatrix} \mathbf{I} & 0 \\ 0 & \widetilde{\mathbf{M}} \end{bmatrix}\begin{bmatrix} 0 \\ \mathbf{H}_0 \end{bmatrix}, \ \mathbf{A}_0 = \begin{bmatrix} 0 & \mathbf{I} \\ -\mathbf{K} & -\mathbf{C} \end{bmatrix},$$

$$\widetilde{\mathbf{M}} = \mathrm{diag}\{1/m_1, 1/m_2, \cdots, 1/m_n\}, \ \mathbf{B}_\omega = \begin{bmatrix} \underbrace{0, \cdots, 0}_{n}, & \underbrace{-1, \cdots, -1}_{n} \end{bmatrix}^T,$$

Remark 1. Some historical earthquake records are listed in Table 1 [40,41]. It is obvious that the ground accelerations and durations are all limited in some special bounds, that is, earthquake excitations can be described as an energy-bounded disturbance, thus, the $\boldsymbol{\omega}(t)$ shown in the paper satisfies $\boldsymbol{\omega}(t) \in L_2[0, +\infty]$, and for a given time interval $[0,T]$,

Table 1
Fundamental information of some earthquakes.

Year	Observation site	Peak of ground acceleration (m/s^2)	Duration (s)
1940	EI Centro, 270 Deg	3.498	53.72
1940	EI Centro, 180 Deg	2.099	53.46
1952	Taft Lincoln School	1.526	54.38
1966	Parkfield Cholame, Shandon	2.323	26.18
1971	San Fernando, 69 Deg	3.091	61.84
1971	San Fernando, 159 Deg	2.652	61.88
1979	James RD., 220 Deg	3.600	37.68
1989	Loma Prieta, 270 Deg	2.704	39.98
1994	Northridge, 90 Deg	5.926	59.98