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Robust adaptive fault-tolerant control of a tandem coaxial ducted fan aircraft with actuator saturation

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Abstract This paper is concerned with the robust adaptive fault-tolerant control of a tandem coaxial ducted fan aircraft under system uncertainty, mismatched disturbance, and actuator saturation. For the proposed aircraft, comprehensive controllability analysis is performed to evaluate the controllability of each state as well as the margin to reject mismatched disturbance without any knowledge of the controller. Mismatched disturbance attenuation is ensured through a structured H-infinity controller tuned by a non-smooth optimization algorithm. Embedded with the H-infinity controller, an adaptive control law is proposed in order to mitigate matched system uncertainty and actuator fault. Input saturation is also considered by the modified reference model. Numerical simulation of the novel ducted fan aircraft is provided to illustrate the effectiveness of the proposed method. The simulation results reveal that the proposed adaptive controller achieves better transient response and more robust performance than classic Model Reference Adaptive Control (MRAC) method, even with serious actuator saturation.

1. Introduction

The ducted fan aircraft, as a novel aircraft design, is driving evident research interest in academic and industrial communities. Since 1990s, many countries have started research in this field one after another, and have developed different ducted aerial aircrafts.[1] Compared with traditional flight aircrafts, the ducted fan aircraft has special characteristics that enable it to complete various applications on areas that are unknown, dangerous, and inaccessible to traditional aircrafts. The protected rotor blades of the ducted fan aircrafts are compatible with the environments potentially cluttered with obstacles. Moreover, a ducted fan produces more thrust than an open rotor at the same blade size. These features also ensure a markedly compact body design with strong mobility, low noise, and high efficiency.[2,3]

In Beijing Institute of Technology (BIT), several prototypes of the ducted fan aircraft have been designed for research on modelling, system identification and flight control algorithms.[2,4,5] The design iterations of the ducted fan aircraft in

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BIT is shown in Fig. 1. However, for the first two prototypes, they have proved to reveal poor stability and controllability due to structural coupling.[4] Under this context, as shown in Fig. 2, the latest prototype adopts two ducts with coaxial rotors and control vanes. In order to illustrate the features of the new design, the moment generation mechanism of these prototypes is given in Table 1. For the latest model, pitch and yaw moment are generated by changing the speed of the four rotors. To be specific, roll moment is regulated by the control vanes. Compared to the previous ones, this newly adopted structure is able to provide more control moments with the same size duct, especially in roll direction. On that case, the new aircraft is expected to achieve better decoupling features and controllability.

In order to achieve various types of civil and military applications, the novel ducted fan aircraft must have the strong ability for trajectory tracking independent of the atmospheric conditions. A number of approaches to flight control of novel ducted fan aircraft and other UAVs have been applied to a variety of problems. For example, as a classic control method, PID controller is used by Sheng and Sun,[6] but it is not robust to noise and disturbance, and therefore fails to ensure performance for full envelop flight. Dynamic inversion control and sliding mode control are also presented.[7,8] Although these control algorithms are able to reject external disturbance and achieve good control performance in simulations, they rely on known and accurate system model. Neural Network (NN) techniques also have been widely employed for robots in literatures. He et al.[9] applies an NN controller to suppress the vibration of a flexible robotic manipulator system with input deadzone. Although input deadzone and unknown dynamics can be approximated, the method does not consider large disturbance and is just validated by Single Input Single Output (SISO) system. Adaptive NN[10] and adaptive fuzzy NN[11] are used to identify system uncertainties and disturbance for a constrained robot. However, their methods are of great complexity and difficult to utilized in practical engineering. In consideration of model errors, H-infinity control and adaptive control are widely adopted. Successive two-loop control architecture[5] is employed and control gains are well tuned by Non-smooth optimization method. This control structure ensures robust stabilization, but transient tracking performance drops when large uncertainty are included. Indirect adaptive control schemes 6 and adaptive gain scheduling algorithm[12] are respectively adopted to deal with parametric uncertainty. These adaptive control methods guaranteed small tracking error and the convergence of adjustable parameters. However, the dynamics is over simplified and dynamic couplings is not considered. Standard Model Reference Adaptive Control (MRAC) framework[13] is proposed to cope with system uncertainty and also guarantees that the tracking error decreases asymptotically to zero. Unfortunately, the previous research does not take mismatched disturbance into consideration.

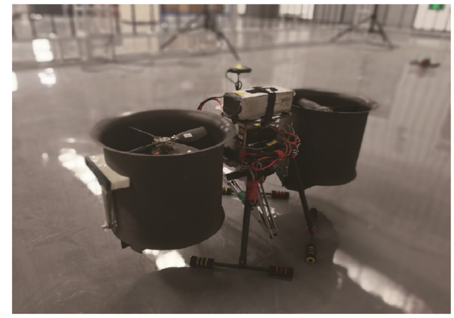

Fig. 2 Novel ducted fan aircraft from BIT (third generation).

Table 1 Moments generation mechanism of ducted fan aircrafts in BIT.

Control moment	1st prototype	2nd prototype	3rd prototype
Roll	Actuation of control vanes	Speed difference of auxiliary ducted fans	Actuation of control vanes
Pitch	Speed difference of main rotors	Speed difference of main rotors	Speed difference of coaxial main rotors
Yaw	Actuation of control vanes	Tilting auxiliary ducted fans	Speed difference of coaxial main rotors

On the other hand, an important problem encountered in practice is actuator saturation because it is frequently one of the main sources of instability, degradation of system performance, and parasitic equilibrium points of a control system.[14] Some solutions have been provided to handle input constraint for flight control system. Based on structured H-infinity optimization, an anti-windup compensator[15] is designed to preserve stability and maintain the performance level under input saturations. Guaranteed transient performance based attitude control with input saturation is also proposed using the backstepping method.[16] Nevertheless, these methods can-

(a) 1st prototype: Tandem ducted fan with control vanes

(b) 2nd prototype: Tandem ducted fan with tilting small ducted fans

(c) 3rd prototype: Tandem coaxial ducted fan with control vanes

Fig. 1 Design iterations of ducted fan aircrafts in BIT.

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