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Robust dynamic output feedback control for switched polytopic systems under asynchronous switching

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Abstract The robust controller design problem for switched polytopic systems under asynchronous switching is addressed. These systems exist in many aviation applications, such as dynamical systems involving rapid variations. A switched polytopic system is established to describe the highly maneuverable technology vehicle within the full flight envelope and a robust dynamic output feedback control method is designed for the switched polytopic system. Combining the Lyapunov-like function method and the average dwell time method, a sufficient condition is derived for the switched polytopic system with asynchronous switching and data dropout to be globally, uniformly and asymptotically stable in terms of linear matrix inequality. The robust dynamic output feedback controller is then applied to the highly maneuverable technology vehicle to illustrate the effectiveness of the proposed approach. The simulation results show that the angle of attack tracking performance is acceptable over the time history and the control surface responses are all satisfying along the full flight trajectory.

1. Introduction

Switched systems, which consist of a finite number of subsystems described by difference or differential equations and a switching signal orchestrating switching between these subsystems, have attracted considerable attention in the last decades.[1–5] Various physical or man-made systems such as mechanical systems, automotive industry, aircraft and air traffic control and many other fields can be modeled as switched systems.[6–8] So far, there are fruitful results on controllability, stability, stabilization and filtering design for switched systems.[9–11] Although the results obtained in these papers are very promising, they do not consider the phenomena of asynchronous switching between system modes and controller candidates.[12–15]

Generally speaking, the phenomena of asynchronous switching exist in reality, because it inevitably needs some time to identify the system modes, transmit data and apply the matched controller.[16] The necessities for efficient control design are presented in a class of chemical systems under asynchronous switching.[17] Mode-dependent full-order filters of considering asynchronous switching for a class of discrete-time switched systems with average dwell time switching are

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investigated.[15] Also, a study shows that the designed time-delayed controllers based on synchronous switching destabilize the system under asynchronous switching.[18] In all the aforementioned control approaches for switched systems, each subsystem is described by a linear model on operating points. For most of modern aircraft, especially for high-performance fighters and hypersonic vehicles, the parameter variation often varies fast so that the aforementioned modeling approach does not satisfy the demand. Switched polytopic system can meet the fast parameter variation, as parameter varying can be naturally described by the switched polytopic system evolving upon arbitrary fast switching law.[19,20] While these works are very encouraging, the problem of robust dynamic output feedback control for switched polytopic systems under asynchronous switching has not been fully investigated yet, which constitutes the main focus of this paper.

This paper addresses the robust controller design problem for switched polytopic systems under asynchronous switching. The highly maneuverable technology (HiMAT)[19,21] vehicle dynamics within the full flight envelope is described by a switched polytopic system. Each polytopic subsystem represents the HiMAT vehicle dynamics in a part of flight envelope and its vertices are the subsystems of a locally overlapped switched system (LOSS)[20] which describes the dynamics on operating points within this part of flight envelope. For each polytopic subsystem, combining the Lyapunov-like function[15,16] method and the average dwell time method, a robust subcontroller, in which asynchronous switching and data dropout are taken into account, is achieved by interpolating between the output feedback controllers on vertices, and the robust controller with respect to full flight envelope is composed of these robust subcontrollers.[22–24] It is worth noting that system parameters can vary fast[25,26] in each polytopic subsystem by the proposed approach and the average dwell time on polytopic subsystems is no smaller than a fixed positive constant. Finally, the robust dynamic output feedback controller is applied to the HiMAT vehicle to illustrate the effectiveness of the proposed approach.

2. Problem formulation

The HiMAT vehicle, an open-loop unstable aircraft sponsored

by NASA and the U.S. Air Force, is studied to incorporate technological advances in many fields, such as advanced transonic aerodynamics and a close-coupled canard configuration.[19,21] The operating points of HiMAT vehicle within the full flight envelope were presented in Refs.[19,21] as depicted in Fig. 1. The performance of the stability and maneuverability of the vehicle primarily depends on the short period motion, so the longitudinal short period models of the operating points are used. Assume that 20 models cover the dynamic behavior of the HiMAT vehicle within the full flight envelope and each model can describe the dynamics in the vicinity of the operating point. The vehicle dynamics on each operating point is given by the following discrete-time linear model:

$$\begin{cases} \boldsymbol{x}(k+1) = \boldsymbol{A}_i\boldsymbol{x}(k) + \boldsymbol{B}_i\boldsymbol{u}(k) \\ \boldsymbol{y}(k) = \boldsymbol{C}_i\boldsymbol{x}(k) \end{cases} \quad i \in \Omega = \{1, 2, \ldots, 20\} \tag{1}$$

where $\boldsymbol{x} = [\alpha, q]^{\mathrm{T}}$, with α and q denoting the angle of attack and the pitch rate, respectively; $\boldsymbol{u} = [\xi_{\mathrm{e}}, \xi_{\mathrm{v}}, \xi_{\mathrm{c}}]^{\mathrm{T}}$, with $\xi_{\mathrm{e}}, \xi_{\mathrm{v}}$ and ξ_{c} denoting the elevator input, elevon input and

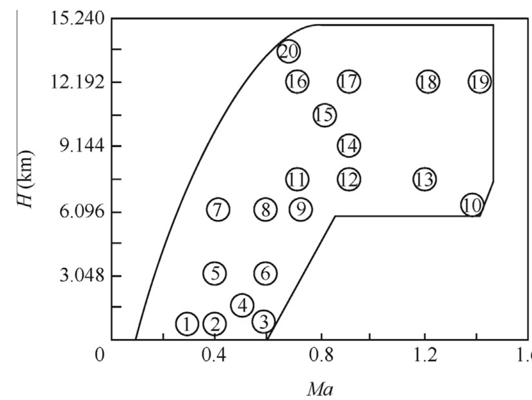

Fig. 1 Flight envelope of HiMAT vehicle.

canard input, respectively; $\boldsymbol{y}$ is the output; the matrices $\boldsymbol{A}_i, \boldsymbol{B}_i$ and $\boldsymbol{C}_i$ are of appropriate dimensions.

Data buses are generally used in modern aircraft to transmit data, so delay and packet dropout induced by network exist inevitably. The delay which is much smaller than the sampling period can be ignored in the modern flight vehicles, while data packet dropout cannot be ignored. Assume that data packet dropout only exists between sensors and controllers. The output of the system can be written as

$$\boldsymbol{z}(k) = \theta(k)\boldsymbol{y}(k) + (1 - \theta(k))\boldsymbol{y}(k-1) \tag{2}$$

where $\boldsymbol{z}$ is the signal received by controller; the stochastic variable $\theta(k)$ is a Bernoulli distributed white sequence which denotes the transmission state of the sensor signals with

$$\begin{cases} \mathrm{Prob}\{\theta(k) = 1\} = E(\theta(k)) = \rho \\ \mathrm{Prob}\{\theta(k) = 0\} = E(1 - \theta(k)) = 1 - \rho \end{cases} \tag{3}$$

where $0 \leqslant \rho \leqslant 1$ is a known constant and $E(\cdot)$ represents the mathematical expectation.

Remark 1. In this paper, we only consider the data packet dropout between sensors and controllers. In more general cases, data packet dropout may exist in both sensor-controller and controller-actuator. Following the similar steps and procedures, two independent Bernoulli distributed white sequences $\theta(k)$ and $\theta_{\boldsymbol{u}}(k)$ can be used to denote the transmission state of sensor signals and controller signals. Thus we have

$$\boldsymbol{u}'(k) = \theta_{\boldsymbol{u}}(k)\boldsymbol{u}(k) + (1 - \theta_{\boldsymbol{u}}(k))\boldsymbol{u}(k-1) \tag{4}$$

$$\begin{cases} \mathrm{Prob}\{\theta_{\boldsymbol{u}}(k) = 1\} = E(\theta_{\boldsymbol{u}}(k)) = \rho_{\boldsymbol{u}} \\ \mathrm{Prob}\{\theta_{\boldsymbol{u}}(k) = 0\} = E(1 - \theta_{\boldsymbol{u}}(k)) = 1 - \rho_{\boldsymbol{u}} \end{cases} \tag{5}$$

where $0 \leqslant \rho_{\boldsymbol{u}} \leqslant 1$ is a known constant.

In this paper, the full flight envelope of the HiMAT vehicle is partitioned into N LOSSs.[15,16] Each LOSS corresponds to a polytopic system whose vertices are subsystems of the LOSS. Further, the full envelope flight dynamics can be described by a switched polytopic system whose subsystems describe the flight dynamics within different parts of flight envelope.

$$\begin{cases} \boldsymbol{x}(k+1) = \boldsymbol{A}_{\sigma(k)}(\lambda_k)\boldsymbol{x}(k) + \boldsymbol{B}_{\sigma(k)}(\lambda_k)\boldsymbol{u}(k) \\ \boldsymbol{y}(k) = \boldsymbol{C}_{\sigma(k)}(\lambda_k)\boldsymbol{x}(k) \\ \boldsymbol{z}(k) = \theta(k)\boldsymbol{y}(k) + (1 - \theta(k))\boldsymbol{y}(k-1) \end{cases} \tag{6}$$