

非线性干扰观测器的高超声速飞行器自适应反演控制*

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摘要:针对高超声速飞行器参数不确定弹性体模型,提出了一种基于非线性干扰观测器的自适应反演控制器设计方法。将曲线拟合模型表示为严格反馈形式,采用反演方法设计控制器。采用动态面方法获取虚拟控制量的导数,避免了传统反演控制“微分项膨胀”问题。为了增强控制器的鲁棒性,基于二阶跟踪-微分器设计了一种新型非线性干扰观测器,以此对模型不确定项进行自适应估计和补偿。仿真结果表明,控制器对模型不确定性和气动弹性影响具有强鲁棒性,且能实现对速度和高度参考指令的稳定跟踪。

关键词:高超声速飞行器;自适应反演控制;动态面;二阶跟踪-微分器;非线性干扰观测器

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Adaptive backstepping control of hypersonic vehicles based on nonlinear disturbance observer

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Abstract: An adaptive backstepping controller based on nonlinear disturbance observer was designed to solve the problem of parameters uncertainty in elastomer model of hypersonic vehicles. The curve-fitted model was expressed as strict feedback form and the method of backstepping was used to design the controller. Dynamic surface method was introduced to obtain the derivatives of virtual control amount, which avoided the explosion of differentiation terms in the traditional backstepping control. In order to enhance the controller's robustness, a new nonlinear disturbance observer which was based on second order tracking-differentiator was introduced to estimate and compensate the model uncertainties adaptively. Simulation results demonstrate that the controller has high robustness to the model uncertainties and aerodynamics and it can track the reference instructions of velocity and altitude steadily.

Key words: hypersonic vehicles; adaptive backstepping control; dynamic surface; second order tracking-differentiator; nonlinear disturbance observer

高超声速飞行器作为一种新型快速突防与战略投送和打击工具,一直以来都受到各航空航天大国的格外关注^[1]。但是,这类新型飞行器多采用细长体布局,加之轻质柔性复合材料的大量使用以及机体薄壁结构特殊设计,导致其在大包线快速飞行时弹性振动显著^[2-4]。机体弹性振动则会进一步增大模型的不确定性和耦合程度,给控制器的设计带来巨大的挑战。

对于高超声速飞行器高阶、快时变、高不确定和强非线性弹性体模型,传统鲁棒控制太过保守,滑模控制以其强鲁棒性的优点在刚体飞行器的控制中应用较多^[5-8],但是因为控制的不连续性,滑模控制输出常有高频抖振,不利于抑制机体弹性振动。反演控制方法以其摆脱了对模型匹配性约

束的限制,近年来获得较快发展。针对高超声速飞行器一体化解析式弹性体模型,文献[9-11]采用反演方法设计控制器,在保证刚体状态稳定的同时,很好地抑制了机体弹性振动。文献[12]设计超扭曲滑模干扰观测器来自适应估计和补偿模型不确定项,在此基础上设计了一种鲁棒反演控制器;但是,当存在扰动时,控制效果一般。文献[13-14]考虑模型部分状态不可测的问题,基于滑模观测器设计了一种准连续的高阶滑模控制器,但是没有给出弹性状态的抑制效果。

本文将研究高超声速飞行器弹性体模型的自适应反演控制问题。考虑弹性状态不可测的问题,将模型中的控制量和弹性状态人为分离。针对模型的高不确定性,设计一种新型非线性干扰

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观测器,通过对模型不确定项进行自适应估计和补偿来提高控制器的鲁棒性。采用动态面方法,即引入一阶低通滤波器对虚拟控制量的一阶导数进行有效估计,简化求导运算。最后,通过实例仿真对控制策略的有效性进行验证。

1 运动学模型

高超声速飞行器控制系统的任务是在保证飞行器姿态稳定的同时,实现速度和高度对参考指令的有效跟踪,且飞行器弹性振动要得到有效抑制。高超声速飞行器纵向运动学模型为

$$\begin{cases} \dot{V} = \frac{T \cos \alpha - D}{m} - \frac{\mu}{(R_E + h)^2} \sin \gamma \\ \dot{h} = V \sin \gamma \\ \dot{\gamma} = \frac{L + T \sin \alpha}{mV} - \frac{\mu - V^2 (R_E + h)}{V (R_E + h)^2} \cos \gamma \\ \dot{\alpha} = Q - \frac{L + T \sin \alpha}{mV} + \frac{\mu - V^2 (R_E + h)}{V (R_E + h)^2} \cos \gamma \\ \dot{Q} = \frac{M}{I_{yy}} \\ \ddot{\eta}_i = -2\zeta_i \omega_i \dot{\eta}_i - \omega_i^2 \eta_i + N_i, \quad i = 1, 2, 3 \end{cases} \quad (1)$$

式中: T 为推力, D 为阻力, L 为升力, M 为俯仰力矩;刚体状态包括 V, h, γ, α 和 Q ,分别表示速度、高度、弹道角、攻角和俯仰角速度; $\boldsymbol{\eta} = [\eta_1, \dot{\eta}_1, \eta_2, \dot{\eta}_2, \eta_3, \dot{\eta}_3]$ 为前三阶弹性状态及其一阶导数; $\zeta_i, \omega_i (i = 1, 2, 3)$ 分别为前三阶弹性状态的阻尼和振动频率; μ 和 R_E 分别为地球引力常量和半径; m 为飞行器质量; I_{yy} 为飞行器转动惯量; $N_i (i = 1, 2, 3)$ 为广义弹性力。

模型(1)的 T, D, L, M 和 $N_i (i = 1, 2, 3)$ 参数拟合形式为

$$\begin{aligned} T &\approx qS [C_{T,\phi}(\alpha) \Phi + C_T(\alpha) + C_T^\eta \boldsymbol{\eta}] \\ C_{T,\phi}(\alpha) &= C_T^{\phi\alpha^3} \alpha^3 + C_T^{\phi\alpha^2} \alpha^2 + C_T^{\phi\alpha} \alpha + C_T^\phi \\ C_T(\alpha) &= C_T^3 \alpha^3 + C_T^2 \alpha^2 + C_T^1 \alpha + C_T^0 \\ L &\approx qS [C_L^\alpha \alpha + C_L^{\delta_e} \delta_e + C_L^0 + C_L^\eta \boldsymbol{\eta}] \\ D &\approx qS [C_D^{\alpha^2} \alpha^2 + C_D^\alpha \alpha + C_D^{\delta_e^2} \delta_e^2 + C_D^{\delta_e} \delta_e + C_D^0 + C_D^\eta \boldsymbol{\eta}] \\ M &\approx z_T T + qS \bar{c} [C_M^{\alpha^2} \alpha^2 + C_M^\alpha \alpha + C_M^{\delta_e} \delta_e + C_M^0 + C_M^\eta \boldsymbol{\eta}] \\ N_i &\approx qS [N_i^{\alpha^2} \alpha^2 + N_i^\alpha \alpha + N_i^{\delta_e} \delta_e + N_i^0 + N_i^\eta \boldsymbol{\eta}], \quad i = 1, 2, 3 \\ C_j^\eta &= [C_j^{\eta_1}, 0, C_j^{\eta_2}, 0, C_j^{\eta_3}, 0], \quad j = T, M, L, D \\ N_i^\eta &= [N_i^{\eta_1}, 0, N_i^{\eta_2}, 0, N_i^{\eta_3}, 0], \quad i = 1, 2, 3 \end{aligned}$$

式中: $q = \rho V^2 / 2$ 为动压, ρ 为空气密度; S, \bar{c} 分别为飞行器参考面积和平均气动弦长; Φ 和 δ_e 分别为燃料-空气比和升降舵偏角; z_T 为推力力矩耦合

系数。

模型(1)中的 T, D, L 和 M 参数拟合过程中必然会引入误差,且机体弹性振动会导致飞行攻角和升降舵偏角扰动,进一步会引起 T, D, L 和 M 扰动^[12]。假设其给模型(1)中的 V, γ, α 和 Q 子系统引入的误差为

$$\begin{cases} \Delta_V = \{ [\varepsilon_T (T + \Delta T) \cos(\alpha + \Delta\alpha)] / m \} - \varepsilon_D (D + \Delta D) / m \\ \Delta_\gamma = \{ [\varepsilon_T (T + \Delta T) \sin(\alpha + \Delta\alpha)] / mV \} + \varepsilon_L (L + \Delta L) / mV \\ \Delta_\alpha = -\Delta_\gamma \\ \Delta_Q = [z_T \varepsilon_T (T + \Delta T) + \varepsilon_M (M + \Delta M)] / I_{yy} \end{cases} \quad (2)$$

式中: $\Delta T, \Delta D, \Delta L, \Delta M$ 和 $\Delta\alpha$ 分别为 T, D, L, M 和 α 的扰动量; $\varepsilon_i (i = T, D, L, M)$ 分别为 T, D, L 和 M 参数拟合误差。分析式(2)可知,由于速度 V 取值较大,因此,模型参数扰动对 γ 和 α 子系统影响较小, Δ_γ 和 Δ_α 均为小量。

取弹性状态 $\boldsymbol{\eta}$ 的平衡值为 $\boldsymbol{\eta}^*$,定义误差 $\tilde{\boldsymbol{\eta}} = \boldsymbol{\eta} - \boldsymbol{\eta}^*$,进一步可变形为 $\boldsymbol{\eta} = \boldsymbol{\eta}^* + \tilde{\boldsymbol{\eta}}$ 。则可以将模型(1)转化为如式(3)面向反演控制的严格反馈形式

$$\begin{cases} \dot{V} = g_V \Phi + f_V(\delta_e^*, \boldsymbol{\eta}^*) + d_V \\ \dot{h} \approx V \gamma \\ \dot{\gamma} = g_\gamma \alpha + f_\gamma(\delta_e^*, \boldsymbol{\eta}^*) + d_\gamma \\ \dot{\alpha} = g_\alpha Q + f_\alpha(\delta_e^*, \boldsymbol{\eta}^*) + d_\alpha \\ \dot{Q} = g_Q \delta_e + f_Q(\boldsymbol{\eta}^*) + d_Q \end{cases} \quad (3)$$

式中: δ_e^* 为升降舵偏角的平衡值。模型不确定项分别为

$$\begin{cases} d_V = \Delta_V + qS (C_T^\eta \cos \alpha - C_D^\eta) \tilde{\boldsymbol{\eta}} / m = \Delta_V + \Delta_V^\eta \\ d_\gamma = \Delta_\gamma + qS (C_L^\eta + C_T^\eta \sin \alpha) \tilde{\boldsymbol{\eta}} / mV = \Delta_\gamma + \Delta_\gamma^\eta \\ d_\alpha = -\Delta_\gamma - \Delta_\gamma^\eta = -d_\gamma \\ d_Q = \Delta_Q + qS (z_T C_T^\eta + \bar{c} C_M^\eta) \tilde{\boldsymbol{\eta}} / I_{yy} = \Delta_Q + \Delta_Q^\eta \end{cases} \quad (4)$$

式中: $\Delta_V^\eta, \Delta_\gamma^\eta, \Delta_\alpha^\eta$ 和 Δ_Q^η 为弹性状态影响项。由式(4)可知, $\Delta_V^\eta, \Delta_\gamma^\eta, \Delta_\alpha^\eta$ 和 Δ_Q^η 都是有界的,且当刚体状态趋于稳态时,由式(1)中的弹性状态方程可知,弹性状态 $\boldsymbol{\eta}$ 将稳定于其平衡值 $\boldsymbol{\eta}^*$,有 $\tilde{\boldsymbol{\eta}} = \boldsymbol{\eta} - \boldsymbol{\eta}^* = 0$ 。此时, $\Delta_V^\eta, \Delta_\gamma^\eta, \Delta_\alpha^\eta, \Delta_Q^\eta$ 都收敛到零。

2 控制器设计

2.1 速度控制器设计

定义跟踪误差 $\tilde{V} = V - V_{ref}$,并沿式(3)的 V

子系统求时间的一阶导数,得

$$\dot{\tilde{V}} = g_v \Phi + f_v + d_v - \dot{V}_{\text{ref}} \quad (5)$$

设计实际控制量 Φ 为

$$\Phi = g_v^{-1} \left[-k_{v,1} \tilde{V} - k_{v,2} \int_0^t \tilde{V} d\tau - f_v - \hat{d}_v + \dot{V}_{\text{ref}} \right] \quad (6)$$

式中: $k_{v,1}, k_{v,2}$ 为待设计的控制器参数; \hat{d}_v 为不确定项 d_v 的估计值。

2.2 高度控制器设计

分别定义跟踪误差

$$\tilde{h} = h - h_{\text{ref}}; \quad \tilde{\gamma} = \gamma - \gamma_{\text{cmd}} \quad (7)$$

$$\tilde{\alpha} = \alpha - \alpha_{\text{cmd}}; \quad \tilde{Q} = Q - Q_{\text{cmd}}$$

分别沿式(3)的 h, γ, α 和 Q 子系统求时间的一阶导数,并结合式(7)得

$$\begin{cases} \dot{\tilde{h}} = V\gamma - \dot{h}_{\text{ref}} \\ \dot{\tilde{\gamma}} = g_\gamma \alpha + f_\gamma + d_\gamma - \dot{\gamma}_{\text{cmd}} \\ \dot{\tilde{\alpha}} = g_\alpha Q + f_\alpha + d_\alpha - \dot{\alpha}_{\text{cmd}} \\ \dot{\tilde{Q}} = g_Q \delta_e + f_Q + d_Q - \dot{Q}_{\text{cmd}} \end{cases} \quad (8)$$

采用反演设计方法,将虚拟控制量 $\bar{\gamma}, \bar{\alpha}$ 和 \bar{Q} 以及实际控制量 δ_e 分别设计为

$$\begin{cases} \bar{\gamma} = V^{-1} \left[-k_{h,1} \tilde{h} - k_{h,2} \int_0^t \tilde{h} d\tau + \dot{h}_{\text{ref}} \right] \\ \bar{\alpha} = g_\gamma^{-1} \left[-k_{\gamma,1} \tilde{\gamma} - k_{\gamma,2} \int_0^t \tilde{\gamma} d\tau - f_\gamma - \hat{d}_\gamma + \dot{\gamma}_{\text{cmd}} \right] \\ \bar{Q} = g_\alpha^{-1} \left[-k_{\alpha,1} \tilde{\alpha} - k_{\alpha,2} \int_0^t \tilde{\alpha} d\tau - f_\alpha - \hat{d}_\alpha + \dot{\alpha}_{\text{cmd}} \right] \\ \delta_e = g_Q^{-1} \left[-k_{Q,1} \tilde{Q} - k_{Q,2} \int_0^t \tilde{Q} d\tau - f_Q - \hat{d}_Q + \dot{Q}_{\text{cmd}} \right] \end{cases} \quad (9)$$

式中: $k_{i,1}, k_{i,2}$ ($i = h, \gamma, \alpha, Q$) 为待设计的控制器参数; $\hat{d}_\gamma, \hat{d}_\alpha$ 和 \hat{d}_Q 分别为不确定项 d_γ, d_α 和 d_Q 的估计值。

式(9)中,虚拟控制量 $\bar{\gamma}, \bar{\alpha}$ 和 \bar{Q} 求导复杂。这里采用动态面方法^[15],引入一阶低通滤波器来估计虚拟控制量的导数。

$$\begin{cases} \dot{\gamma}_{\text{cmd}} = (\bar{\gamma} - \gamma_{\text{cmd}}) / \tau_1; \quad \bar{\gamma}(0) = \gamma_{\text{cmd}}(0) \\ \dot{\alpha}_{\text{cmd}} = (\bar{\alpha} - \alpha_{\text{cmd}}) / \tau_2; \quad \bar{\alpha}(0) = \alpha_{\text{cmd}}(0) \\ \dot{Q}_{\text{cmd}} = (\bar{Q} - Q_{\text{cmd}}) / \tau_3; \quad \bar{Q}(0) = Q_{\text{cmd}}(0) \end{cases} \quad (10)$$

式中: τ_1, τ_2 和 τ_3 为待设计常数; $\gamma_{\text{cmd}}, \alpha_{\text{cmd}}$ 和 Q_{cmd} 分别为虚拟控制量 $\bar{\gamma}, \bar{\alpha}$ 和 \bar{Q} 的估计值。

2.3 非线性干扰观测器设计

为了对模型(3)中的不确定项进行自适应估计,基于二阶跟踪微分器^[16],可以设计一种新型

非线性干扰观测器。

为了不失一般性,考虑如下系统

$$\dot{x} = f + gu + d \quad (11)$$

式中: x, u 分别为系统状态量和控制量; d 为不确定项; f, g 为已知函数。

基于二阶跟踪-微分器,将非线性干扰观测器设计为如下形式

$$\begin{cases} \dot{\hat{x}} = f + gu + \hat{d} \\ \dot{\hat{d}} = -R \text{sgn}(\hat{x} - x + \frac{|\hat{d}| \hat{d}}{2R}) \end{cases} \quad (12)$$

式中: \hat{x}, \hat{d} 分别为 x 和 d 的估计值; R 为待设计常数。

定义估计误差 $e_1 = \hat{x} - x, e_2 = \hat{d} - d$,将式(12)化为如下误差系统

$$\begin{cases} \dot{e}_1 = e_2; & (a) \\ \dot{e}_2 = -R \text{sgn}(e_1), R \rightarrow +\infty; & (b) \end{cases} \quad (13)$$

对于误差系统(13),显然有误差 (e_1, e_2) 渐进收敛于 $(0, 0)$ 。

证明:若 $e_1 > 0, e_2 > 0$,则式(b)将调节 $e_2 \rightarrow 0$;若 $e_1 > 0, e_2 < 0$,则式(a)将调节 $e_1 \rightarrow 0$;若 $e_1 < 0, e_2 < 0$,则式(b)将调节 $e_2 \rightarrow 0$;若 $e_1 < 0, e_2 > 0$,则式(a)将调节 $e_1 \rightarrow 0$ 。综上分析, (e_1, e_2) 渐进收敛于 $(0, 0)$ 。□

用饱和函数 $\text{sat}(\cdot)$ 代替符号函数 $\text{sgn}(\cdot)$,不仅可以有效削弱观测器输出抖振,且不会影响原系统式(12)的稳定性^[16]。则基于系统式(12),分别对模型式(3)中的不确定项进行估计

$$\begin{cases} \hat{V} = f_v + g_v \Phi + \hat{d}_v \\ \dot{\hat{d}}_v = -R_v \text{sat}(\hat{V} - V + \frac{|\hat{d}_v| \hat{d}_v}{2R_v}) \end{cases} \quad (14)$$

$$\begin{cases} \hat{\gamma} = f_\gamma + g_\gamma \alpha + \hat{d}_\gamma \\ \dot{\hat{d}}_\gamma = -R_\gamma \text{sat}(\hat{\gamma} - \gamma + \frac{|\hat{d}_\gamma| \hat{d}_\gamma}{2R_\gamma}) \end{cases} \quad (15)$$

$$\begin{cases} \hat{\alpha} = f_\alpha + g_\alpha Q + \hat{d}_\alpha \\ \dot{\hat{d}}_\alpha = -R_\alpha \text{sat}(\hat{\alpha} - \alpha + \frac{|\hat{d}_\alpha| \hat{d}_\alpha}{2R_\alpha}) \end{cases} \quad (16)$$

$$\begin{cases} \hat{Q} = f_Q + g_Q \delta_e + \hat{d}_Q \\ \dot{\hat{d}}_Q = -R_Q \text{sat}(\hat{Q} - Q + \frac{|\hat{d}_Q| \hat{d}_Q}{2R_Q}) \end{cases} \quad (17)$$

式(14)~(17)中: R_v, R_γ, R_α 和 R_Q 为待设计常数。

2.4 稳定性分析

定义一阶低通滤波器估计误差

$$y_1 = \gamma_{\text{cmd}} - \bar{\gamma}, y_2 = \alpha_{\text{cmd}} - \bar{\alpha}, y_3 = Q_{\text{cmd}} - \bar{Q} \quad (18)$$

沿式(18)对时间求一阶导数,并结合式(10)得

$$\dot{y}_1 = -\frac{y_1}{\tau_1} - \dot{\gamma}, \dot{y}_2 = -\frac{y_2}{\tau_2} - \dot{\alpha}, \dot{y}_3 = -\frac{y_3}{\tau_3} - \dot{Q} \quad (19)$$

分别取 $|\dot{\gamma}|$ 、 $|\dot{\alpha}|$ 和 $|\dot{Q}|$ 的上界为 B_1 、 B_2 和 B_3 。

定义不确定项估计误差

$$\begin{cases} \tilde{d}_V = \hat{d}_V - d_V, \tilde{d}_\gamma = \hat{d}_\gamma - d_\gamma \\ \tilde{d}_\alpha = \hat{d}_\alpha - d_\alpha, \tilde{d}_Q = \hat{d}_Q - d_Q \end{cases} \quad (20)$$

由式(13)可知,选取合适的参数 R_V 、 R_γ 、 R_α 和 R_Q ,估计误差 \tilde{d}_V 、 \tilde{d}_γ 、 \tilde{d}_α 和 \tilde{d}_Q 都是有限时间收敛的。

将 Lyapunov 函数取为

$$W = W_V + W_h + W_\gamma + W_\alpha + W_Q \quad (21)$$

其中

$$W_V = \tilde{V}^2/2 + k_{V,2} \left(\int_0^t \tilde{V} d\tau \right)^2/2$$

$$W_h = \tilde{h}^2/(2\bar{V}^2) + k_{h,2} \left(\int_0^t \tilde{h} d\tau \right)^2/(2\bar{V}^2) + y_1^2/2$$

$$W_\gamma = \tilde{\gamma}^2/2 + k_{\gamma,2} \left(\int_0^t \tilde{\gamma} d\tau \right)^2/2 + y_2^2/2$$

$$W_\alpha = \tilde{\alpha}^2/2 + k_{\alpha,2} \left(\int_0^t \tilde{\alpha} d\tau \right)^2/2 + y_3^2/2$$

$$W_Q = \tilde{Q}^2/2 + k_{Q,2} \left(\int_0^t \tilde{Q} d\tau \right)^2/2$$

式中: \bar{V} 是速度 V 的上界。沿式(21)求时间的一阶导数,并根据式(5)~(9)和式(19)得:

$$\dot{W}_V = -k_{V,1} \tilde{V}^2 \quad (22)$$

$$\begin{aligned} \dot{W}_h \leq & -k_{h,1} \tilde{h}^2/\bar{V}^2 - y_1^2/\tau_1 + B_1 y_1 + \\ & V \tilde{\gamma} \tilde{h}/\bar{V}^2 + V y_1 \tilde{h}/\bar{V}^2 \end{aligned} \quad (23)$$

$$\begin{aligned} \dot{W}_\gamma \leq & -k_{\gamma,1} \tilde{\gamma}^2 - y_2^2/\tau_2 + g_\gamma \tilde{\alpha} \tilde{\gamma} + \\ & g_\gamma y_2 \tilde{\gamma} + B_2 y_2 \end{aligned} \quad (24)$$

$$\begin{aligned} \dot{W}_\alpha \leq & -k_{\alpha,1} \tilde{\alpha}^2 - y_3^2/\tau_3 + g_\alpha \tilde{Q} \tilde{\alpha} + \\ & g_\alpha y_3 \tilde{\alpha} + B_3 y_3 \end{aligned} \quad (25)$$

$$\dot{W}_Q = -k_{Q,1} \tilde{Q}^2 \quad (26)$$

对于式(23)~(25),有

$$\begin{cases} V \tilde{\gamma} \tilde{h}/\bar{V}^2 \leq (\tilde{h}^2 + V^2 \tilde{\gamma}^2)/(2\bar{V}^2) \\ V y_1 \tilde{h}/\bar{V}^2 \leq (\tilde{h}^2 + V^2 y_1^2)/(2\bar{V}^2) \\ B_1 y_1 \leq |B_1| |y_1| \leq (B_1^2 y_1^2 + 1)/2 \\ g_\gamma \tilde{\alpha} \tilde{\gamma} \leq |g_\gamma| |\tilde{\alpha}| |\tilde{\gamma}| \leq |g_\gamma| (\tilde{\alpha}^2 + \tilde{\gamma}^2)/2 \\ g_\gamma y_2 \tilde{\gamma} \leq |g_\gamma| |y_2| |\tilde{\gamma}| \leq |g_\gamma| (y_2^2 + \tilde{\gamma}^2)/2 \\ B_2 y_2 \leq |B_2| |y_2| \leq (B_2^2 y_2^2 + 1)/2 \\ g_\alpha \tilde{Q} \tilde{\alpha} \leq |g_\alpha| |\tilde{Q}| |\tilde{\alpha}| \leq |g_\alpha| (\tilde{Q}^2 + \tilde{\alpha}^2)/2 \\ g_\alpha y_3 \tilde{\alpha} \leq |g_\alpha| |y_3| |\tilde{\alpha}| \leq |g_\alpha| (y_3^2 + \tilde{\alpha}^2)/2 \\ B_3 y_3 \leq |B_3| |y_3| \leq (B_3^2 y_3^2 + 1)/2 \end{cases}$$

则式(21)可以化为

$$\begin{aligned} \dot{W} \leq & -k_{V,1} \tilde{V}^2 + (-k_{h,1} + 1) \tilde{h}^2/\bar{V}^2 + \\ & (-k_{\gamma,1} + |g_\gamma| + 0.5) \tilde{\gamma}^2 + \\ & (-k_{\alpha,1} + |g_\alpha| + |g_\gamma|/2) \tilde{\alpha}^2 + \\ & (-k_{Q,1} + |g_\alpha|/2) \tilde{Q}^2 + \\ & (-1/\tau_1 + B_1^2/2 + 0.5) y_1^2 + \\ & (-1/\tau_2 + B_2^2/2 + |g_\gamma|/2) y_2^2 + \\ & (-1/\tau_3 + B_3^2/2 + |g_\alpha|/2) y_3^2 + 1.5 \end{aligned} \quad (27)$$

取: $k_{V,1} \geq r$; $k_{h,1} \geq 1 + r$; $k_{\gamma,1} \geq |g_\gamma| + 0.5 + r$; $k_{\alpha,1} \geq |g_\alpha| + |g_\gamma|/2 + r$; $k_{Q,1} \geq |g_\alpha|/2 + r$; $1/\tau_1 \geq B_1^2/2 + 0.5 + r$; $1/\tau_2 \geq B_2^2/2 + |g_\gamma|/2 + r$; $1/\tau_3 \geq B_3^2/2 + |g_\alpha|/2 + r$ 。则式(27)化为

$$\dot{W} \leq -2rW + 1.5 \quad (28)$$

若令 $r \geq 1.5/(2W)$,则有 $\dot{W} \leq 0$,解式(28)得

$$W(t) \leq 1.5/(2r) + (W(0) - 1.5/(2r))e^{-2rt} \quad (29)$$

由 Lyapunov 稳定性理论可知,速度跟踪误差 \tilde{V} 和高度跟踪误差 \tilde{h} 是有限时间收敛的。

3 仿真实验

针对高超声速飞行器模型式(1)进行闭环系统仿真,模型详细气动参数和飞行器几何参数见文献[9]。在保持动压 $q = 90\ 148\text{Pa}$ 不变的前提下,要求速度由初始值 $V = 2\ 331.7\text{m/s}$ 阶跃 $\Delta V = 351.6\text{m/s}$;高度由初始值 $h = 26\ 212.8\text{m}$ 阶跃 $\Delta h = 1\ 828.8\text{m}$ 。高度参考输入由阻尼为 0.95、自然频率为 0.03rad/s 的二阶参考模型给出^[9]。

在 Matlab/simulink 环境下进行仿真,采用步长为 0.01s 的四阶 Runge - Kutta 法进行求解。控制器参数分别取为 $k_{V,1} = 20$, $k_{V,2} = 5$, $k_{h,1} = 1.5$, $k_{h,2} = 3$, $k_{\gamma,1} = 1.5$, $k_{\gamma,2} = 0.3$, $k_{\alpha,1} = 2$, $k_{\alpha,2} = 1$, $k_{Q,1} = 1.5$, $k_{Q,2} = 0.5$ 。一阶低通滤波器参数取为 $\tau_1 = \tau_2 = \tau_3 = 0.1$ 。非线性干扰观测器参数分别取为 $R_V = 1$, $R_\gamma = R_\alpha = 10^{-4}$, $R_Q = 0.1$ 。饱和函数边界层都取 $\delta = 0.01$ 。为了验证控制器的鲁棒性和观测器的估计效果,同时考虑 γ 和 α 子系统的扰动为小量,分别取 $\Delta_V = 0.61\sin(0.01\pi t)\text{m/s}$, $\Delta_\gamma = 0^\circ$, $\Delta_\alpha = 0^\circ$, $\Delta_Q = 1.72\sin(0.01\pi t)^\circ/\text{s}$ 。

仿真结果如图 1~7 所示。其中图 1~4 中变量的下标“1”表示没有干扰观测器;下标“2”表示加入干扰观测器。由仿真结果可知,当没有非线性干扰观测器时,模型不确定性对控制精度影响较大,且升降舵偏角 δ_e 存在高频抖振,导致弹性振动较剧烈且收敛速度慢。当控制系统加入非线性

干扰观测器时,观测器可以实现对模型不确定项和弹性状态影响项的精确估计,因而获得了更高的速度和高度跟踪精度,且控制输入和飞行器的弹道角、攻角和俯仰角速度都处于合理的范围内,控制输入较平滑,因而获得了更好的弹性振动抑制效果。

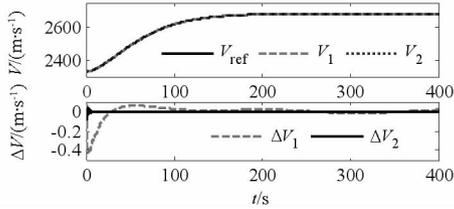


图 1 速度跟踪曲线

Fig. 1 Velocity command tracking curve

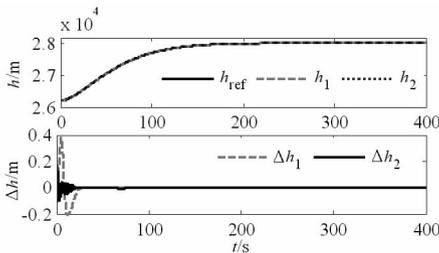


图 2 高度跟踪曲线

Fig. 2 Altitude command tracking curve

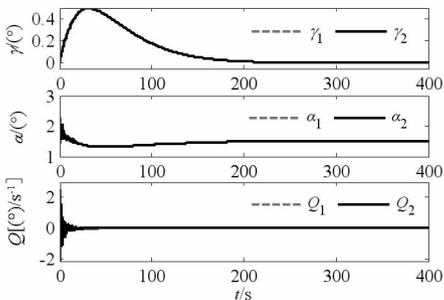


图 3 弹道角、攻角和俯仰角速度响应

Fig. 3 The responses of flight-path angle, attack angle and pitch rate

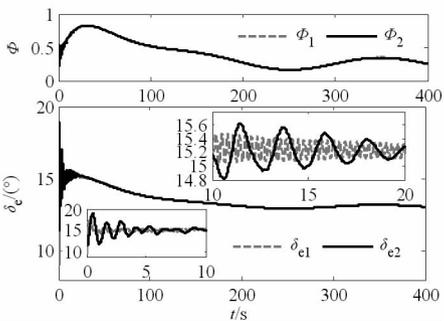


图 4 控制输入曲线

Fig. 4 Control inputs curves

4 结论

针对存在参数摄动的高超声速飞行器弹性体模型,设计了一种自适应反演控制器。设计的新

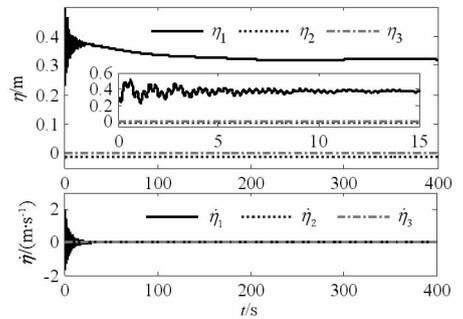


图 5 有干扰观测器时弹性状态响应及变化率曲线

Fig. 5 Elastic states responses and change rate curves with disturbance observer

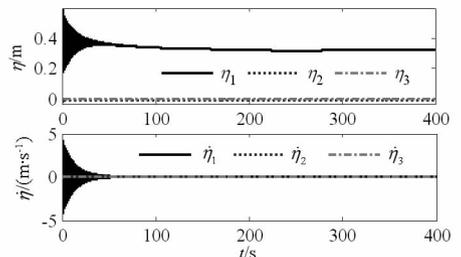


图 6 无干扰观测器时弹性状态响应及变化率曲线

Fig. 6 Elastic states responses and change rate curves without disturbance observer

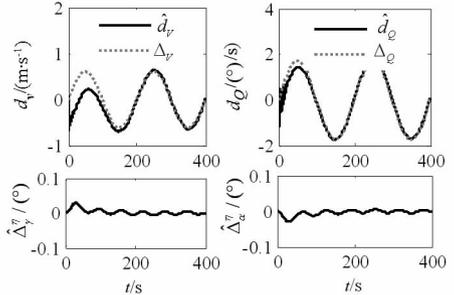


图 7 模型不确定项估计曲线

Fig. 7 Model uncertainties estimate curves

型非线性干扰观测具有算法简单、参数易于确定的优点,可以对模型不确定项进行高精度估计和补偿,增强了单纯反演控制器的鲁棒性。引入一阶低通滤波器,简化了虚拟控制量求导运算。仿真结果充分说明,所设计控制器对模型不确定项具有强鲁棒性,在保证刚体状态稳定的同时,较好地抑制了机体弹性振动,且能够实现对速度和高度参考输入的高精度稳定跟踪。

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