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Adaptive non-affine control for the short-period model of a generic hypersonic flight vehicle

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This paper presents an adaptive non-affine control scheme for the longitudinal short-period model of a generic hypersonic flight vehicle (HFV). Firstly, the non-affine nonlinear characteristics of the aerodynamic coefficients are analyzed, which have great influence on the flight dynamical behaviors. Secondly, without ignoring the non-affine nonlinear aerodynamics, a fuzzy sliding mode adaptive non-affine controller is designed. Under the existence of external disturbances and unmodeled dynamics, the controller can still ensure that the angle of attack tracks the desired signal robustly and asymptotically. Furthermore, the proposed controller does not require the exact bound values of the external disturbances and unmodeled dynamics, which is very important for hypersonic vehicles because the values usually cannot be obtained at hypersonic flight conditions. Finally, the simulation results are provided to illustrate the feasibility and effectiveness of the proposed scheme.

1. Introduction

Hypersonic flight vehicles (HFVs) are a kind of highly sensitive vehicles to flight condition changes due to their hypersonic speeds. Their flight dynamics have some unique characteristics, such as complex nonlinearities, strong couplings, large uncertainties, and extensive unmodeled dynamics, which will greatly affect the flight stabilities of HFVs and bring tremendous challenges to control them [1,2]. Furthermore, because the deflection angles of control surfaces and engine thrust of HFVs are limited control inputs, and the flight attitudes can also not be adjusted arbitrarily, all of these features also increase the difficulties of controller design.

Therefore, the flight control of HFVs is a type of control problem to apply limited control inputs and limited dynamic behaviors to overcome fast time-varying, complex nonlinearities, strong couplings, and large uncertain dynamics, in order to achieve good performance with high accuracy, strong robustness, and quick response [3–5]. With regards to this challenging issue, many valuable results have been achieved. Initially, to simplify the complex control problem, it is generally assumed that the flight vehicle dynamics can be described by a simplified linear uncertain model in a specific flight condition. These studies mainly apply linear robust control theories to design flight controllers [6–10]. Subsequently, without the need of linearization, flight control systems are usually designed based on the affine nonlinear models of HFVs by using affine nonlinear control methods, such as feedback linearization control [11], dynamic inversion [12], backstepping [13–15], adaptive control [16–18], and neural network [19–21]. Additionally, due to the existence of external disturbances and unmodeled dynamics, it is very difficult to obtain a precise mathematical model. Therefore, by applying the approximation abilities of fuzzy systems, several stable fuzzy control schemes have been developed for the hypersonic vehicles with uncertainties [22–25].

Without any doubt, the above results contribute a lot to hypersonic research. However, the effects of aerodynamic non-affine characteristics on HFVs are not considered in the above-mentioned studies. As is well-known, the flight dynamics of HFVs in hypersonic phase ($M_a \geq 5$) are obviously different from those in subsonic and supersonic phases. Therefore, a lot of existing relevant documentation and data of subsonic and supersonic vehicles cannot be straightforwardly applied to the flight control for hypersonic vehicles. From Ref. [26] and Ref. [27], it can be seen that, in hypersonic phase, the aerodynamic coefficients have complicated nonlinear relationships not only with the angle of attack and Mach number, but also with the deflection angles of control surfaces, which makes the flight control problem into a non-affine-in-control nonlinear one. Needless to say, the non-affine flight control problem for a hypersonic vehicle is more difficult than the affine nonlinear one. The traditional solutions are usually to ignore the nonlinear effects of control surfaces to aerodynamic coefficients [13–15,18, 22] or consider them as system bounded uncertainties [8,12]. If the control requirements are not high enough, these solutions may be

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Nomenclature

C_D	total drag coefficient .... n.d.	$\hat{q}$	aerodynamic pressure .... lb/ft^2
C_L	total lift coefficient .... n.d.	T	engine net thrust .... lb
C_m	total pitch moment coefficient .... n.d.	α	angle of attack .... deg
M_a	Mach number .... n.d.	δ_e, δ_a	left and right elevon deflection angle, respectively deg
q	pitch rate .... deg/s		

feasible, however, at hypersonic speeds, a high-precision flight control system is always desired. Therefore, ignoring non-affine effects may not be the right way, because a simplified affine nonlinear model cannot accurately describe the dynamical behaviors of a hypersonic vehicle.

In recent years, the research on non-affine nonlinear systems has attracted increasing attention and achieved many notable results [28–30]. To avoid strict conditions and complex theoretic proof, sliding mode control [31,32] considered here has been studied in Refs. [33,34] for non-affine nonlinear systems. Ref. [33] applies linear time-varying (LTV) systems to approximate rotor-active magnetic bearing system with non-affine nonlinear dynamics and designs a sequence of sliding mode controllers. The results demonstrate that the presented method is effective, but it is difficult to straightforwardly extend it to some complex nonlinear systems due to the need for a sequence of known linear sub-systems. Ref. [34] designs a controller by combining sliding mode and fuzzy adaptive methods for a class of non-affine nonlinear system and achieves satisfactory control effect. However, the stringent stability conditions without considering uncertainties and external disturbances limit its application to HFVs.

In the field of hypersonic vehicle control, some scholars have begun to conduct exploratory research for the problems concerning control input nonlinearities [35,36]. Ref. [35] discusses the attitude control problem with control input saturation for a near space vehicle. Ref. [36] presents a robust adaptive neural control for a flexible hypersonic flight vehicle with dead-zone input nonlinearity. However, the aforementioned control input nonlinearities [35,36] are mainly focused on dead-zone or saturation, complex nonlinearities are not involved yet. Therefore, the achievements of the non-affine flight control for the hypersonic vehicles with complicated input nonlinearities are very few.

Based on the above analysis, this paper presents a novel fuzzy sliding mode adaptive non-affine control method for the longitudinal short-period dynamics of a generic HFV. The main contributions of this paper are: (1) The non-affine nonlinear aerodynamics of a generic HFV is analyzed, and it has a significant effect on the hypersonic flight dynamics. To using a more accurate model possible, the non-affine nonlinear aerodynamics does not need to be simplified or ignored for the controller design. (2) The non-affine flight control for the HFV is presented, which has seldom been discussed, but it is very useful to develop control algorithms using a non-affine model and draw some more important inclusions which are conformed to the actual flights. (3) An output tracking controller is designed for the HFV's model with non-affine inputs, which can ensure that the system achieves good tracking performance under the existence of external disturbances and unmodeled dynamics. (4) The proposed non-affine controller does not require the exact bound values of external disturbances and unmodeled dynamics except for the proof of stability, which increases the practicability of the controller.

2. Non-affine dynamics of the longitudinal short-period model of a generic HFV

At a constant height and a steady speed, the longitudinal short-period dynamics of a generic HFV can be described as:

Table 1
The basic parameters of the HFV.

Parameter	Nomenclature	Value	Unit
b	Lateral–directional reference length, span	60	ft
c	Mean aerodynamic chord	80	ft
M	Unladen weight	300,000	lbs
I_{yy}	Pitch moment of inertia	1.1×10^7	slg·ft^2
S	Reference area	3603	ft^2
X_{cg}	Longitudinal distance from momentum reference to vehicle center of gravity	9.5	ft
X_{mrc}	Distance from momentum reference center to front	124.01	ft
X_{rc}	Distance from action line of engine to body axis	3.75	ft

$$\begin{cases} \dot{\alpha} = q \\ \dot{q} = \frac{1}{I_{yy}}(m_A + m_T) \end{cases} \tag{1}$$

where

$$m_A = m_{mrc} - X_{cg} \cdot Z, \quad m_{mrc} = c\hat{q}SC_m, \quad m_T = T \cdot X_{rc} \tag{2}$$

$$Z = -D\sin\alpha - L\cos\alpha, \quad D = \hat{q}SC_D, \quad L = \hat{q}SC_L \tag{3}$$

$$\begin{aligned} C_D &= C_{D,\alpha}(\alpha, M_a) + C_{D,\delta_e}(\alpha, M_a, \delta_e) + C_{D,\delta_a}(\alpha, M_a, \delta_a) \\ C_L &= C_{L,\alpha}(\alpha, M_a) + C_{L,\delta_e}(\alpha, M_a, \delta_e) + C_{L,\delta_a}(\alpha, M_a, \delta_a) \\ C_m &= C_{m,\alpha}(\alpha, M_a) + C_{m,\delta_e}(\alpha, M_a, \delta_e) + C_{m,\delta_a}(\alpha, M_a, \delta_a) \\ &\quad + C_{m,q}\frac{qc}{2V} \end{aligned} \tag{4}$$

The basic parameters of the HFV [26,37] are given in Table 1. In addition, according to the CFD-data of Ref. [26], Table A.1–Table A.3 are provided to show the analytical expressions of the aerodynamic coefficients C_D, C_L, and C_m of Eq. (4).

As can be seen from Table A.1–Table A.3, the nonlinearities of the aerodynamic coefficients C_D, C_L, and C_m are dependent not only on the angle of attack and Mach number, but also on the elevon deflection angles δ_e and δ_a, where $C_{D,\alpha}, C_{L,\alpha}$, $C_{m,\alpha}$, and $C_{m,q}$ have nonlinear relationships only with the angle of attack and Mach number, while C_{D,δ_e}, C_{D,δ_a}, C_{L,δ_e}, C_{L,δ_a}, C_{m,δ_e}, and C_{m,δ_a} are also the functions of the control inputs δ_e and δ_a besides of α and M_a. Especially, C_{D,δ_e} and C_{D,δ_a} have nonlinear relationships with δ_e and δ_a unlike other coefficients. Because δ_e and δ_a are the control inputs of the flight vehicle, the HFV model is a non-affine nonlinear model, which brings more challenges to design a controller. To make the problem simple, the non-affine terms $(6.84 \cdot 10^{-6}\delta_e^2 + 5.28 \cdot 10^{-12}(\alpha \cdot M_a)^2 \cdot \delta_e^2)$ and $(6.84 \cdot 10^{-6}\delta_a^2 + 5.28 \cdot 10^{-12}(\alpha \cdot M_a)^2 \cdot \delta_a^2)$ are usually ignored in traditional ways. In order to decide whether they should be ignored, subsequently, the effects of the non-affine terms on the flight vehicle are studied.

According to the expressions of Table A.1–Table A.3, Fig. 1 and Fig. 2 show the curves of the aerodynamic coefficient C_{D,δ_e} with the angle of attack and the deflection angle of the left elevon.

Remark 1. Because C_{D,δ_e} and C_{D,δ_a} have similar analytical expressions, C_{D,δ_e} are only studied here.