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Robust-optimal active vibration controllers design for the uncertain flexible mechanical systems possessing integrity via genetic algorithm

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Abstract

In this paper, a robust-optimal control approach is proposed to treat the active vibration control (or active vibration suppression) problem of flexible mechanical systems under mode truncation, linear time-varying parameter uncertainties in both the controlled and residual parts, feedback gain perturbations, estimator gain perturbations and partial actuator failures. A sufficient condition is proposed to ensure that the flexible mechanical systems with time-varying structured parameter uncertainties are asymptotically stable against partial actuator failures. Systems which have such a property of keeping stable under partial actuator failures are said to possess integrity, and this is an inherent property of MIMO systems. Based on the robust stability constraint and the minimization of a defined H_2 performance, a hybrid Taguchi-genetic algorithm (HTGA) is applied to solve the optimal state feedback controller and observer design problem of uncertain flexible mechanical systems. A design example of a flexible rotor system is given to demonstrate the applicability of the proposed approach. It is shown that the proposed approach can obtain satisfactory results.

Keywords: Flexible mechanical systems; Active vibration control; Parameter uncertainties; Stability robustness; Genetic algorithm; Actuator failures

1. Introduction

The flexible mechanical systems to be controlled are often described by distributed-parameter models and so are essentially infinite dimensional. Control of the entire infinite modes is not possible. In a common strategy, most high-frequency modes of the system are truncated as residual part since they are difficult to excite, and only some critical low-frequency modes are used for designing the vibration controllers (see, for example, [1–14]; and references therein). Those researchers divided the finite-dimensional model into two parts: controlled part and residual part. The controlled part, which is used for designing the vibration controllers, is composed of those critical modes which have large contribution to the elastodynamic response, and the residual part is composed of the remainder modes of the finite-dimensional model. The residual part may lead to control and observation spillover that can destabilize one or more of the poorly damped modes. Consequently, those researchers proposed some methods in the above-mentioned literature to investigate the problem of spillover suppression to avoid instability.

In flexible mechanical systems, the system parameters are often subject to parameter uncertainties due to inaccuracies in the calculations of the frequencies and damping due to approximations in the structural model, material properties, mass, damping, and so forth. These parameter uncertainties can degrade the system performance, and it is sometimes possible to destabilize the system [9,11]. Recently, many articles ([6–11]; and references therein) have addressed the active vibration control problem of flexible mechanical systems under both residual modes and linear structured parameter uncertainties. Note that the results proposed by Lin et al. [11], Chou et al. [8], Chen et al. [7] and Chen [6] are valid for linear time-varying structured parameter uncertainties, whereas the results given by Khot and Heise [9] and Khot and Oz [10] are

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applicable only to linear time-invariant structured parameter uncertainties. It is well known that any analysis used for the time-varying case can be specified to the time-invariant case (but not vice versa). That is, the results of Lin et al. [11], Chou et al. [8], Chen et al. [7] and Chen [6] are valid for both the time-invariant case and the time-varying case. Besides, because it is impossible in practice to precisely implement the active control law, it is reasonable to consider the perturbations exist in the control gains, due to the limited wordlength of digital controller or the manufacturing inprecision of controller elements. So, the perturbations in the presence of the feedback gain and estimator gain are also considered in this paper. In addition, a multivariable feedback control system may become unstable when the feedback signals are switched off by a failure in the actuators or the sensors. The system possessing integrity means that the system still remains asymptotically stable in the presence of such failures [15]. Till now, to the authors' best knowledge, the problem of stability robustness of the flexible mechanical systems under mode truncation, linear time-varying parameter uncertainties in both controlled and residual parts, feedback gain perturbations, estimator gain perturbations and partial actuator failures has not been discussed in the literature yet. That is, the problem on stability robustness of the flexible mechanical systems under mode truncation, linear time-varying structured parameter uncertainties in both the controlled and residual parts, feedback gain perturbations, estimator gain perturbations and partial actuator failures is worth investigating.

On the other hand, only robust stability is often not enough in control system design. The quadratic optimal performance is also considered in many practical control engineering applications. Hence, the robust-optimal active vibration control designs are needed for robust stability and performance design for flexible mechanical systems under mode truncation, linear time-varying structured parameter uncertainties, feedback gain perturbations, estimator gain perturbations and partial actuator failures. The robust-optimal active vibration control design is to find a stabilizing controller and observer that minimize an H_2 performance index (i.e., the integral of the squared error (ISE) or the integral of the time-weighted squared error (ITSE)) subjects to the stability robustness inequality constraint. Therefore, the purpose of this paper is to use the hybrid Taguchi-genetic algorithm (HTGA) for finding the active vibration controllers of the flexible mechanical systems with linear time-varying structured parameter uncertainties in both controlled and residual parts, feedback gain perturbations, estimator gain perturbations and partial actuator failures such that the control objective of minimizing an H_2 performance index subject to the stability robustness constraint is achieved. The reason why the HTGA is applied in this paper is that Chou and his associates have shown that the HTGA can obtain both better and more robust results than those existing improved genetic algorithms reported in the literature [16,17]. In this paper, we determine the optimal controller and observer gains by applying HTGA to directly minimize a defined performance index.

This paper is organized as follows. The model of the flexible mechanical system is described in Section 2. In Section 3, a new robust stability condition is presented for the flexible mechanical systems with linear time-varying structured parameter uncertainties in both controlled and residual parts, feedback gain perturbations, estimator gain perturbations and partial actuator failures. The HTGA for the robust-optimal active vibration controller design is described in Section 4. A design example of flexible rotor control system is also given in this section for demonstrating the applicability of the proposed approach. Finally, Section 5 offers some conclusions.

2. System description

Consider the class of flexible mechanical systems described by a generalized wave equation [2]

$$m(x)u_{tt}(x,t) + 2\xi A^{1/2}u_t(x,t) + Au(x,t) = f(x,\ t), \tag{1}$$

which relates the displacement $u(x,\ t)$ of the equilibrium position of a body Ω in the n-dimensional space to the applied force distribution $f(x,\ t)$. The operator A is a time-invariant, symmetric, nonnegative differential operator with a square root $A^{1/2}$, and domain $D(A)$ is dense in the Hilbert space $H = L^2(\Omega)$ with the usual inner product and the associated norm. The mass density $m(x)$ is a positive function of the location x on the body; the change of variables $u(x,\ t) \to u(x,\ t)/m(x)^{1/2}$ eliminates $m(x)$ without changing the properties of Eq. (1) and, henceforth, we will assume this has been done and take $m(x) = 1$ in Eq. (1). The nonnegative number ξ is the damping coefficient of the flexible mechanical system and depends on the construction materials and methods used. For structures such as spacecraft, ξ may be very small [2].

We will assume that the spectrum of the operator A contains only isolated eigenvalues λ_k with corresponding orthogonal eigenfunctions $\phi_k(x)$ in $D(A)$ such that

$$0<\lambda_1<\lambda_2<\lambda_3<\cdots$$

and

$$A\phi_k(x) = \lambda_k\phi_k(x), \quad A^{1/2}\phi_k(x) = \lambda_k^{1/2}\phi_k(x),$$

which are the eigenfunctions forming a basis for H; this can be guaranteed by the condition that A has compact resolvent [2]. The eigenfunctions $\phi_k(x)$ are the mode shapes of the flexible mechanical system, and the mode frequencies are $\omega_k = \lambda_k^{1/2}$.

By applying the standard technique of the expansion theorem with

$$u(x,\ t) = \sum_{k=1}^{L} u_k(t)\phi_k(x), \tag{2}$$