DOI: 10.7641/CTA.2018.17065

具有非线性不确定性的高超声速飞行器的分布式鲁棒反步跟踪控制

王 晴[1], 余 瑶[1†], 孙长银[2]

(1. 北京科技大学 自动化学院, 北京 100083; 2. 东南大学 自动化学院, 江苏 南京 210096)

摘要: 本文针对具有外部干扰, 参数摄动和非连续未知非线性气动影响的一般高超声速飞行器纵向动力学问题, 设计了分布式鲁棒反步跟踪控制器. 为了处理复杂的系统, 将标准反步控制和信号补偿方法结合起来构成一个"简单"的鲁棒控制器. 该方法不仅可以保证闭环系统半全局鲁棒跟踪性能, 也可保证系统跟踪误差以期望的收敛速度收敛到期望的误差范围内. 最后, 带有非线性不确定性, 外部干扰和参数扰动的仿真系统说明了该方法的有效性.

关键词: 高超声速飞行器; 鲁棒; 反步; 非线性不确定性

引用格式: 王晴, 余瑶, 孙长银. 具有非线性不确定性的高超声速飞行器的分布式鲁棒反步跟踪控制. 控制理论与应用, 2018, 35(7): 963 – 972

中图分类号: TP273　　**文献标识码**: A

Robust backstepping decentralized tracking control for the hypersonic flight vehicle with nonlinear uncertainties

WANG Qing[1], YU Yao[1†], SUN Chang-yin[2]

(1. School of Automation and Electrical Engineering, University of Science and Technology Beijing, Beijing 100083, China;
2. School of Automation, Southeast University, Nanjing Jiangsu 210096, China)

Abstract: In this paper, the design of robust backstepping decentralized tracking controller is addressed for the longitudinal dynamics of a generic hypersonic flight vehicle with external disturbances, parameter perturbations, and non-continuous unknown nonlinear aerodynamic influence. To deal with the complex system, the standard backstepping and signal compensation method are combined to construct a 'simple' robust controller. The proposed method can not only ensure the semi-global robust practical tracking property of the closed-loop system, but also guarantee the tracking error as small as desired with expected convergence rate. Simulation results with nonlinear uncertainties, external disturbances and parameter perturbations illustrate the effectiveness of the methodology.

Key words: hypersonic vehicle; robust; backstepping; nonlinear uncertainties

Citation: WANG Qing, YU Yao, SUN Changyin. Robust backstepping decentralized tracking control for the hypersonic flight vehicle with nonlinear uncertainties. *Control Theory & Applications*, 2018, 35(7): 963 – 972

1 Introduction

Hypersonic flight vehicles (HFVs) are widely concerned due to the advantages of rapid flight speed, low launch cost, and long running time, which can make HFVs access space more reliably and efficiently. HFVs are exploited to test the necessary disruptive technology and develop a new weapon that can precisely strike enemy targets in just an hour [1–4]. Compared with traditional flight vehicles, the research on hypersonic vehicles is extremely challenging due to the facts such as strong nonlinearity and high flight altitude.

Recently, with respect to the challenges mentioned above, the design of guidance and control systems for HFVs has attracted much attention. Based on the technique of input/output linearization, different kinds of control strategies have been employed, such as linear output feedback control[5], observer-based control[6] and neural network[7–8], and linear parameter-varying control[9–10]. Despite the fact that these linear control schemes could be effective for linear models near the equilibrium point, they could lead to unstable behavior when the flight states are far from the equilibrium

Received 17 May 2017; accepted 26 January 2018.
†Corresponding author. E-mail: yuyao@ustb.edu.cn; Tel.: +86 10-82376656.
Recommended by Associate Editor: GUAN Zhihong.
Supported by the National Natural Science Foundation of China (61703037, 61520106009, 61533008, 61473324) and the Fundamental Research Funds for the Central Universities (FRF–GF–17–B46).

point. Thus, for nonlinear dynamic models of HFVs, various advanced nonlinear control strategies, such as sliding mode control[11], robust control[12–14], guaranteed cost control[15], gain-scheduling control[16], fuzzy control[17–19], and backstepping control[20–21], have been developed for the control design of the longitudinal dynamics of the HFVs. However, these nonlinear control schemes required that the system parameters should be precisely known and system nonlinearities were smooth functions. Obviously, the designed controller may exhibit undesired performance when great parameter perturbations and highly complex nonlinear uncertainties in HFVs are considered. To deal with the possible problems encountered by the above control approaches, adaptive control[22–24] and disturbance observer-based control methods were investigated in the literature[25–26]. In [26–27], systems uncertainties were caused by external disturbances and parameter perturbations. The external disturbances were bounded by constants with match or mismatch condition. In [28] the high gain observer was investigated on flexible hypersonic flight dynamics with lumped uncertainties.

Although these control methods discussed above were proved to be efficient to the HFVs, they mainly focused on external disturbance or smooth nonlinear functions. It was difficult for these methods to take into account external disturbances, great parameter perturbations and non-continuous unknown nonlinear functions together. Moreover, the tracking performances, such as convergence rate, were not discussed.

Over the last 20 years, backstepping control has become one of the most popular control methods for some special classes of nonlinear systems, since it provides a systematic procedure for designing a controller by a step-by-step recursive algorithm. For better control performance, different control strategies are combined together by taking advantage of their strengths respectively[29–31]. Combined with backstepping control strategy, many effective methods have been proposed for stability analysis and controller design. However, backstepping control has the drawback of the phenomenon of “explosion of complexity” in the control law due to repeated differentiations of the virtual control functions.

Another important issue associated with the control of nonlinear systems, concerns convergence rate and steady state tracking error bounds. A new robust adaptive controller for multi-input multi-output (MIMO) feedback linearizable nonlinear systems, capable of guaranteeing a prescribed performance, was developed in [32]. By prescribed performance, the tracking error should be made as small as desired, with a maximum overshoot less than a sufficiently small prespecified constant, exhibiting convergence rate no less than a prespecified value. Visualizing the prescribed performance characteristics as tracking error constraints, the key idea of the technique in [32] was to provide an error transformation function that transforms the original “constrained” nonlinear system into an equivalent “unconstrained” one. Stabilizing the equivalent “unconstrained” system was sufficient to achieve prescribed performance guarantees. However, a tangent hyperbolic function which was generally used as the transformation function, combined with prescribed smooth function to transform the tracking error, made the controller design very complex. Furthermore, this technique had a singularity problem for a certain prescribed performance condition[32–33].

In this paper, the main contributions are as follows: A “simple” robust controller is proposed to deal with the uncertain MIMO nonlinear model with non-continuous nonlinear uncertainties, parameter perturbations, external disturbances, unknown virtual control coefficients and strongly coupled interconnections. The controller is constructed with less limitation, which implies that the reference output is not required to be smooth and the uncertain nonlinearities are not expected to be continuous. The transient and steady state properties are explored. The tracking error can be made as small as desired with expected convergence rate. The whole designed controller has a simple structure, and can be realized easily.

The signal compensation method was first proposed in [34] to deal with robust output tracking problem for linear time-invariant system with parameter perturbations. This idea was further utilized to treat the control problems for nonlinear time-varying systems[35–36]. In this paper, signal compensation framework and backstepping design method are combined together to get desired robust control property for HFVs.

The paper is organized as the following: Section 2 presents the longitudinal dynamics of a generic HFV. In Section 3 the block-triangular form is formulated. Section 4 proposes the robust controller design method. The robust control properties are stated and the main results are proven in Section 5. The simulation result is given in Section 6. Finally, conclusions are stated in Section 7.

2 The hypersonic model and strict-feedback formulation

2.1 The hypersonic model

The model for the longitudinal dynamics of the hypersonic vehicle is developed by National Aerospace Plane Program. The longitudinal dynamics of the hypersonic vehicle model can be described by a set of fiveorder differential equations taken from [26] and [27].

$$\dot{V}=\frac{T\cos\alpha-D}{m}-\frac{\mu\sin\gamma}{r^2}+d_{\rm V}, \tag{1}$$

$$\dot{h}=V\sin\gamma, \tag{2}$$

$$\dot{\gamma}=\frac{L+T\sin\alpha}{mV}-\frac{(\mu-V^2r)\cos\gamma}{Vr^2}+d_{\gamma}, \tag{3}$$

$$\dot{\alpha}=q-\dot{\gamma}, \tag{4}$$

$$\dot{q}=\frac{M_{\rm yy}}{I_{\rm yy}}+d_{\rm q}. \tag{5}$$

The variables in the model of the longitudinal dynamics of the HFVs are listed in Table 1.

Table 1 Aircraft model nomenclature

$C_{\rm T}$	thrust coefficient
$C_{\rm L}$	lift coefficient
$C_{\rm D}$	drag coefficient
$C_{\rm M}(q)$	pitch moment coefficient due to pitch rate
$C_{\rm M}(\alpha)$	pitch moment coefficient due to angle of attack
$C_{\rm M}(\delta_{\rm e})$	pitch moment coefficient due to elevator deflection
$\bar{c}$	reference length
h	altitude
$I_{\rm yy}$	moment of inertia
m	mass
$M_{\rm yy}$	pitching moment
q	pitch rate
$R_{\rm E}$	radius of the Earth
r	radial distance from centre of the Earth
S	reference area
V	velocity
D	drag
T	thrust
L	lift
α	angle of attack
$\beta_{\rm c}$	throttle setting
$\delta_{\rm e}$	elevator deflection
γ	flight-path angle
μ	gravitational constant
ρ	density of air

Where

$$\bar{q}=\frac{1}{2}\rho V^2,\ T=\bar{q}SC_{\rm T},\ L=\bar{q}SC_{\rm L},\ D=\bar{q}SC_{\rm D},$$
$$M_{\rm yy}=\bar{q}S\bar{c}[C_{\rm M}(\alpha)+C_{\rm M}(\delta_{\rm e})+C_{\rm M}(q)],$$
$$r=h+R_{\rm E},\ C_{\rm T}=(1+\Delta C_{\rm T})C_{{\rm T}_0},$$
$$C_{\rm L}=(1+\Delta C_{\rm L})C_{{\rm L}_0},\ C_{\rm D}=(1+\Delta C_{\rm D})C_{{\rm D}_0},$$
$$C_{\rm M}(\alpha)=(1+\Delta C_{\rm M}(\alpha))C_{\rm M}(\alpha)_0,$$
$$C_{\rm M}(\delta_{\rm e})=(1+\Delta C_{\rm M}(\delta_{\rm e}))C_{\rm M}(\delta_{\rm e})_0,$$
$$C_{\rm M}(q)=(1+\Delta C_{\rm M}(q))C_{\rm M}(q)_0.$$

According to [26], $d_i(i=V,\gamma,q)$ are unknown external disturbances. $\Delta C_{\rm T}$, $\Delta C_{\rm L}$, $\Delta C_{\rm D}$, $\Delta C_{\rm M}(\alpha)$, $\Delta C_{\rm M}(\delta_{\rm e})$, $\Delta C_{\rm M}(q)$ are aerodynamic parameter perturbations. The nominal values of the parameters are listed as follows:

$$C_{{\rm T}_0}=\begin{cases}0.02576\beta, & \beta<1,\\ 0.02240+0.003360\beta, & \beta\geqslant 1,\end{cases}$$
$$C_{{\rm L}_0}=0.6203\alpha,$$
$$C_{{\rm D}_0}=0.6450\alpha^2+0.0043378\alpha+0.003772,$$
$$C_{\rm M}(\alpha)_0=-0.035\alpha^2+0.036616\alpha+5.3621\times10^{-6},$$
$$C_{\rm M}(\delta_{\rm e})_0=0.0292\left(\delta_{\rm e}-\alpha\right),$$
$$C_{\rm M}(q)_0=\frac{\bar{c}}{2V}q\left(-6.796\alpha^2+0.3015\alpha-0.2289\right).$$

The engine dynamics can be described as follows:

$$\ddot{\beta}=-2\xi\omega_n\dot{\beta}-\omega_n^2\beta+\omega_n^2\beta_{\rm c}. \tag{6}$$

The model is high nonlinear and inner coupling. In the the longitudinal analytical model (1)–(5), parameters m, μ, $I_{\rm yy}$, ρ, S, $\bar{c}$, $R_{\rm E}$ are modeled with an additive perturbation [26]. In the design process, the bounds of parameters perturbation need to be known, because functions $\varphi_{ij}(i=1,2)$ introduced in (9) should be known.

Assumption 1 γ is very small during the gliding phase, so $\sin\gamma\simeq\gamma$ in (2) for simplification. The thrust term $T\sin\alpha$ is generally much smaller than L, so it can be neglected in (3)[20–21].

2.2 Strict-feedback formulation

A) Velocity subsystem (1) can be rewritten as

$$\begin{cases}\dot{x}_{11}=\phi_{11}(x_{11},x_{22},x_{23},d_{11})+\\ \qquad g_{11}(x_{11},x_{23},d_{11})x_{12},\\ \dot{x}_{12}=\phi_{12}(x_{11},x_{12},d_{12})+g_{12}(d_{12})x_{13},\\ \dot{x}_{13}=\phi_{13}(x_{11},x_{12},x_{13},d_{13})+g_{13}(d_{13})u_1,\\ y_1=x_{11},\end{cases} \tag{7}$$

where

$$x_{11}=V,\ x_{12}=\beta,\ x_{13}=\dot{\beta},$$
$$x_{22}=\gamma,\ x_{23}=\alpha,\ u_1=\beta_{\rm c}.$$

y_1 is the output, and d_{11}, d_{12}, d_{13} are external disturbances of velocity subsystem.

Due to parameter perturbations and external disturbances $d_{11}, d_{12}, d_{13}, \phi_{1j}$ and $g_{1j}(j=1,2,3)$ are nonlinear uncertainties. Ignore the influence of disturbances, the nominal values of ϕ_{1j} and g_{1j} can be described as follows:

$$\phi_{n11}=-(D/m+\mu\sin x_{22}/r^2)+$$
$$\bar{q}S\times0.0224\cos x_{23}/m,$$
$$g_{n11}=\bar{q}S\times0.00336\cos x_{23}/m,\ \beta>1.$$

Otherwise $\phi_{n11}=-(D/m+\mu\sin x_{22}/r^2)$, $g_{n11}=\bar{q}S\times0.02576\cos x_{23}/m$. $\phi_{n12}=0$, $g_{n12}=1$, $\phi_{n13}=-2\xi\omega_nx_{13}-\omega_n^2x_{12}$, $g_{n13}=\omega_n^2$ with uncertain parameters defined above.

B) With Assumption 1, the dynamics of altitude subsystem (2)–(5) can be written as

$$\begin{cases}\dot{x}_{21} = \phi_{21}(x_{21}, d_{21}) + g_{21}(x_{11}, d_{21})x_{22},\\ \dot{x}_{22} = \phi_{22}(x_{21}, x_{22}, x_{11}, d_{22})+\\ \qquad g_{22}(x_{11}, d_{22})x_{23},\\ \dot{x}_{23} = \phi_{23}(x_{21}, x_{22}, x_{23}, x_{11}, d_{23})+\\ \qquad g_{23}(d_{23})x_{24},\\ \dot{x}_{24} = \phi_{24}(x_{21}, x_{22}, x_{23}, x_{24}, x_{11}, d_{24})+\\ \qquad g_{24}(x_{11}, d_{24})u_2,\\ y_2 = x_{21},\end{cases} \tag{8}$$

where $x_{21} = h$, $x_{24} = q$, $u_2 = \delta_{\rm e}$. y_2 is the output, and d_{21}, d_{22}, d_{23} are external disturbances of altitude subsystem.

Similarly, ϕ_{2j} and $g_{2j}(j = 1, 2, 3, 4)$ are nonlinear uncertainties. Ignore the influence of disturbances, the nominal values of ϕ_{2j} and g_{2j} are as follows: $\phi_{n21} = 0$, $g_{n21}{=}x_{11}$, $\phi_{n22}{=}-(\mu-x_{11}^2 r)\cos x_{22}/(x_{11}r^2)$, $g_{n22}{=}0.6203\bar{q}S/(mx_{11})$, $\phi_{n23} = (\mu-x_{11}^2 r)\cos x_{22}/(x_{11}r^2)$ $-0.6203\bar{q}Sx_{23}/(mx_{11})$, $g_{n23}{=}1$, $\phi_{n24}{=}\bar{q}S\bar{c}[C_{\rm M}(\alpha)$ $+C_{\rm M}(q) - 0.0292\alpha]/I_{\rm yy}$, $g_{n24} = 0.0292\bar{q}S\bar{c}/I_{\rm yy}$ with uncertain parameters defined above.

$x(t){=}[x_{11}(t)\ x_{12}(t)\ x_{13}(t)\ x_{21}(t)\ x_{22}(t)\ x_{23}(t)$ $x_{24}(t)]^{\rm T}$ is the state vector of the system, $u(t) = [u_1(t)$ $u_2(t)]^{\rm T}$ is the control input vector, $y(t) = [y_1\ \ y_2]^{\rm T}$ is the output vector, $d(t){=}[d_{11}(t)\ d_{12}(t)\ d_{13}(t)\ d_{21}(t)$ $d_{22}(t)\ d_{23}(t)\ d_{24}(t)]^{\rm T}$ is the external disturbance vector, $y_{\rm d}(t) = [y_{\rm d1}\ \ y_{\rm d2}]^{\rm T}$ is the reference output vector.

Assumption 2 There are positive constants η_1 and η_2 such that reference output $|y_{{\rm d}i}(t)| \leqslant \eta_1$ and $|\dot{y}_{{\rm d}i}(t)| \leqslant \eta_2 (i = 1, 2)$.

Assumption 3 There is a positive constant η_3 such that the external disturbance vector $\|d(t)\| \leqslant \eta_3$.

Remark 1 $\phi_{ij}(x, d_{ij})$ and $g_{ij}(x, d_{ij})$ are unknown non-continues nonlinear functions caused by parameter perturbations, external disturbances and aerodynamic influences. According to (7) and (8), there are known nonnegative-valued functions $\varphi_{ij}(x, \eta_3)$, such that $|\phi_{ij}(x, d_{ij})| \leqslant \varphi_{ij}(x, \eta_3)$. That is

$$\begin{cases}|\phi_{11}(x_{11}, x_{22}, x_{23}, d_{11})| \leqslant \varphi_{11}(x_{11}, x_{22}, x_{23}, \eta_3),\\ |\phi_{12}(x_{11}, x_{12}, d_{12})| \leqslant \varphi_{12}(x_{11}, x_{12}, \eta_3),\\ |\phi_{13}(x_{11}, x_{12}, x_{13}, d_{13})| \leqslant \varphi_{13}(x_{11}, x_{12}, x_{13}, \eta_3),\\ |\phi_{21}(x_{21}, d_{21})| \leqslant \varphi_{21}(x_{21}, \eta_3),\\ |\phi_{22}(x_{21}, x_{22}, x_{11}, d_{22})| \leqslant \varphi_{22}(x_{21}, x_{22}, x_{11}, \eta_3),\\ |\phi_{23}(x_{21}, x_{22}, x_{23}, x_{11}, d_{23})| \leqslant\\ \varphi_{23}(x_{21}, x_{22}, x_{23}, x_{11}, \eta_3),\\ |\phi_{24}(x_{21}, x_{22}, x_{23}, x_{24}, x_{11}, d_{24})|\\ \leqslant \varphi_{24}(x_{21}, x_{22}, x_{23}, x_{24}, x_{11}, \eta_3),\end{cases} \tag{9}$$

where $\varphi_{ij}(x, \eta_3)(i = 1, 2)$ are known functions. From hypersonic vehicle model (7) and (8), one has that $g_{ij}(x, d_{ij}) \geqslant g_{ijN}(t) > 0$.

For simplicity of statement, in the sequel, $\phi_{ij}(x, d_{ij})$, $g_{ij}(x, d_{ij})$ will be denoted as $\phi_{ij}(t)$, $g_{ij}(t)$, respectively.

The control object is to design the robust controller for systems (7) and (8) such that:

1) all the states in the closed-loop systems remain bounded;

2) the tracking error $\|y(t) - y_{\rm d}(t)\|$ can be made as small as desired with expected convergence rate.

3 Robust control of hypersonic flight vehicles

In this section, the design procedure of robust backstepping method for the ith subsystem is presented. For the ith subsystem of (7) and (8), the controller design procedure contains ρ_i steps. At each backstepping step, the subsystem is divided into a nominal model and the equivalent disturbance. A nominal controller is designed to stabilize the nominal model, and a robust compensator is designed to suppress the effects of the equivalent disturbance.

Step 1 The tracking error variable of the ith subsystem is defined as $z_{i1}(t) = x_{i1}(t) - y_{{\rm d}i}(t)$. Then one has that

$$\dot{z}_{i1}(t) = g_{i1}(t)x_{i2}(t) + \tilde{\phi}_{i1}(t), \tag{10}$$

where $\tilde{\phi}_{i1}(t) = \phi_{i1}(t) - \dot{y}_{{\rm d}i}(t)$. By viewing $x_{i2}(t)$ as a virtual control input, design the virtual feedback control law as

$$\hat{x}_{i2}(t) = -\frac{\alpha_{i1}}{g_{i1N}(t)}z_{i1}(t) + \frac{f_{i1}}{g_{i1N}(t)}w_{i1}(t), \tag{11}$$

where α_{i1} is a positive constant to be designed later.

Define $z_{i2}(t) = x_{i2}(t) - \hat{x}_{i2}(t)$, one has

$$\dot{z}_{i1}(t) = -\alpha_{i1}z_{i1}(t) + \hat{\phi}_{i1}(t) + f_{i1}w_{i1}(t), \tag{12}$$

where $\hat{\phi}_{i1}(t) = \tilde{\phi}_{i1}(t) + g_{i1N}(t)z_{i2}(t) + [g_{i1}(t) - g_{i1N}(t)]x_{i2}(t)$, which is viewed as the equivalent disturbance. To obtain robust tracking property, the robust virtual compensating signal is designed as follows:

$$w_{i1}(t) = -\frac{1}{s + f_{i1}}\hat{\phi}_{i1}(t). \tag{13}$$

From (12), one has

$$\hat{\phi}_{i1}(t) = (s + \alpha_{i1})z_{i1}(t) - f_{i1}w_{i1}(t). \tag{14}$$

From (13) and (14), $w_{i1}(t)$ can be expressed as

$$w_{i1}(t) = -(1 + \frac{\alpha_{i1}}{s})z_{i1}(t). \tag{15}$$

Remark 2 Dynamic surface control (DSC) method and signal compensation method were typical techniques to solve the problem of "explosion of complexity"[36–37]. The nonlinear functions were required to be smooth within DSC technique[37]. The signal compensation method aims to design a robust compensator to approximate and restrain the effect of nonlinear uncertainties, which are not required to be continuous[36]. If f_{i1} is sufficiently large, the robust compensator f_{i1} w_{i1} would approximate and weaken the effects of the equivalent disturbance $\hat{\phi}_{i1}(t)$ to achieve robust tracking property.

Step $j(2 \leqslant j < \rho_i)$ Define $z_{ij}(t) = x_{ij}(t) - \hat{x}_{ij}(t)$. Then one has an error subsystem

$$\begin{aligned}\dot{z}_{ij}(t) = g_{ij}(t)x_{i(j+1)}(t) + \phi_{ij}(t) - \dot{\hat{x}}_{ij}(t) = \\ g_{ij}(t)x_{i(j+1)}(t) + \tilde{\phi}_{ij}(t),\end{aligned} \tag{16}$$

where

$$\begin{aligned}\hat{x}_{ij}(t) = &-\frac{\alpha_{i(j-1)}}{g_{i(j-1)N}(t)}z_{i(j-1)}(t)+ \\ &\frac{f_{i(j-1)}}{g_{i(j-1)N}(t)}w_{i(j-1)}(t), \\ \tilde{\phi}_{ij}(t) = \phi_{ij}(t) &- \frac{\alpha^2_{i(j-1)}}{g_{i(j-1)N}(t)}z_{i(j-1)}(t)+ \\ &\frac{f_{i(j-1)} + \alpha_{i(j-1)}}{g_{i(j-1)N}(t)}[\hat{\phi}_{i(j-1)}(t)+ \\ &f_{i(j-1)}w_{i(j-1)}(t)].\end{aligned}$$

A virtual control input $x_{i(j+1)}(t)$ is constructed to stabilize the jth error subsystem

$$\hat{x}_{i(j+1)}(t) = -\frac{\alpha_{ij}}{g_{ijN}(t)}z_{ij}(t) + \frac{f_{ij}}{g_{ijN}(t)}w_{ij}(t), \tag{17}$$

then

$$\dot{z}_{ij}(t) = -\alpha_{ij}z_{ij}(t) + \hat{\phi}_{ij}(t) + f_{ij}w_{ij}(t),$$

where

$$\begin{aligned}\hat{\phi}_{ij}(t) = \tilde{\phi}_{ij}(t) + [g_{ij}(t) - g_{ijN}(t)]\, x_{i(j+1)}(t) + \\ g_{ijN}(t)z_{i(j+1)}(t).\end{aligned}$$

The robust virtual compensating signal is designed as follows:

$$w_{ij}(t) = -\frac{1}{s+f_{ij}}\hat{\phi}_{ij}(t).$$

Note that $\hat{\phi}_{ij}(t) = (s + \alpha_{ij})z_{ij}(t) - f_{ij}w_{ij}(t)$, $w_{ij}(t)$ can be expressed as

$$w_{ij}(t) = -(1 + \frac{\alpha_{ij}}{s})z_{ij}(t). \tag{18}$$

Step ρ_i Define $z_{i\rho_i}(t) = x_{i\rho_i}(t) - \hat{x}_{i\rho_i}(t)$. Its derivative is

$$\begin{aligned}\dot{z}_{i\rho_i}(t) = g_{i\rho_i}(t)u_i(t) + \phi_{i\rho_i}(t) - \dot{\hat{x}}_{i\rho_i}(t) = \\ g_{i\rho_i}(t)u_i(t) + \tilde{\phi}_{i\rho_i}(t),\end{aligned} \tag{19}$$

where

$$\begin{aligned}\hat{x}_{i\rho_i}(t) = &-\frac{\alpha_{i(\rho_i-1)}}{g_{i(\rho_i-1)N}(t)}z_{i(\rho_i-1)}(t) + \\ &\frac{f_{i(\rho_i-1)}}{g_{i(\rho_i-1)N}(t)}w_{i(\rho_i-1)}(t), \\ \tilde{\phi}_{i\rho_i}(t) = \phi_{i\rho_i}(t) &- \frac{\alpha^2_{i(\rho_i-1)}}{g_{i(\rho_i-1)N}(t)}z_{i(\rho_i-1)}(t) + \\ &\frac{f_{i(\rho_i-1)} + \alpha_{i(\rho_i-1)}}{g_{i(\rho_i-1)N}(t)}[\hat{\phi}_{i(\rho_i-1)}(t) + \\ &f_{i(\rho_i-1)}w_{i(\rho_i-1)}(t)].\end{aligned}$$

The real control input $u_i(t)$ for ith subsystem is constructed as

$$u_i(t) = -\frac{\alpha_{i\rho_i}}{g_{i\rho_iN}(t)}z_{i\rho_i}(t) + \frac{f_{i\rho_i}}{g_{i\rho_iN}(t)}w_{i\rho_i}(t). \tag{20}$$

Similarly, the robust virtual compensating signal $w_{i\rho_i}(t)$ is designed as

$$\begin{aligned}w_{i\rho_i}(t) = -\frac{1}{s+f_{i\rho_i}}\hat{\phi}_{i\rho_i}(t) = \\ -(1+\frac{\alpha_{i\rho_i}}{s})z_{i\rho_i}(t),\end{aligned} \tag{21}$$

where

$$\hat{\phi}_{i\rho_i}(t) = \tilde{\phi}_{i\rho_i}(t) + [g_{i\rho_i}(t) - g_{i\rho_iN}(t)]\, u_i(t).$$

The whole controller can be described as

$$\begin{cases} u_i(t) = -\dfrac{\alpha_{i\rho_i}}{g_{i\rho_iN}(t)}z_{i\rho_i}(t) + \dfrac{f_{i\rho_i}}{g_{i\rho_iN}(t)}w_{i\rho_i}(t), \\ z_{i1}(t) = x_{i1}(t) - y_{\mathrm{d}i}(t), \\ z_{ij}(t) = x_{ij}(t) + \dfrac{\alpha_{i(j-1)}}{g_{i(j-1)N}(t)}z_{i(j-1)}(t) - \\ \qquad \dfrac{f_{i(j-1)}}{g_{i(j-1)N}(t)}w_{i(j-1)}(t), \\ \qquad j = 2, 3, \cdots, \rho_i, \\ w_{ij}(t) = -(1+\dfrac{\alpha_{ij}}{s})z_{ij}(t),\ j = 1, 2, \cdots, \rho_i, \\ i = 1, 2. \end{cases} \tag{22}$$

Remark 3 From equation (22), one has that the controller is decentralized. The whole designed controller is linear time-invariant, and can be realized easily.

4 Robust property

At the beginning of this section, several Lemmas are introduced firstly.

Lemma 1 $\phi_{ij}(t)(i = 1, 2; j = 1, 2, \cdots, \rho_i)$ satisfy that

$$\begin{aligned}&|\phi_{11}(t)| \leqslant \widetilde{\varphi}_{11}(\|z\|, \|w\|, \eta_1, \eta_3, f_{21}, f_{22}), \\ &|\phi_{12}(t)| \leqslant \widetilde{\varphi}_{12}(\|z\|, \|w\|, \eta_1, \eta_3, f_{11}, f_{21}, f_{22}), \\ &|\phi_{13}(t)| \leqslant \widetilde{\varphi}_{13}(\|z\|, \|w\|, \eta_1, \eta_3, f_{11}, f_{12}, f_{21}, f_{22}), \\ &|\phi_{21}(t)| \leqslant \widetilde{\varphi}_{21}(\|z\|, \|w\|, \eta_1, \eta_3), \\ &|\phi_{22}(t)| \leqslant \widetilde{\varphi}_{22}(\|z\|, \|w\|, \eta_1, \eta_3, f_{21}), \\ &|\phi_{23}(t)| \leqslant \widetilde{\varphi}_{23}(\|z\|, \|w\|, \eta_1, \eta_3, f_{21}, f_{22}), \\ &|\phi_{24}(t)| \leqslant \widetilde{\varphi}_{24}(\|z\|, \|w\|, \eta_1, \eta_3, f_{21}, f_{22}, f_{23}),\end{aligned}$$

where $\widetilde{\varphi}_{ij}$ are known nonnegative functions.

Proof From the definitions of z_{ij} it follows that

$$\begin{bmatrix} x_{i1}(t) \\ x_{i2}(t) \\ \vdots \\ x_{i\rho_i}(t) \end{bmatrix} = \begin{bmatrix} z_{i1}(t) \\ z_{i2}(t) \\ \vdots \\ z_{i\rho_i}(t) \end{bmatrix} - \begin{bmatrix} 0 \\ \dfrac{\alpha_{i1}}{g_{i1N}(t)}z_{i1}(t) \\ \vdots \\ \dfrac{\alpha_{i(\rho_i-1)}}{g_{i(\rho_i-1)N}(t)}z_{i(\rho_i-1)}(t) \end{bmatrix} +$$

$$\begin{bmatrix} 0 \\ \dfrac{f_{i1}}{g_{i1N}(t)}w_{i1}(t) \\ \vdots \\ \dfrac{f_{i(\rho_i-1)}}{g_{i(\rho_i-1)N}(t)}w_{i(\rho_i-1)}(t) \end{bmatrix} + \begin{bmatrix} y_{\mathrm{d}i}(t) \\ 0 \\ \vdots \\ 0 \end{bmatrix}.$$

From dynamic model (7) and (8) and controller (22), the conclusions of Lemma 1 hold.

Let

$$\psi_{ij}(t) = \hat{\phi}_{ij}(t) - [\frac{g_{ij}(t)}{g_{ijN}(t)} - 1]f_{ij}w_{ij}(t).$$

Lemma 2 For $\psi_{ij}(t)(i = 1,2; j = 1,2,\cdots,\rho_i - 1)$, the following inequalities hold:

$$|\psi_{11}(t)| \leqslant \hat{\varphi}_{11}(\|z\|, \|w\|, \eta_1, \eta_2, \eta_3, f_{21}, f_{22}),$$
$$|\psi_{12}(t)| \leqslant \hat{\varphi}_{12}(\|z\|, \|w\|, \eta_1, \eta_2, \eta_3, f_{11}, f_{21}, f_{22}),$$
$$|\psi_{13}(t)| \leqslant \hat{\varphi}_{12}(\|z\|, \|w\|, \eta_1, \eta_2, \eta_3, f_{11}, f_{12}, f_{21}, f_{22}),$$
$$|\psi_{21}(t)| \leqslant \hat{\varphi}_{21}(\|z\|, \|w\|, \eta_1, \eta_2, \eta_3),$$
$$|\psi_{22}(t)| \leqslant \hat{\varphi}_{22}(\|z\|, \|w\|, \eta_1, \eta_2, \eta_3, f_{21}),$$
$$|\psi_{23}(t)| \leqslant \hat{\varphi}_{23}(\|z\|, \|w\|, \eta_1, \eta_2, \eta_3, f_{21}, f_{22}),$$
$$|\psi_{24}(t)| \leqslant \hat{\varphi}_{24}(\|z\|, \|w\|, \eta_1, \eta_2, \eta_3, f_{21}, f_{22}, f_{23}),$$

where $\hat{\varphi}_{ij}$ are known nonnegative functions.

Proof From the definition of $\hat{\phi}_{ij}(t)$ and $\psi_{ij}(t)$ $(i = 1,2)$, and from (22), one has that

$$\begin{aligned}
\psi_{i1}(t) = {} & g_{i1}(t)z_{i2}(t) - \alpha_{i1}[\frac{g_{i1}(t)}{g_{i1N}(t)} - 1]z_{i1}(t) + \\
& \phi_{i1}(t) - \dot{y}_{\mathrm{d}i}(t), \\
\psi_{ij}(t) = {} & g_{ij}(t)z_{i(j+1)}(t) - \\
& \alpha_{ij}[\frac{g_{ij}(t)}{g_{ijN}(t)} - 1]z_{ij}(t) + \phi_{ij}(t) + \\
& \frac{f_{i(j-1)}(f_{i(j-1)} + \alpha_{i(j-1)})}{g^2_{i(j-1)N}(t)} \times \\
& g_{i(j-1)}(t)w_{i(j-1)}(t) - \frac{\alpha^2_{ij}}{g_{i(j-1)N}(t)}z_{i(j-1)} + \\
& \frac{f_{i(j-1)} + \alpha_{i(j-1)}}{g_{i(j-1)N}(t)}\psi_{i(j-1)}(t), \\
\psi_{i\rho_i}(t) = {} & -\alpha_{i\rho_i}[\frac{g_{i\rho_i}(t)}{g_{i\rho_iN}(t)} - 1]z_{i\rho_i}(t) - \\
& \frac{\alpha^2_{i\rho_i-1}}{g_{i(\rho_i-1)N}(t)}z_{i(\rho_i-1)} + \\
& \frac{f_{i(\rho_i-1)}(f_{i(\rho_i-1)} + \alpha_{i(\rho_i-1)})}{g^2_{i(\rho_i-1)N}(t)} \times \\
& g_{i(\rho_i-1)}(t)w_{i(\rho_i-1)}(t) + \phi_{i\rho_i}(t) + \\
& \frac{f_{i(\rho_i-1)} + \alpha_{i(\rho_i-1)}}{g_{i(\rho_i-1)N}(t)}\psi_{i(\rho_i-1)}(t)
\end{aligned}$$

From Lemma 1, the conclusions of Lemma 2 hold. QED.

Lemma 3 For any given positive constant ε_ϕ, if positive constants f_{ij} satisfy the inequalities $f_{i(j+1)} \gg f_{ij}$, and $f_{11} \gg f_{22}$, then

$$\sum_{i=1}^{2}\sum_{j=1}^{\rho_i}\frac{\psi^2_{ij}(t)}{f_{ij}} \leqslant \varepsilon_\phi\bar{\varphi}(\|z\|, \|w\|)(\|z\|^2 + \|w\|^2 + 1), \tag{23}$$

where $\bar{\varphi}(\|z\|, \|w\|)$ is a nonnegative function.

Proof According to Lemma 2, for any positive constant ε_{ij}, there exist sufficiently large positive constants f_{ij}, such that if the inequalities $f_{i(j+1)} \gg f_{ij}$, and $f_{11} \gg f_{22}$ hold, then

$$\frac{\psi^2_{ij}(t)}{f_{ij}} \leqslant \varepsilon_{ij}\bar{\varphi}(\|z\|, \|w\|)(\|z\|^2 + \|w\|^2 + 1).$$

Choose $\varepsilon_\phi = \sum\limits_{i=1}^{2}\sum\limits_{j=1}^{\rho_i}\varepsilon_{ij}$, then the conclusions of Lemma 3 hold. QED.

Theorem 1 Under Assumption 1–3, the closed-loop system has semi-global robust tracking property, that is, for any constants $\varepsilon > 0$, $r_z \geqslant 0$ and $r_w \geqslant 0$, if $\|z(t_0)\| \leqslant r_z$, $\|w(t_0)\| \leqslant r_w$, there exist sufficiently large constants $f_{ij}(i = 1,2)$ and constant $T \geqslant t_0$, such that if $f_{i(j+1)} \gg f_{ij}$, and $f_{11} \gg f_{22}$ the states $x(t)$, $z(t)$ and $w(t)$ are bounded and, moreover

$$\|z(t)\| \leqslant \varepsilon,\ \|w(t)\| \leqslant \varepsilon,\ t \geqslant T.$$

If the initial values $z(t_0)$ and $w(t_0)$ are zero, then

$$\|z(t)\| \leqslant \varepsilon,\ \|w(t)\| \leqslant \varepsilon,\ t \geqslant t_0.$$

Proof Consider the following Lyapunov function candidate:

$$V = \sum_{i=1}^{2}\sum_{j=1}^{\rho_i}V_{ij},$$

where

$$V_{ij} = [z_{ij}(t)\ \ w_{ij}(t)]\,P\begin{bmatrix} z_{ij}(t) \\ w_i(t) \end{bmatrix},\ P = \begin{bmatrix} 1 & 1 \\ 1 & 2 \end{bmatrix}.$$

From Lemma 3, by taking the time derivative of V along the trajectories of the closed-loop system, one obtains that

$$\begin{aligned}
& \dot{V} = \sum_{i=1}^{2}\sum_{j=1}^{\rho_i}\dot{V}_{ij} = \\
& -\sum_{i=1}^{2}\sum_{j=1}^{\rho_i}2\{\alpha_{ij}z^2_{ij}(t) + \alpha_{ij}z_{ij}(t)w_{ij}(t) + \\
& f_{ij}w^2_{ij}(t) + w_{ij}(t)\hat{\phi}_{ij}(t)\} = \\
& -\sum_{i=1}^{2}\sum_{j=1}^{\rho_i}\{\alpha_{ij}V_{ij} + \alpha_{ij}z^2_{ij}(t) + 2w_{ij}(t)\psi_{ij}(t) + \\
& 2[\frac{g_{ij}(t)}{g_{ijN}(t)}f_{ij} - \alpha_{ij}]w^2_{ij}(t)\} \leqslant \\
& -\sum_{i=1}^{2}\sum_{j=1}^{\rho_i}\{\alpha_{ij}V_{ij} + \alpha_{ij}z^2_{ij}(t) - \frac{\psi^2_{ij}(t)}{f_{ij}} + \\
& (f_{ij} - 2\alpha_{ij})w^2_{ij}(t)\} \leqslant
\end{aligned}$$

$$-\underline{\alpha}V-\underline{\alpha}\|z(t)\|^2-(\underline{f}-2\bar{\alpha})\|w(t)\|^2+$$
$$\varepsilon_\phi\bar{\varphi}(\|z(t)\|,\|w(t)\|)(\|z(t)\|^2+\|w(t)\|^2+1),$$

where

$$\underline{\alpha}=\min_{1\leqslant i\leqslant 2,\ 1\leqslant j\leqslant \rho_i}\{\alpha_{ij}\},$$
$$\bar{\alpha}=\max_{1\leqslant i\leqslant 2,\ 1\leqslant j\leqslant \rho_i}\{\alpha_{ij}\},$$
$$\underline{f}=\min_{1\leqslant i\leqslant 2,\ 1\leqslant j\leqslant \rho_i}\{f_{ij}\}.$$

Consider a set $\Omega(r_{\rm a},r_{\rm b})$ in $\mathbb{R}^{2n}$ defined as

$$\Omega(r_{\rm a},r_{\rm b})=$$
$$\{\begin{pmatrix}z(t)\\w(t)\end{pmatrix}|r_{\rm b}\leqslant V\leqslant r_{\rm a},z(t)\in\mathbb{R}^n,w(t)\in\mathbb{R}^n\}.$$

Let $\chi=\max_{(z,w)\in\Omega(r_{\rm a},r_{\rm b})}\bar{\varphi}(\|z\|,\|w\|)$. Choosing $\underline{f}$ and ε_ϕ satisfying

$$\underline{f}>2\bar{\alpha}+\frac{\underline{\alpha}}{2} \tag{24}$$

and

$$\varepsilon_\phi\leqslant\min\{\frac{\underline{\alpha}r_{\rm b}}{2\chi\lambda_{\rm p2}},\frac{\underline{\alpha}}{2\chi},\frac{\underline{f}-2\bar{\alpha}-\frac{\underline{\alpha}}{2}}{\chi}\}, \tag{25}$$

respectively, where $\lambda_{\rm p2}=\lambda_{\max}(P)$, then for any $\begin{pmatrix}z(t)\\w(t)\end{pmatrix}\in\Omega(r_{\rm a},r_{\rm b})$, one has

$$\underline{\alpha}\|z(t)\|^2+(\underline{f}-2\bar{\alpha})\|w(t)\|^2-$$
$$\varepsilon_\phi\bar{\varphi}(\|z(t)\|,\|w(t)\|)(\|z(t)\|^2+\|w(t)\|^2+1)=$$
$$\frac{\underline{\alpha}}{2}\|z(t)\|^2+\frac{\underline{\alpha}}{2}\|w(t)\|^2-\varepsilon_\phi\bar{\varphi}(\|z(t)\|,\|w(t)\|)+$$
$$\frac{\underline{\alpha}}{2}\|z(t)\|^2(1-\frac{2\varepsilon_\phi\bar{\varphi}(\|z(t)\|,\|w(t)\|)}{\underline{\alpha}})+$$
$$(\underline{f}-2\bar{\alpha}-\frac{\underline{\alpha}}{2})\|w(t)\|^2(1-\frac{\varepsilon_\phi\bar{\varphi}(\|z(t)\|,\|w(t)\|)}{\underline{f}-2\bar{\alpha}-\frac{\underline{\alpha}}{2}})\geqslant$$
$$\frac{\underline{\alpha}}{2\lambda_{\rm p2}}V(t)-\varepsilon_\phi\chi+\frac{\underline{\alpha}}{2}\|z(t)\|^2(1-\frac{2\varepsilon_\phi\chi}{\underline{\alpha}})+$$
$$(\underline{f}-2\bar{\alpha}-\frac{\underline{\alpha}}{2})\|w(t)\|^2(1-\frac{\varepsilon_\phi\chi}{\underline{f}-2\bar{\alpha}-\frac{\underline{\alpha}}{2}})\geqslant 0.$$

Therefore, for any given constants $\varepsilon>0$, $r_z\geqslant 0$ and $r_w\geqslant 0$, if choose $r_{\rm b}=\lambda_{\rm p1}\varepsilon^2$ with $\lambda_{\rm p1}=\lambda_{\min}(P)$ and $r_{\rm a}\geqslant\max\{r_{\rm b},\lambda_{\rm p2}(r_z^2+r_w^2)\}$, then $V(t_0)\leqslant r_{\rm a}$, and one can find sufficiently large positive constant $\underline{f}$ satisfying inequality (24) and sufficiently small positive constant ε_ϕ satisfying inequality (25) such that

$$\dot{V}(t)\leqslant-\underline{\alpha}V(t),\ \forall\begin{pmatrix}z(t)\\w(t)\end{pmatrix}\in\Omega(r_{\rm a},r_{\rm b}), \tag{26}$$

which implies that $z(t)$ and $w(t)$ are bounded, and converge exponentially to the following domain and stay in it

$$\{\begin{pmatrix}z(t)\\w(t)\end{pmatrix}\|z(t)\|\leqslant\varepsilon,\|w(t)\|\leqslant\varepsilon\}.$$

From above analysis it follows that for any given constants $\varepsilon>0$, $r_z\geqslant 0$ and $r_w\geqslant 0$, if $\|z(t_0)\|\leqslant r_z$, $\|w(t_0)\|\leqslant r_w$, one can find sufficiently large constants $f_{ij}(i=1,2)$ and positive constant $T\geqslant t_0$, such that if $f_{i(j+1)}\gg f_{ij}$ and $f_{11}\gg f_{22}$, then $z(t)$, $w(t)$ and $x(t)$ are bounded, and $\|z(t)\|\leqslant\varepsilon$, $\|w(t)\|\leqslant\varepsilon$, $t\geqslant T$. If the initial values $z(t_0)$ and $w(t_0)$ are zero, then $\|z(t)\|\leqslant\varepsilon$, $\|w(t)\|\leqslant\varepsilon$, $t\geqslant t_0$. QED.

Remark 4 The reference output vector $y_{\rm d}(t)$ could be non-smooth. The uncertain nonlinearities $g_{ij}(t)$ and $\phi_{ij}(t)$ are not required to be continuous. The tracking error can be made as small as expected by choosing robust controller parameters appropriately.

5 Simulation results

To verify the tracking performance of the proposed robust controller for the generic hypersonic vehicle, the same controller is applied to the longitudinal dynamic model of HFVs in two different cases with both parameter uncertainties and external disturbances. The robust controller is constructed by equation (22) with expected convergence rate $\alpha_{ij}=0.5(i=1,2)$ and robust controller parameters $f_{11}=300$, $f_{12}=600$, $f_{13}=8000$, $f_{21}=100$, $f_{22}=100$, $f_{23}=300$, $f_{24}=600$. For simulation, the initial values of the states are set as $v_0=7850$ ft/s, $h_0=86000$ ft, $\alpha_0=0.0659$ rad, $\gamma_0=0$, $q_0=0$[38]. The nominal values of the parameters are listed as follows[26]:

$$m=9375\text{ slugs},\ \mu=1.39\times10^{16}\text{ ft}^3/\text{s}^2,$$
$$I_{\rm yy}=7\times10^6\text{ slugs}\cdot\text{ft}^2,$$
$$\rho=0.24325\times10^{-4}\text{ slugs/ft}^3,$$
$$S=3603\text{ ft}^2,\ \bar{c}=80\text{ ft},$$
$$R_{\rm E}=20903500\text{ ft}.$$

The tracking commands of velocity varies from 7850 ft/s to 8250 ft/s, while altitude varies from 86000 ft to 87000 ft.

Case 1 The uncertain parameters (m, μ, $I_{\rm yy}$, ρ, S, $\bar{c}$, $R_{\rm E}$) are set to be 20% additive perturbations of nominal values. The external disturbances are considered and taken as $d_{ij}=(i+j)\sin(\pi t/(i+j))(i=1,2)$. The tracking curves and the steady state tracking error of the velocity and altitude are plotted in Figs. 1–4.

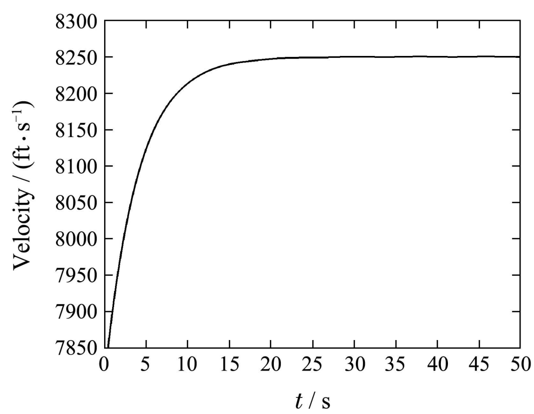

Fig. 1 Velocity tracking curve

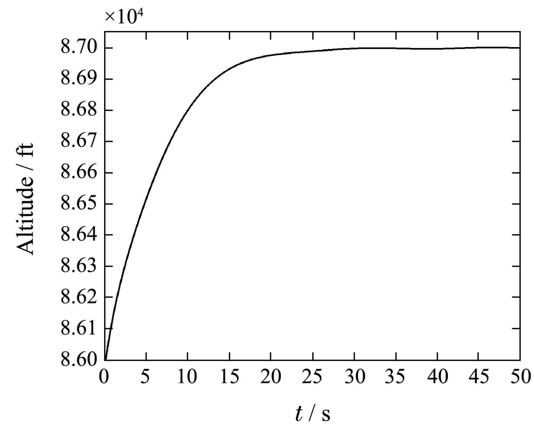

Fig. 2 Altitude tracking curve

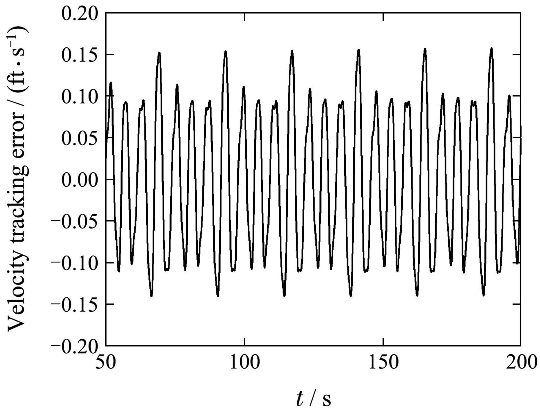

Fig. 3 Steady state tracking error of velocity

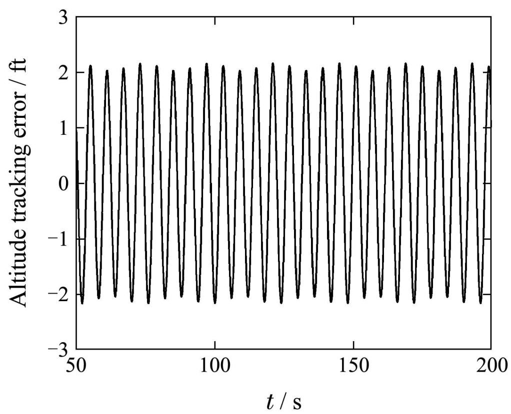

Fig. 4 Steady state tracking error of altitude

Case 2 The uncertain parameters (m, μ, $I_{\rm yy}$, ρ, S, $\bar{c}$, $R_{\rm E}$) are subject to -20% additive perturbations of nominal values. The external disturbances are

$$d_{1j}=\begin{cases}0, & 0\leqslant t<20,\\ 5(t-20), & 20\leqslant t<40,\\ -\dfrac{5}{7}(t-60)+100, & 40\leqslant t,\end{cases}$$
$$j=1,2,3,$$
$$d_{2j}=(2+j)\sin(\pi t/(2+j)),\ j=1,2,3,4.$$

The tracking curves and the steady state tracking error of the closed-loop system are plotted in Figs. 5–8.

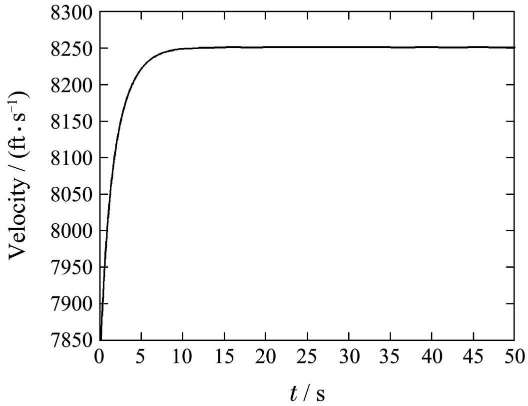

Fig. 5 Velocity tracking curve

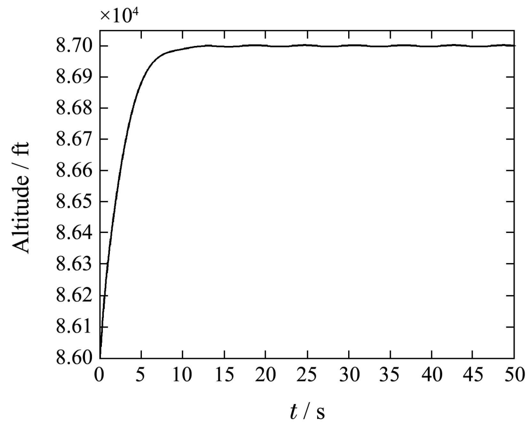

Fig. 6 Altitude tracking curve

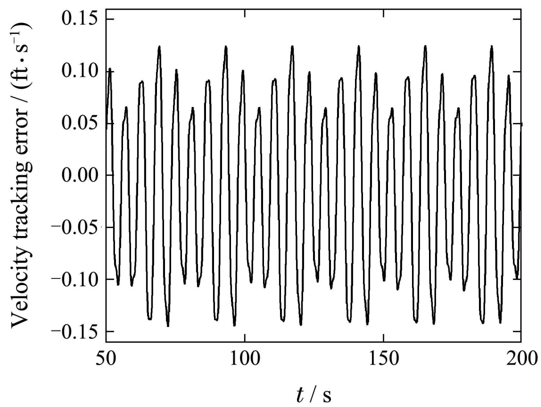

Fig. 7 Steady state tracking error of velocity

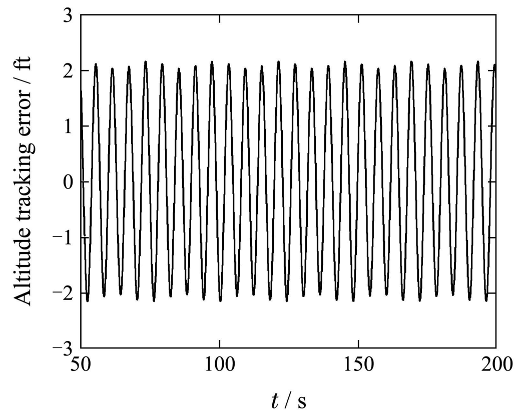

Fig. 8 Steady state tracking error of altitude

The same robust controller is applied to the HFVs under different flight conditions. From the simulation results, it is obvious that the proposed robust control method could achieve excellent robust tracking performance with nonlinear uncertainties, external disturbances and strongly coupled interconnections.

6 Conclusions

In this paper, a "simple" robust controller is applied to deal with the control problem of HFVs. The problem is challenging due to the uncertain MIMO nonlinear model with uncertainties, disturbances, and the couplings among the subsystems. By combining backstepping technology with signal compensation method, the proposed controller can ensure the robust s practical tracking property of the closed-loop system and guarantee the tracking error as small as desired with expected convergence rate. Finally, simulation results are given to verify the effectiveness of of the proposed robust controller.

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作者简介:

王　晴　(1990–), 女, 博士研究生, 目前研究方向为多智能体系统协同控制, E-mail: sunnyqing1020@163.com;

余　瑶　(1982–), 女, 副教授, 目前研究方向为鲁棒控制、智能控制理论与方法, E-mail: yuyao@ustb.edu.cn;

孙长银　(1975–), 男, 教授, 目前研究方向为人工智能、神经网络、智能控制理论与方法, E-mail: cysun@seu.edu.cn.