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Booster stage adaptive backstepping tracking control for interceptor

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ABSTRACT

An adaptive backstepping tracking controller in the presence of uncertain parameters and external disturbance is designed for the thrust vector-controlled interceptor during its booster stage. The dynamic equation is formulated into a parametric-strict-feedback form under reasonable assumption. The controller design is decomposed into two loops, which are aerodynamic angle loop and angular rate loop. The whole closed system is proved to converge into a compact set asymptotically by employing feedback control laws and adaptive estimate laws designed in this paper. The controller proposed here has two main advantages. First, it can deal with the disturbances whose bounds have the expression of all system states. Second, there is no chattering in the tracking process by using continuous hyperbolic tangent function in place of sign function. Simulation results demonstrate that the proposed method in this paper not only afford strong capability but also achieve a fast and accurate response of resistance to parameters uncertainty and external disturbances.

1. Introduction

The booster stage of the interceptor begins after being ejected from the carrier vehicle. To obtain high maneuverability, the thrust vector control is equipped on interceptor during booster stage fight. The booster stage flight of interceptor is seldom discussed in literature [1]. Because of high speed and complex flight environment, the dynamic of the interceptor is full of uncertainty, nonlinearity and strong coupling between channels, which make the control system design be a hard task. Attitude controller has been designed by Zhi et al. [1], where a kind of differential geometry based feedback-linearization technique is employed. This method depends on the knowledge of all the plant parameters, and it is difficult to evaluate the robustness with respect to the plant parameters, dynamic model uncertainty. A bad knowledge of plant parameters may even lead to the sharp controller performance degradation [2]. What is more, feedback-linearization technique cannot manage the control problem in the presence of external disturbance. Thus, a kind of technical that can deal with the problem stated in this fragment is really needed.

In recent years, backstepping control is extensively studied in many areas. This technique in fact is a kind of sequential loop closure method. Even more, the coupling of sequential subsystem is considered, which is a great evolution in compare with traditional inner-outer loop control based on the assumption of timescale separation.

Considering the uncertainty parameters, an adaptive backstepping method combining robust adaptive method and traditional backstepping technical is proposed. In the area of flight vehicle control, this method was rapidly then introduced into general use [3–9]. The aerodynamic forces and moment coefficients are not required to be known, so the controller is not rely on the accurate knowledge of the plant parameters but through estimation method based on online updating laws. In addition, the proof of the closed-loop system stability includes the updating law validates the robustness with respect to the dynamic model uncertainty.

There still exists an interesting problem to be studied for better using of adaptive backstepping in the area of flight vehicle control, that is how to dispose unknown external disturbances acted on the flight vehicle. The booster stage of interceptor is always in the height where external disturbances such as wind disturbance are easily encountered. External disturbances may lead to big tracking error even unstable flight. Recently, in [10], an adaptive SMC law is designed in the presence of external disturbances. The external disturbance is well compensated in the SMC law. But when this method is extended to the adaptive backstepping law, the use of norm in the controller

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will cause non-differentiable of the virtual control command, thus make the adaptive backstepping control law not work. In this paper, a smooth hyperbolic tangent function is introduced to dispose the external disturbances, which is an extent of the adaptive backstepping method.

This paper focuses on the adaptive backstepping controller design for the interceptor booster stage flight in the presence of unknown parameters and external disturbances. Section 2 depicts the interceptor dynamic model and the control objective. In Section 3, the adaptive backstepping control considering parameters uncertainty only and considering external disturbance is also presented progressively. Section 4 gives the simulation results.

2. Interceptor dynamic model and problem formulation

The nonlinear dynamic model of interceptor in the booster stage is as follows [1]:

$$\dot{\alpha} = -\omega_x \cos\alpha \tan\beta + \omega_y \sin\alpha \tan\beta + \omega_z - \frac{T\cos\xi_T \cos\eta_T \sin\alpha + qSC_y^{\alpha}\alpha}{mV\cos\beta} - \frac{T\sin\xi_T\cos\alpha}{mV\cos\beta} \tag{1}$$

$$\dot{\beta} = \omega_x \sin\alpha + \omega_y\cos\alpha + \frac{qSC_z^{\beta}\beta - T\cos\xi_T\cos\eta_T\cos\alpha\sin\beta}{mV} + \frac{T\sin\xi_T\sin\alpha\sin\beta + T\cos\xi_T\sin\eta_T\cos\beta}{mV} \tag{2}$$

$$\dot{\gamma}_V = \omega_x\frac{\cos\alpha}{\cos\beta} - \omega_y\frac{\sin\alpha}{\cos\beta} \tag{3}$$

$$J_x\dot{\omega}_x = qSLm_x^{\tilde{\omega}_x}\frac{D}{2V}\omega_x + T_{ay} \tag{4}$$

$$J_y\dot{\omega}_y = qSLm_y^{\beta}\beta + qSLm_y^{\tilde{\omega}_y}\frac{L}{V}\omega_y + (J_z - J_x)\omega_x\omega_z + T\eta_T(L - x_{cg}) \tag{5}$$

$$J_z\dot{\omega}_z = qSLm_z^{\alpha}\alpha + qSLm_z^{\tilde{\omega}_z}\frac{L}{V}\omega_z + (J_x - J_y)\omega_y\omega_x - T\xi_T(L - x_{cg}) \tag{6}$$

where $\omega_z, \omega_y, \omega_x$ are pitch, yaw and roll rates in body coordinate; V is velocity of interceptor, and $q = \rho V^2/2$ is dynamic pressure; T is booster thrust; T_{ay} is the attitude motor thrust; ξ_T and η_T are thrust vector motor deflection angles. m, L, S, and D are reference length, reference area and body diameter of the interceptor, respectively; J_z, J_y, J_x are the moments of inertia around z, y, x directions of body axes. C_y^{α}, C_z^{β}, $m_x^{\tilde{\omega}_x}$, $m_y^{\tilde{\omega}_y}$, $m_z^{\tilde{\omega}_z}$, m_z^{α}, m_y^{β} are aerodynamics parameters.

In a real-world situation, ξ_T and η_T are always smaller than 15°, the following approximations exit as:

$$\frac{T\sin\xi_T\cos\alpha}{mV\cos\beta} \approx 0$$

$$\frac{T\sin\xi_T\sin\alpha\sin\beta + T\cos\xi_T\sin\eta_T\cos\beta}{mV} \approx 0$$

$$T\cos\xi_T\cos\eta_T\sin\alpha \approx T\sin\alpha\, T\cos\xi_T\cos\eta_T\cos\alpha\sin\beta \approx T\cos\alpha\sin\beta$$

Thus, the dynamic equations of the interceptor (1)–(6) can be simplified into the form as follows:

$$\dot{\alpha} = -\omega_x \cos\alpha \tan\beta + \omega_y \sin\alpha \tan\beta + \omega_z - \frac{qSC_y^{\alpha}\alpha}{mV\cos\beta} - \frac{T\sin\alpha}{mV\cos\beta} \tag{7}$$

$$\dot{\beta} = \omega_x \sin\alpha + \omega_y\cos\alpha + \frac{qSC_z^{\beta}\beta - T\cos\alpha\sin\beta}{mV} \tag{8}$$

$$\dot{\gamma}_V = \omega_x\frac{\cos\alpha}{\cos\beta} - \omega_y\frac{\sin\alpha}{\cos\beta} \tag{9}$$

$$J_x\dot{\omega}_x = qSLm_x^{\tilde{\omega}_x}\frac{D}{2V}\omega_x + T_{ay} \tag{10}$$

$$J_y\dot{\omega}_y = qSLm_y^{\beta}\beta + qSLm_y^{\tilde{\omega}_y}\frac{L}{V}\omega_y + (J_z - J_x)\omega_x\omega_z + T\eta_T(L - x_{cg}) \tag{11}$$

$$J_z\dot{\omega}_z = qSLm_z^{\alpha}\alpha + qSLm_z^{\tilde{\omega}_z}\frac{L}{V}\omega_z + (J_x - J_y)\omega_y\omega_x - T\xi_T(L - x_{cg}) \tag{12}$$

2.1. Control objective

In this study, we aim at the angular tracking problem of the interceptor during the booster stage. The objective can be formulated as follows:

$$\lim_{t\to\infty}(\alpha(t) - \alpha^{ref}(t)) = 0 \tag{13}$$

$$\lim_{t\to\infty}(\beta(t) - \beta^{ref}(t)) = 0 \tag{14}$$