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# Flight dynamic modeling and control for a telescopic wing morphing aircraft via asymmetric wing morphing

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ABSTRACT

In this paper, a sliding mode flight controller is formulated in order to enhance the lateral maneuverability for a tailless telescopic wing morphing aircraft by using additional asymmetric wing telescoping. Based on the nonlinear time-varying equations of motion and the approximate aerodynamic model obtained by wind tunnel tests, a nonlinear time-varying model with coupling between aerodynamic parameters and control inputs is established and the open-loop dynamic response characteristics are analyzed. According to the difficulty of precise aerodynamic modeling during both sides of wing telescoping, the sliding mode control approach is used to design the control law to track maneuver reference command, which has a low requirement for modeling precision and is suitable for the nonlinear time-varying system. In addition, the control inputs are allocated to asymmetric wing telescoping and aerodynamic control surfaces based on the minimum energy method. The closed-loop simulation results of a roll agility maneuvering called "$T_{90}$ maneuvering" are presented. The results show that a larger roll angular velocity is produced and the control surfaces in the maneuvering flight can maintain a large control margin, which means the maneuverability is significantly improved and the control burden of the aerodynamic control surfaces has been reduced compared with the aircraft without use of telescopic wings; moreover, the robustness of the sliding mode controller is verified by simulation of aerodynamic perturbations.





## 1. Introduction

Morphing aircraft can change its aerodynamic configuration to adapt to multiple missions and has multi-objective adaptability [1, 2]. The force and moment characteristics of the morphing aircraft can change significantly and quickly through wing morphing [3–6], which enables to dramatically enhance the flight performance and combat effect of the morphing aircraft [7–11]. Various types of morphing aircraft have been proposed, and an innovative way of morphing is using telescopic wing design.

Actually, for the telescopic wing morphing aircraft, wing telescoping can be considered to be a new control input for the morphing aircraft, especially to enhance maneuverability in maneuvering flight. In wing telescoping process, the dramatic and rapid changes of inertia of moment, the center of gravity (CG) position and aerodynamic forces and moments of the aircraft are involved. Compared to symmetric wing telescoping, asymmetric wing telescoping will lead to three-axis dynamic response variation of the morphing aircraft [12]. Moreover, unlike traditional aerodynamic control surfaces, asymmetry wing telescoping will result in a large change of the aerodynamic and configuration parameters in the model of motion; meanwhile, the changes of parameters in the model and state variables such as angle of attack and sideslip angle, will, in turn, affect the control efficiency of asymmetry wing telescoping. Therefore, the coupling between control inputs and the aerodynamics cannot be ignored, and the morphing aircraft in asymmetric wing telescoping is a complex nonlinear time-varying dynamic system. In addition, the telescopic wing design may make it difficult to mount control surfaces on the telescopic wing; therefore, the control surfaces can be only mounted on the inner fixed wing. It will lead to low efficiency of control surfaces, and the maneuverability of the telescopic wing morphing aircraft may be unsatisfactory only by control surfaces' deflection. As a result, the flight control design to enhance the lateral maneuverability for morphing aircraft using asymmetric wing telescoping becomes a critical issue.

Currently, a considerable amount of literature has been carried out on the flight control design for morphing aircraft in symmetric morphing [13–19], specifically focusing on static configuration or wing morphing process. A few studies have investigated asymmetric morphing simulation and control. In several studies, the flight dynamic characteristics of the morphing aircraft in asym-

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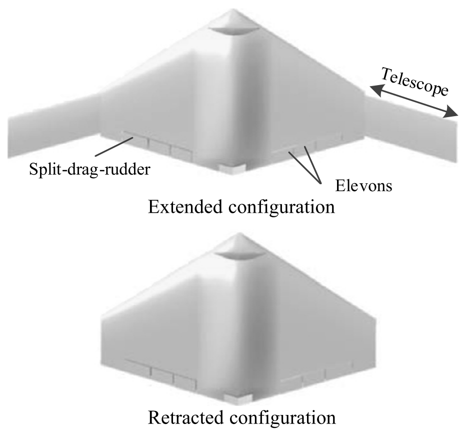


**Fig. 1.** The tailless telescopic wing morphing aircraft.

metric morphing were investigated [20–22]; as well, a multi-body dynamic model of an asymmetric variable sweep morphing aircraft was constructed and the idea of aircraft roll control based on the decoupled one-degree-of-freedom roll equation of motion using asymmetric wing sweep angle change was explored by Tong et al. [23]. However, the existing literature does not consider the three-axis coupling effect of asymmetric morphing, and there is a lack of published research on the flight control design using asymmetric wing morphing control based on six-degrees of freedom nonlinear time-varying model. Furthermore, the coordinated allocation between the control surfaces and asymmetric wing morphing is not taken into account.

In fact, when considering the asymmetric wing telescoping as a new control input, the telescopic wing morphing aircraft is a nonlinear time-varying system, and coupling of the aerodynamic parameters with the control inputs should be considered. This causes a difficulty in modeling the aerodynamics precisely for the morphing aircraft, which will have uncertain dynamic behavior. According to the uncertain nonlinear time-varying system, a feasible method for flight control design is using sliding mode control theory, which can guarantee the dynamic quality of the sliding mode motion and approaching motions by designing the sliding mode function and approaching rate, respectively [24,25].

In this paper, a tailless telescopic wing morphing aircraft is investigated. First, the nonlinear time-varying model of motion and the aerodynamic model obtained by wind tunnel tests are established. Second, the dynamic response of asymmetric wing telescoping is simulated and analyzed. Third, a sliding mode controller is formulated by using the coordinated control allocation between asymmetric wing telescoping and aerodynamic control surfaces. The closed-loop system is desired to achieve satisfactory command tracking performance and improve the maneuverability of the tailless telescopic wing morphing aircraft. Finally, the validation of the controller and its robustness are verified through the simulation of $T_{90}$ maneuver flight called "loaded roll", which is a roll performed while holding the angle of attack and a measure of an aircraft's agility in the roll axis [26].

## 2. Dynamic modeling of morphing aircraft with asymmetric wing morphing control and aerodynamics coupling

### 2.1. Configuration characteristics of the tailless telescopic wing morphing aircraft

In this paper, a tailless telescopic wing morphing aircraft is studied. The wing includes inner fixed wing and outer telescopic wing, and the outer wing can telescope along the wing span direction by actuators arranged inside, as shown in Fig. 1. The morphing aircraft can change the wing area and span by wing telescoping to adapt to different flight conditions and achieve maneuvering flight control. The configuration parameters of the telescopic wing morphing aircraft are shown in Table 1, where the moment of inertia $I_x$, $I_y$ and $I_z$ are defined in body axis. As $I_{zx}$ is very small, it is neglected in this paper.

**Table 1**
Configuration parameters of the telescopic wing morphing aircraft in different configurations.

| Configuration parameters | Extended configuration | Retracted configuration |
|---|---|---|
| $S/\text{m}^2$ | 9.052 | 7.248 |
| $c/\text{m}$ | 1.651 | 1.895 |
| $b/\text{m}$ | 6.992 | 4.226 |
| $I_x$ | 2625 | 1811.2 |
| $I_y$ | 1586 | 1536.4 |
| $I_z$ | 3371 | 2507.5 |
| CG position from the nose/m | 1.132 | 0.989 |

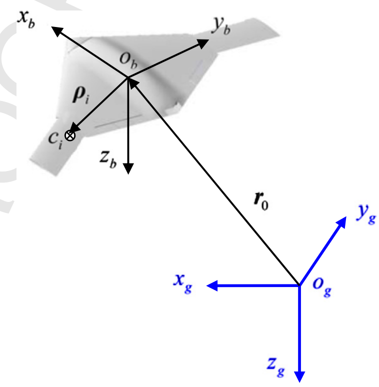


**Fig. 2.** Coordinate axis system.

### 2.2. Nonlinear equations of motion in asymmetric morphing

In asymmetric wing morphing process, the movement of wings will cause a shift of the aircraft's center of gravity. Here, the origin of the body coordinate system $O_b x_b y_b z_b$ is set to locate at a fixed point of the fuselage, and the ground coordinate system is described as $O_g x_g y_g z_g$, as shown in Fig. 2. The center of gravities of the fuselage and moving parts of the wing are described as $c_i$ $(i = 1, \dots, n)$.

As the origin of body coordinates is not located at the CG of the morphing aircraft in asymmetric wing morphing process, the dynamic equations of motion for the telescopic wing morphing aircraft with asymmetric wing morphing can be expressed in vector form as [27]

$$\begin{cases} \boldsymbol{F} = m(\dot{\boldsymbol{V}} + \boldsymbol{\omega} \times \boldsymbol{V}) + \dfrac{\delta \boldsymbol{\omega}}{\delta t} \times \boldsymbol{S} + 2\boldsymbol{\omega} \times \dfrac{\delta \boldsymbol{S}}{\delta t} \\ \quad + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \boldsymbol{S}) + \dfrac{\delta^2 \boldsymbol{S}}{\delta t^2} \\ \boldsymbol{M} = \boldsymbol{I} \cdot \dfrac{\delta \boldsymbol{\omega}}{\delta t} + \dfrac{\delta \boldsymbol{I}}{\delta t} \cdot \boldsymbol{\omega} + \boldsymbol{\omega} \times (\boldsymbol{I} \cdot \boldsymbol{\omega}) + \boldsymbol{S} \times \dfrac{\delta \boldsymbol{V}}{\delta t} + \boldsymbol{S} \times (\boldsymbol{\omega} \times \boldsymbol{V}) \\ \quad + \displaystyle\sum_{i=1}^{n} \Big\{ \boldsymbol{I}_i \cdot \dfrac{\delta \boldsymbol{\omega}_i}{\delta t} + \dfrac{\delta \boldsymbol{I}_i}{\delta t} \cdot \boldsymbol{\omega}_i + \boldsymbol{\omega}_i \times (\boldsymbol{I}_i \cdot \boldsymbol{\omega}_i) \\ \quad + \dfrac{1}{m_i} \Big[ \boldsymbol{S}_i \times \dfrac{\delta^2 \boldsymbol{S}_i}{\delta t^2} + \boldsymbol{\omega} \times \Big( \boldsymbol{S}_i \times \dfrac{\delta \boldsymbol{S}_i}{\delta t} \Big) \Big] \Big\} \end{cases} \tag{1}$$

where $\boldsymbol{F}$ and $\boldsymbol{M}$ are the total force and moment, $m$ is the mass of the aircraft, $\boldsymbol{I}$ is the inertia matrix, $\boldsymbol{\omega} = [p, q, r]^T$ is the angular



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