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Dynamic surface control design of post-stall maneuver under unsteady aerodynamics

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ABSTRACT

This paper presents an efficient method that overcomes the problem of the control design of the post-stall maneuver under unsteady aerodynamics. On the basis of adequate data of the large amplitude oscillation experiment device in wind tunnel test, the unsteady aerodynamics model with nonlinearity, coupling and hysteresis is established by the improved Extreme Learning Machine (ELM) method. Considering the nonlinearity of the longitudinal model of the advanced fighter and the aerodynamics characteristics of the post-stall maneuver, the control law under large attack angle is designed combining the backstepping method and the daisy chain allocation method. The first order filter is adopted to prevent the "differential explosion" problem. The designed control allocation law guarantees that the conventional surfaces and the vector nozzle deflect coordinately within the position limits and the rate limits. The Radial Basis Function (RBF) network is applied to model the uncertainty, and the stability of the proposed control law which considering the uncertainty is also proved. Digital simulations of the typical "Cobra" maneuver under the unsteady aerodynamics are completed with comparisons under different conditions. Simulations results verify the validity of the proposed control law under unsteady aerodynamics and the aerodynamics uncertainty.

1. Introduction

Close combat, one of the essential capabilities of the advanced fighters, is still inevitable for quite a long time. Because of the decoupling of nose direction and flight path, the post-stall maneuver greatly increases the speed of the nose pointing to the target and strongly increases the chance of fighter attack in combat. Typical post-stall maneuvers include Cobra maneuver, Herbst maneuver and barrel roll. When the plane undergoes the post-stall maneuver, the airflow through the surfaces changes from attached flow to swirling flow, then switches to swirl broken and finally separated flow. The mutual interference between the airflow lag and each part of vortexes is so serious that the aerodynamics forces and moments of advanced fighters are more nonlinear, multi axis coupled and hysteretic. For this reason, the conventional aerodynamics model is no longer suitable for post-stall maneuver. Therefore, it is necessary to establish an accurate unsteady aerodynamics model.

Well-known methods for modeling of unsteady aerodynamics are step function model [1,2], algebraic polynomial model [3], Fourier function analysis model [4], state space model [5–7], differential equation model [8,9] and fuzzy logic model [10], and so forth. These methods can deal with the unsteady aerodynamics. However, the uses of them are limited in practice because that some variables cannot be accessed in actual flight test. In order to solve the unsteady modeling problem generally, an improved ELM modeling method has been proposed to establish the unsteady aerodynamics model of the single axis oscillation and biaxial coupling axis oscillation [11]. As expected, this method is developed to create the wind tunnel test data model of the large amplitude pitch oscillation which simulates the Cobra maneuver. The unsteady aerodynamics model can provide accurate aerodynamics data for subsequent control design.

The nonlinear control method is considered an inevitable approach to realize the control design in post-stall maneuver. With the development of Lyapunov theory and the adaptive control theory, the backstepping method is one of the most widely used methods among nonlinear control methods. The backstepping method was proposed by Kokotovic in 1991 [12]. The advantages of backstepping method are listed here [13]: (1) it can deal with the nonlinear model, the control input nonlinearity and the uncertainty in the controller design process while guaranteeing its control stability; (2) the method does not need to adjust the parameters so it owns fast convergence speed and high efficiency. Combining with other techniques, the backstepping method has

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Nomenclature

V	Velocity of aircraft
γ	Climb angle
α	Attack angle
θ	Pitch angle
q	Body-axis pitch rate
X	X value in ground coordinate system
h	Height
m	Mass
g	Gravitational acceleration
L	Lift
D	Drag
F_x	Force of x axis in Body coordinate system
F_z	Force of z axis in Body coordinate system
M	Pitch moment
T_x	Engine force of x axis in Body coordinate system
T_z	Engine force of z axis in Body coordinate system
M_t	Engine pitch moment
Q	Dynamic pressure
S_w	Wing area
C_A	Mean aerodynamics chord
k	Reduced frequency
J_y	The inertia of the Y body-axis
δ_e	Deflection of elevator
δ_{fj}	Deflection of leading edge flap
δ_{bj}	Deflection of trailing edge flap
δ_z	Deflection of longitudinal vector nozzle (deflecting in the longitudinal plane)

developed rapidly. Researchers integrated backstepping and small-gain approach to realize the global adaptive output feedback control of a class of uncertain nonlinear systems [14,15]. Based on the backstepping method, the dynamic surface control (DSC) has received much attention. The DSC method can end the complexity of the "explosion of terms" phenomenon which makes other methods difficult to implement in practice [16,17]. The backstepping method is gradually and widely utilized in the flight control. A command filtered backstepping approach using adaptive function approximation to control unmanned air vehicles was presented that in [18]. With the backstepping technique, an adaptive controller was synthesized for the purpose of accomplishing desired responses under a wide range of flight envelope in [19]. Furthermore, adaptive backstepping method has seen applications in the flight control system, and the constraints conditions of the aircraft have been taken into account as actually as possible [20–22]. In recent years, the research objects of backstepping method have been more specific. The authors presented a novel application of backstepping controller for autonomous landing of a rotary wing unmanned aerial vehicle (RUAV). Its application, which holds good for the full flight envelope control, was an extension of a backstepping algorithm for general rigid body velocity control [23]. In [24], authors showed the design of a mini-UAV attitude controller using the backstepping method. A constrained adaptive backstepping approach was used to design a flight control law for the nonlinear model of an F-16/MATV fighter aircraft. On-line parameter update laws that make use of B-spline neural networks were used to approximate the aerodynamics force and moment coefficients in [25]. An Incremental backstepping scheme that relied on estimates of the angular accelerations and measurements of the current control deflections was used to reduce the dependency on the F-16 aircraft model [26]. A novel adaptive backstepping control scheme based on invariant manifolds for unmanned aerial vehicles in the presence of some uncertainties was presented in [27].

Although the backstepping method has been successfully applied in flight control system, the hysteresis of the aerodynamics has been estimated or ignored in the control design process, especially in the post-stall control. And there is rare literature that focuses on both the unsteady aerodynamics modeling and post-stall maneuver controlling. In this paper, the overall goal is to design control law under the unsteady aerodynamics. The improved ELM unsteady aerodynamics modeling method and the backstepping – daisy chain control allocation method will be employed. The methods reported here would provide useful information for flight test in the days to come.

This paper is organized as follows. In Section 2, the unsteady aerodynamics modeling and post-stall control problems are introduced. In Section 3, a typical large amplitude pitch oscillation model is established based on the improved ELM method. The backstepping control law is designed in Section 4, where the stability of the method is proved and the daisy chain allocation method is also described. Section 5 involves the comparison and analysis of digital simulation results. Section 6 concludes the paper.

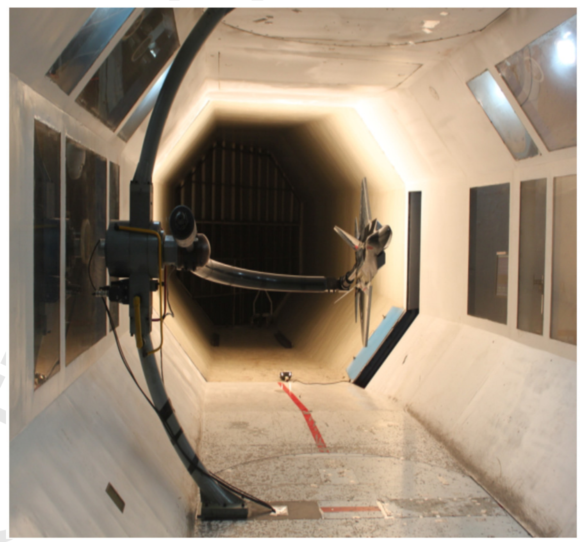

Fig. 1. The experimental device in the wind tunnel.

2. Problem description

In order to study the effect of unsteady aerodynamics on the control law design during post-stall maneuver, hydraulic wind tunnel test equipment of 2 degree of freedoms (DOFs) oscillation with large amplitude shown in Fig. 1 is utilized for an advanced fighter [28]. The plane is a scaled model of the advanced fighter. The experimental device of the wind tunnel can carry out single DOF and 2 DOFs of coupling large amplitude oscillation experiment. With the large oscillation experiments in the wind tunnel, aerodynamics simulation of post-stall maneuver at high attack angle can be achieved to provide accurate aerodynamics reference for control law design. The detailed information of the wind tunnel test device can be seen in [11].

In this paper, we focus on the longitudinal control in post-stall maneuver for the advanced fighter. The object of study is a scaled model of the advanced fighter in Fig. 2 with blended wings, two