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Nonlinear robust control of tail-sitter aircrafts in flight mode transitions

Zhaoying Li [a], Lixin Zhang [a], Hao Liu [a,*], Zongyu Zuo [b], Cunjia Liu [c]

[a] School of Astronautics, Beihang University, Beijing 100191, PR China
[b] The Seventh Research Division, Beihang University, Beijing 100191, PR China
[c] Department of Aeronautical and Automotive Engineering, Loughborough University, Leicestershire, England LE11 3TU, United Kingdom

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ABSTRACT

In this paper, a nonlinear robust controller is proposed to deal with the flight mode transition control problem of tail-sitter aircrafts. During the mode transitions, the control problem is challenging due to the high nonlinearities and strong couplings. The tail-sitter aircraft model can be considered as a nominal part with uncertainties including nonlinear terms, parametric uncertainties, and external disturbances. The proposed controller consists of a nominal H_∞ controller and a nonlinear disturbance observer. The nominal H_∞ controller based on the nominal model is designed to achieve the desired trajectory tracking performance. The uncertainties are regarded as equivalent disturbances to restrain their influences by the nonlinear disturbance observer. Theoretical analysis and simulation results are given to show advantages of the proposed control method, compared with the standard H_∞ control approach.
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1. Introduction

In recent years, the unmanned aerial vehicles (UAVs) have attracted much attention because of their various applications (see, e.g., [1–5]). Tail-sitter aircrafts are a new type of UAVs, which can vertical take off and land (VTOL) on their tails, and fly forward with high speeds and heavy loads. Due to these advantages, the tail-sitter aircrafts have drawn much attention and have various applications in civil and military fields, as shown in [1]. The flight mode transition of tail-sitter aircraft is a process that the aircraft flies forward from hovering, or vice versa [3,6]. During the flights of the tail-sitter aircraft, including flying forward, hovering, mode transition, take-off and landing, multiple challenges exist such as nonlinearities and uncertainties involved in the vehicle dynamics for the flight control method design, especially in the flight mode transitions [7]. The tail-sitter aircraft is the combination of the fixed-wing aircraft and the rotorcraft, which has the both characteristics of the fixed-wing aircraft and rotorcraft. It can vertically taking off and hover like rotorcraft while cruise with high flight speed and long flight time and can accomplish multiple complex tasks, which is hard for either fixed-wing aircraft or rotorcraft. The main difficulty of control is about that the flight mode transition due to the large maneuver, the serious nonlinearity and influences of the uncertainty. In the mode transition, the fuselage is tilted and the wings are kept at a given small angle of attack. However, it is difficult to analyze the aerodynamics of the tilting fuselage during the mode transition, and moreover, the tilting structure is difficult to control. Several design methodologies of tail-sitter aircrafts are introduced in [8,9].

In recent years, developments of the tail-sitters have made significant progress. Many efforts have been applied to deal with the flight control problem of the tail-sitter aircrafts. As shown in [10,11], a twin helicopter rotor tail sitter aircrafts are presented. A model of an agile tail-sitter aircraft was presented in [12], which could operate as a helicopter as well as have the capable of transition to fixed-wing flight. A novel hybrid UAV called U-Lion was introduced in [13], which had autonomous VTOL and cruise flying capabilities. As shown in [14], an accurate and robust altitude control method was presented for VTOL aircrafts equipped with turbine engines in order to achieve the quasi-stationary flight. To support navigation and control research for indoor micro air vehicles, a four wing tail-sitter type rotorcraft micro air vehicle was developed in [15]. Based on aerodynamics characteristics of a fixed-wing micro air vehicle, the influence of a propeller slipstream was investigated in [16].

The tail-sitter aircraft is a typical multi-input, multi-output, and nonlinear time-varying system with cross couplings and uncertainties. It can be regarded as a helicopter when hovering and a fixed-wing aircraft when flying forward [17]. Several control strategies

* Corresponding author.
E-mail addresses: lizhaoying@buaa.edu.cn (Z. Li), buaazlx@buaa.edu.cn (L. Zhang), liuhao13@buaa.edu.cn (H. Liu), zzybobby@buaa.edu.cn (Z. Zuo), c.liu5@lboro.ac.uk (C. Liu).

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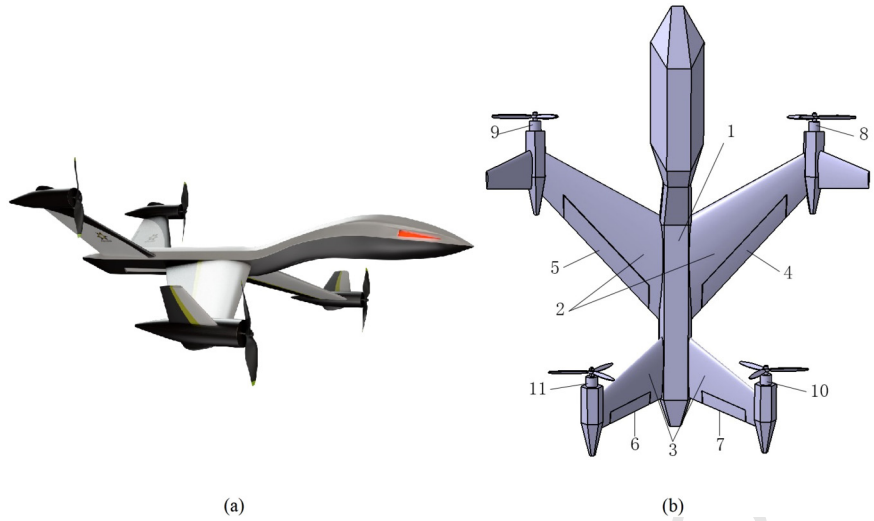

Fig. 1. X-hound vehicle: (a) X-hound tail-sitter aircraft, (b) schematics of X-hound tail-sitter aircraft. Notations: 1: fuselage, 2: wings, 3: V tail, 4: vane 1, 5: vane 2, 6: vane 3, 7: vane 4, 8: rotor 1, 9: rotor 2, 10: rotor 3, 11: rotor 4.

have been proposed, which can be applied to achieve the desired tracking control performance. In [18], an active model based predictive control method was developed for the flight control of unmanned helicopters in full flight envelope. Similarly, a model-based tracking control design for small-scale unmanned helicopters was presented in [19]. As shown in [20], a method for using linear matrix inequalities was introduced to synthesize controller gains for a quadrotor system. In [21] and [22], the control problem of flexible spacecraft with communication delays was discussed, and distributed formation control of multiple quadrotor aircraft was proposed. In [23], a robust adaptive tracking control system for the attitude dynamics of a rigid body was presented. In [24], a feedback control strategy was proposed to make the dynamics of a class of under-actuated VTOL aircraft tracking a desired trajectory. Based on a nonlinear model of the uncertain robotic quadrotors, a robust nonlinear attitude control method was designed in [25]. However, the effects of the uncertainties to the closed-loop systems were not fully discussed in these works, and the controllers were designed based on the nonlinear systems without further analyzing of the influences of external disturbances.

The dynamics of the tail-sitter aircrafts are nonlinear with couplings, and sensitive to external disturbances. To deal with the control problem in the presence of uncertainties, various robust control techniques have been developed. In [26], a nonlinear L_2-disturbance rejection control method to a laboratory twin-rotor system was proposed for the highly nonlinear and strongly coupled dynamics. In [27], a novel asymptotic tracking controller was introduced for an underactuated quadrotor UAV by the robust integral of the signum of the error method. To solve the multiple uncertainties control problems, the robust decentralized and linear time-invariant controller with the robust compensator was proposed to achieve trajectory tracking for quadrotors, in [28,29]. An adaptive compensation control scheme with disturbance observer for four-rotor helicopter was proposed in [30], to handle the attitude control problems with the unknown actuator failures and external disturbances. In [31], a new method was developed to improve the disturbance-rejection performance of a servo system by the estimation of an equivalent input disturbance. In [32], a disturbance rejection control strategy was presented for attitude tracking with disturbance observer to restrain the influences of both internal uncertainties and external disturbances. In these works, further studies on reducing the influences of uncertainties caused by parametric perturbations, external disturbances, nonlinear and coupled dynamics were not discussed fully in the stability analysis of the closed-loop control system.

In the current paper, a six-degrees-of-freedom control problem was studied for the tail-sitter aircrafts. The purpose of the control here is to improve the signal tracking capability, as well as the performance of robust stability for uncertainties including unmodeled nonlinearities, parametric uncertainties, and external disturbances. In order to design the controller for practical implementation, the system model is decoupled into a nominal model with the uncertainties parts. A robust H_∞ controller, which is low-order, linear and time-invariant, is introduced for the nominal model to achieve the desired trajectory tracking. As the effects of uncertainties on the aircraft control system cannot be reduced as desired in the whole frequency range by the standard H_∞ method, a disturbance observer is proposed for the uncertainties to improve the robustness of the closed-loop system. The proposed controller can guarantee to achieve the tracking performance and robustness against uncertainties. The simulation results show that the proposed robust control strategy can achieve better robust tracking control performance, compared with a standard H_∞ controller.

This paper is organized as follows. In Section 2, the dynamic model of the tail-sitter aircraft is presented. The robust control based on the disturbance observer method is proposed in Section 3. The stability analysis for proof of the stability of the system is shown in Section 4. The simulation comparison and conclusions are given in Section 5 and Section 6, respectively.

2. System dynamic model

2.1. Mechanical structure of tail-sitters

In this article, a new type tail-sitter aircraft called X-hound developed by the AOS Company is discussed. This tail-sitter aircraft consists of a fuselage, wings and a V tail as shown in Fig. 1(a). A brief outline of the aircraft is shown in Fig. 1(b). All the vanes can generate aerodynamic torques by deflection. The motors are mounted on the aircraft wings and the V tail, driving the propeller to generate thrusts, and also can generate torques by the different rates of each motor. The forces and torques generated by four rotors and four vanes can change the movements of the tail-sitter aircraft. The forces and torques for the tail-sitter aircraft during mode transition are shown in Fig. 2(a). The four rotors generate thrust and produce torques around the aerodynamic center due to the blades of rotors. The four rotors are symmetrically mounted

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