论 文

一类高超声速飞行器自适应容错控制器设计

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摘要 高超声速飞行器控制系统具有非常突出的强耦合、强非线性、时变的力学特性, 在其研究与设计过程中, 需要处理高速飞行带来的弹性形变、多输入多输出、气动参数不确定以及高温高热等原因导致的各种传感器故障和部分作动器故障等一系列问题, 因此该类飞行器控制系统的设计面临着传统飞行器控制系统研究所未有的困难和挑战. 针对高超声速飞行器飞行过程中遇到的部分作动器故障问题, 本文提出了非线性观测器与控制器一体化设计的高超声速飞行器自适应反演容错控制方法. 首先将飞行器作动器故障模型转换为一类状态不能完全测量, 且具有未知参数和未知控制增益的 SISO 输出反馈非线性最小相位系统, 然后, 基于改进的 K -滤波器理论对状态向量进行重构, 在系统只有输出可以测量的情况下, 设计了一种新型观测器, 确定出收敛的状态向量, 设计出强自适应能力的控制器, 保证了系统所有信号的有界性. 在自适应反演设计时, 采用动态面设计方法, 引入一阶滤波器, 得到虚拟控制量的微分, 消除传统反演设计中的“项数膨胀”问题, 用 Lyapunov 稳定性定理保证误差一致有界. 仿真实验验证了该算法的有效性. 最后以高超声速飞行器纵向通道为例, 验证了上述理论.

关键词 高超声速飞行器 观测器 K -滤波器 动态面自适应反演 容错控制

1 引言

对高超声速飞行器而言, 其飞行环境复杂, 一旦发生事故, 将导致无法挽回的后果, 这就要求高超声速飞行器必须具备应付突发事件的能力, 即具备自动故障诊断和容错控制的能力.

容错控制的目的在于通过控制器的调节使得故障系统仍能保持满意的性能或者至少达到可以接受的性能指标. 容错控制技术取得应用成果最多的对象是飞机, 飞控系统容错控制技术经过数十年的发展, 取得了丰硕的成果, 如 Tao 等^[1] 针对发生故障的线性定常系统, 建立在直接自适应控制的基础上, 用状态反馈控制进行输出跟踪. Zhang 等^[2] 建立在故障诊断的基础上, 结合自适应控制方案和神经网络技术, 利用故障的信息设计容错控制器, 能使输出跟踪误差收敛到零的很小邻域. 类似的工作还出现在文献 [3,4] 中. 在文献 [5] 中, 提出了一种基于神经网络动态补偿的鲁棒模型跟随重构控制策略, 确保系统发生故障时闭环系统一致有界鲁棒稳定. 上述工作大都是针对线性系统 (或者是具有局

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部非线性特性的系统) 进行研究的, 所涉及的状态重构方式也以线性观测器为主. 像高超声速飞行器这种强耦合的非线性系统研究较少, 用于补偿故障影响的非线性观测器理论研究也相对较少.

观测器理论也是解决飞行器的故障诊断和重构的重要研究手段. 文献 [6~9] 实现了飞行器的状态及控制信号重构问题. 从理论角度, 这一研究领域也是非线性观测器在飞行器控制领域的应用问题.

当飞行器的传感器发生故障时, 要使飞控系统仍能保持正常, 必须至少设计一个稳定控制器, 以便抑制外部扰动和输入参数的变化. 同样, 当部分作动器故障时, 参数会发生很大的跳变, 因此控制器的设计必须具有很强的适应性. 为了解决这些问题, 本文解决出现部分作动器故障时系统的容错控制问题.

本文的主要工作是研究在“部分作动器故障”情况下, 高超声速飞行器纵向通道的观测器和控制器设计问题. 即在系统状态向量不能全部测量的情况下, 设计控制器使系统稳定, 同时保证系统良好的动态性能. 由于预先并不知道作动器故障发生的时间和类型, 所以要求控制器必须具有很强的自适应能力, 适应作动器的故障情况, 使得飞行器在部分作动器故障的情况下安全飞行.

2 系统描述

考虑如下非线性飞行器控制系统方程

$$\dot{\bar{x}} = f(\bar{x}) + \sum_{i=1}^m \theta_i g_i(\bar{x}) u_i, \quad y = h(\bar{x}), \quad (1)$$

其中, $u_i \in \mathbb{R}$, $i = 1, 2, \dots, m$ 是作动器输入值, $\bar{x} \in \mathbb{R}^n$ 是不可测量状态向量, $y \in \mathbb{R}$ 是系统输出可以测量, $f(\bar{x}) \in \mathbb{R}^n$, $g_i(\bar{x}) \in \mathbb{R}^n$, $i = 1, 2, \dots, m$, $h(\bar{x}) \in \mathbb{R}$ 是光滑方程, $\theta_i \in \mathbb{R}$, $i = 1, 2, \dots, m$ 是未知常数. 飞行器方程 (1) 可以转换为输出反馈形式.

通过一个参数独立的微分同胚 $z = \Phi(\bar{x}) = [\Phi_1(\bar{x}), \Phi_2(\bar{x}), \dots, \Phi_n(\bar{x})]^T$, 满足

$$\begin{aligned} \Phi_1(\bar{x}) &= h(\bar{x}), \\ \frac{\partial \Phi_i(\bar{x})}{\partial \bar{x}} f(\bar{x}) &= \Phi_{i+1}(\bar{x}) + \varphi_i(h(\bar{x})), \quad i = 1, \dots, \rho - 1, \\ \frac{\partial \Phi_i(\bar{x})}{\partial \bar{x}} &= 0, \quad i = 1, \dots, \rho - 1, \\ \frac{\partial \Phi_i(\bar{x})}{\partial \bar{x}} f(\bar{x}) &= \Phi_{i+1}(\bar{x}) + \varphi_i(h(\bar{x})), \quad i = 1, \dots, n - 1, \\ \frac{\partial \Phi_i(\bar{x})}{\partial \bar{x}} \left(\sum_{j=1}^m \theta_j g_j(\bar{x}) \right) &= b_{n-i,j} \delta_j(h(\bar{x})), \quad i = \rho, \dots, n - 1, \\ \frac{\partial \Phi_i(\bar{x})}{\partial \bar{x}} f(\bar{x}) &= \varphi_n(h(\bar{x})), \\ \frac{\partial \Phi_n(\bar{x})}{\partial \bar{x}} \left(\sum_{j=1}^m \theta_j g_j(\bar{x}) \right) &= b_{0,j} \delta_j(h(\bar{x})), \end{aligned} \quad (2)$$

并充分考虑系统中的作动器故障, 可以得到

$$\begin{aligned} \dot{x}_1 &= x_2 + \varphi_1(y), \\ &\vdots \end{aligned}$$

$$\begin{aligned}
\dot{x}_{\rho-1} &= x_{\rho} + \varphi_{\rho-1}(y), \\
\dot{x}_{\rho} &= x_{\rho+1} + \varphi_{\rho}(y) + \sum_{i=i_1, \dots, i_p}^l b_{m,i} \sigma_{\rho,i}(y) \bar{u}_i + \sum_{i \neq i_1, \dots, i_p}^l b_{m,i} \sigma_{\rho,i}(y) u_i, \\
&\vdots \\
\dot{x}_{n-1} &= x_n + \varphi_{n-1}(y) + \sum_{i=i_1, \dots, i_p}^l b_{1,i} \sigma_{n-1,i}(y) \bar{u}_i + \sum_{i \neq i_1, \dots, i_p}^l b_{1,i} \sigma_{n-1,i}(y) u_i, \\
\dot{x}_n &= \varphi_n(y) + \sum_{i=i_1, \dots, i_p}^l b_{0,i} \sigma_{n,i}(y) \bar{u}_i + \sum_{i \neq i_1, \dots, i_p}^l b_{0,i} \sigma_{n,i}(y) u_i, \\
y &= x_1,
\end{aligned} \tag{3}$$

式中, $u_i(t) = \bar{u}_i$, $i = i_1, \dots, i_l$ 为作动器故障产生的控制输入值, 在其余时刻 $u_i(t) = u_i$, $i \neq i_1, \dots, i_l$ 为作动器故障后系统的应用控制信号. $b_{m,i}, \dots, b_{0,i}$, $i = 1, 2, \dots, m$ 是未知常数. 为研究方便, 假设某段时间间隔内有 $l = \sum_{i=1}^k l_i$ 个作动器故障, $0 \leq l \leq m-1$, u_i , $i = 1, 2, \dots, m$ 是来自反馈设计的控制输入. 则输出反馈系统 (3) 改写成

$$\begin{aligned}
\dot{x}_1 &= x_2 + \varphi_1(y), \\
&\vdots \\
\dot{x}_{\rho-1} &= x_{\rho} + \varphi_{\rho-1}(y), \\
\dot{x}_{\rho} &= x_{\rho+1} + \varphi_{\rho}(y) + \sum_{i=1, \dots, l-1}^l b_{m,i} \sigma_{i,\rho}(y) \bar{u}_i + b_m \sigma_0(y) u, \\
&\vdots \\
\dot{x}_{n-1} &= x_n + \varphi_{n-1}(y) + \sum_{i=1, \dots, l-1}^l b_{1,i} \sigma_{i,n-1}(y) \bar{u}_i + b_1 \sigma_0(y) u, \\
\dot{x}_n &= \varphi_n(y) + \sum_{i=1, \dots, l-1}^l b_{0,i} \sigma_{i,n}(y) \bar{u}_i + b_0 \sigma_0(y) u, \\
y &= x_1,
\end{aligned} \tag{4}$$

其中, u 为控制输入. 定义 $a_i = b_{r,i} \bar{u}_i$, $r = 0, 1, \dots, m$, $i = 1, \dots, l$, 进一步将式 (4) 归纳写成

$$\begin{aligned}
\dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \boldsymbol{\varphi}(y) + \mathbf{H}(y)\mathbf{a} + [0 \quad \mathbf{b}]^T \sigma_0(y) u \\
&= \mathbf{A}\mathbf{x} + \boldsymbol{\varphi}(y) + \mathbf{e}_{n-r} \sum_{i=1}^l \sigma_{i,j}(y) a_i + [0 \quad \mathbf{b}]^T \sigma_0(y) u, \\
y &= \mathbf{C}\mathbf{x},
\end{aligned} \tag{5}$$

这里

$$\boldsymbol{\varphi}(y) = [\varphi_1(y) \quad \cdots \quad \varphi_n(y)]^T,$$

$$H(y) = \begin{bmatrix} \sigma_{1,\rho}(y) & \sigma_{2,\rho}(y) & \cdots & \sigma_{l,\rho}(y) \\ \sigma_{1,\rho+1}(y) & \sigma_{2,\rho+1}(y) & \cdots & \sigma_{l,\rho+1}(y) \\ \vdots & \vdots & \ddots & \vdots \\ \sigma_{1,n}(y) & \sigma_{2,n}(y) & \cdots & \sigma_{l,n}(y) \end{bmatrix}_{l \times n}, \quad A = \begin{bmatrix} 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ 0 & 0 & \cdots & 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 1 & 0 & \cdots & 0 \end{bmatrix}^T, \quad r = 0, \dots, m,$$

$j = \rho, \dots, n$. $\mathbf{a} = [0, \dots, a_1, a_2, \dots, a_l]^T \in \mathbb{R}^l$, $\mathbf{b} = [b_m, \dots, b_0]^T \in \mathbb{R}^{m+1}$, $x \in \mathbb{R}^n$ 为状态向量且不能完全测量得到. $u \in \mathbb{R}$ 和 $y \in \mathbb{R}$ 分别表示系统的输入和输出, 只有输出 y 可以测量. $\mathbf{a}$ 和 $\mathbf{b}$ 均为未知定常参数矢量. $\mathbf{e}_{n-r}$ 表示 $\mathbb{R}^n$ 中的第 $n-r$ 个坐标矢量. $\sigma_{i,q}(y)$, $0 \leq i \leq l$, $\rho \leq j \leq n$, 以及 $\sigma_0(y)$ 为已知光滑函数, 同时存在常数 $\sigma_k > 0$ 使得 $\sigma(y) > \sigma_k, \forall y \in \mathbb{R}$.

针对系统 (5), 本文作以下几个假设:

假设 1 系统满足最小相位条件, 即多项式 $B(s) = b_m s^m + \cdots + b_1 s + b_0$ 为 Hurwitz 多项式 [5].

假设 2 系统控制增益 b 的符号 $\text{sgn}(b_r)$, $r = 0, \dots, m$ 已知, 并且存在已知正常数 b_M , 使得 $0 < b_m < b_M$.

2.1 自适应补偿器设计

自从 Krstic 于 1995 年创建 K -滤波器理论 [10] 之后, 许多文献 [11~13] 都在此该领域进行了一定的研究, 并在系统观测、参数辨识、控制方向未知等方面取得了一定的成果. 上述研究的基础均是基于传统反演控制进行的, 设计中多次出现对虚拟控制量的微分项, 导致设计过程复杂, 且大都没有实际应用对象, 目前仅处于理论探讨阶段.

设计如下状态滤波器

$$\begin{cases} \dot{\boldsymbol{\eta}} = \mathbf{A}_0 \boldsymbol{\eta} + K_0 y + \boldsymbol{\varphi}(y), \\ \dot{\boldsymbol{\xi}} = \mathbf{A}_0 \boldsymbol{\xi} + \mathbf{H}(y), \\ \dot{\boldsymbol{\lambda}} = \mathbf{A}_0 \boldsymbol{\lambda} + \mathbf{e}_n \sigma_0(y) u, \\ \mathbf{v}_j = \mathbf{A}_0^j \boldsymbol{\lambda}, \quad j = 0, \dots, m, \end{cases} \quad (6)$$

这里

$$\mathbf{A}_0 = \begin{bmatrix} -k_1 & & & \\ \vdots & & I_{n-1} & \\ -k_n & 0 & \cdots & 0 \end{bmatrix}, \quad \boldsymbol{\varphi}(y) = \begin{bmatrix} \varphi_1(y) & \cdots & \varphi_n(y) \end{bmatrix}^T,$$

通过选择参数矢量 $\mathbf{K}_0 = (k_1, k_2, \dots, k_n)^T$ 使得矩阵 $\mathbf{A}_0$ 为 Hurwitz 矩阵, 即有 $\mathbf{P} \mathbf{A}_0 + \mathbf{A}_0^T \mathbf{P} = -\mathbf{I}$, $\mathbf{P} = \mathbf{P}^T > 0$. $\mathbf{e}_i$ 表示 $\mathbb{R}^n$ 中的第 i 个坐标矢量.

定义 $\boldsymbol{\theta} = (b_m, \dots, b_0, a_1, \dots, a_q)^T$, $\boldsymbol{\Omega}^T = (v_m, \dots, v_0, \xi)$, 则设计状态观测器为 $\hat{\mathbf{x}} = \boldsymbol{\eta} + \boldsymbol{\Omega}^T \boldsymbol{\theta}$. 定义观测器误差 $\boldsymbol{\delta} = \mathbf{x} - \hat{\mathbf{x}}$, 可得

$$\boldsymbol{\delta} = \mathbf{x} - \boldsymbol{\eta} - \boldsymbol{\Omega}^T \boldsymbol{\theta}. \quad (7)$$

本文将对系统 (6) 设计一个具有如下形式的自适应控制器 $\dot{\mathbf{z}} = \mathbf{f}(\mathbf{z}, y)$, $\boldsymbol{\mu}_0 = \boldsymbol{\mu}(\mathbf{z}, y)$, 使得闭环系统所有信号是一致有界的, 同时使得系统状态量调节到零.

2.2 控制器设计

将系统的状态 x 用滤波信号取代, 可得 $\mathbf{x} = \boldsymbol{\eta} + \boldsymbol{\Omega}^T \boldsymbol{\theta} + \boldsymbol{\delta}$. 定义 $z_1 = y - y_d$, $z_i = v_{m,i} - \alpha_{i-1}$, $i = 2, \dots, n$.

步骤 1 根据方程 (6) 和 (7), 可得

$$\dot{z}_1 = x_2 + \varphi_{0,1} + \sum_{j=1}^q a_j \varphi_{j,1} - \dot{y}_d = \eta_2 + \boldsymbol{\Omega}_2^T \boldsymbol{\theta} + \delta_2 + \varphi_{0,1} + \mathbf{H}_{(1)} \mathbf{a} - \dot{y}_d = b_m v_{m,2} + \eta_2 + \varphi_{0,1} + \bar{\mathbf{w}}^T \boldsymbol{\theta} + \delta_2 - \dot{y}_d,$$

这里 $\bar{\mathbf{w}}^T = [0, v_{m-1,2}, \dots, v_{0,2}, \mathbf{H}_{(1)} + \boldsymbol{\xi}_{(2)}]$, $\mathbf{w}^T = [v_{m-1,2}, \dots, v_{0,2}, \mathbf{H}_{(1)} + \boldsymbol{\xi}_{(2)}]$, $\mathbf{H}_{(1)}$ 表示矩阵 $\boldsymbol{\Phi}$ 的第一行, $\boldsymbol{\Omega}_{(2)}^T$ 和 $\boldsymbol{\xi}_{(2)}$ 分别表示矩阵 $\boldsymbol{\Omega}$ 和 $\boldsymbol{\xi}$ 的第二行, η_2 表示列向量 $\boldsymbol{\eta}$ 的第二个分量. 设

$$\begin{cases} \dot{v}_{m,j} = v_{m,i+1} - k_i v_{m,1}, & i = 2, \dots, \rho - 1, \\ \dot{v}_{m,\rho} = \sigma_0(y)u + v_{m,\rho+1} - k_\rho v_{m,1}. \end{cases} \quad (8)$$

定义 $z_2 = v_{m,2} - \alpha_1$, 这里 α_1 为第一个虚拟控制量. 即 $v_{m,2} = z_2 + \alpha_1$, 则

$$\dot{z}_1 = b_m z_2 + b_m \alpha_1 + \eta_2 + \varphi_{0,1}(y) + \bar{\mathbf{w}}^T \boldsymbol{\theta} + \delta_2. \quad (9)$$

设 $\kappa = \frac{1}{b_m}$, 将 α_1 设计为

$$\begin{cases} \alpha_1 = \hat{\kappa} \bar{\alpha}_1, \\ \dot{\hat{\kappa}} = -\mu_2 \text{sgn}(b_m) \bar{\alpha}_1 z_1, \\ \dot{\bar{\alpha}}_1 = -(l_1 z_1 + \eta_2 + \varphi_{0,1}(y) + \bar{\mathbf{w}}^T \hat{\boldsymbol{\theta}} - \dot{y}_d), \end{cases} \quad (10)$$

其中, l_1, μ_2 为正的设计参数, $\hat{\boldsymbol{\theta}}, \hat{\kappa}$ 表示 $\boldsymbol{\theta}, \kappa$ 在 t 时刻的估计值, 设 $\tilde{\boldsymbol{\theta}} = \boldsymbol{\theta} - \hat{\boldsymbol{\theta}}, \tilde{\kappa} = \kappa - \hat{\kappa}$. 定义如下的 Lyapunov 函数

$$V_1 = \frac{1}{2} z_1^2 + \frac{1}{2} \tilde{\boldsymbol{\theta}}^T \mu_1^{-1} \tilde{\boldsymbol{\theta}} + \frac{1}{2\mu_2} \tilde{\kappa}^2 + \frac{1}{2d} \boldsymbol{\delta}^2. \quad (11)$$

对时间 t 求导可得

$$\begin{aligned} \dot{V}_1 &= z_1 \cdot \dot{z}_1 - \tilde{\boldsymbol{\theta}}^T \mu_1^{-1} \dot{\tilde{\boldsymbol{\theta}}} - \frac{1}{\mu_2} \tilde{\kappa} \dot{\tilde{\kappa}} + \frac{1}{2d} \boldsymbol{\delta}^2 \\ &\leq b_m v_{m,2} z_1 + \eta_2 z_1 + \varphi_{0,1} z_1 + \bar{\mathbf{w}}^T \boldsymbol{\theta} z_1 + \delta_2 z_1 - \dot{y}_d z_1 - \frac{1}{\mu_1} \tilde{\boldsymbol{\theta}}^T \dot{\tilde{\boldsymbol{\theta}}} - \frac{1}{\mu_2} \tilde{\kappa} \dot{\tilde{\kappa}} + \frac{1}{2d} \boldsymbol{\delta}^2. \end{aligned} \quad (12)$$

所以, 可以选择第一个参数调节律

$$\boldsymbol{\tau}_1 = \dot{\tilde{\boldsymbol{\theta}}} = \mu_1 \bar{\mathbf{w}} z_1. \quad (13)$$

步骤 2 z_2 对时间 t 求导, 采用动态面技术引入新的变量 χ_2 , 可用以下一阶滤波器获得

$$\varepsilon_2 \dot{\chi}_2 + \chi_2 = \alpha_1, \quad \chi_2(0) = \alpha_1(0), \quad (14)$$

其中, 时间常数 $\varepsilon_2 > 0$ 为较小正数.

令 $S_2 = \chi_2 - \alpha_1$, 则 $\dot{\chi}_2 = -\frac{S_2}{\varepsilon_2}$, 方程 $z_1 \dot{z}_1 = z_1(b_m v_{m,2} + \eta_2 + \varphi_{0,1}(y) + \bar{\mathbf{w}}^T \boldsymbol{\theta} + \delta_2 - \dot{y}_d)$ 要进行改写. 由 Young 不等式, 有 $ab \leq a^2 + \frac{1}{4}b^2$, $v_{m,2} = z_2 + \chi_2 = z_2 + S_2 + \alpha_1$, 并由假设 2 和式 (9) 可得

$$z_1 \dot{z}_1 = z_1(b_m z_2 + b_m S_2 + b_m \alpha_1 + \eta_2 + \varphi_{0,1}(y) + \bar{\mathbf{w}}^T \boldsymbol{\theta} + \delta_2 - \dot{y}_d)$$

$$\begin{aligned}
&\leq b_M \left(z_1^2 + \frac{1}{4} z_2^2 \right) + b_M \left(z_1^2 + \frac{1}{4} S_2^2 \right) + b_m z_1 \alpha_1 + z_1 \eta_2 + z_1 \varphi_{0,1}(y) + z_1 \bar{\mathbf{w}}^T \hat{\boldsymbol{\theta}} + z_1 \delta_2 - z_1 \dot{y}_d \\
&\leq b_M \left(z_1^2 + \frac{1}{4} z_2^2 \right) + b_M \left(z_1^2 + \frac{1}{4} S_2^2 \right) - z_1 (l_1 z_1 + \eta_2 + \varphi_{0,1}(y) + \bar{\mathbf{w}}^T \hat{\boldsymbol{\theta}} - \dot{y}_d) \\
&\quad + \tilde{b}_m z_1 \alpha_1 + z_1 \eta_2 + z_1 \varphi_{0,1}(y) + z_1 \bar{\mathbf{w}}^T \boldsymbol{\theta} + z_1 \delta_2 - z_1 \dot{y}_d \\
&\leq b_M \left(z_1^2 + \frac{1}{4} z_2^2 \right) + b_M \left(z_1^2 + \frac{1}{4} S_2^2 \right) - l_1 z_1^2 + z_1^2 + \frac{1}{4_1} \delta_2^2 + \tilde{b}_m z_1 \alpha_1 + z_1 \bar{\mathbf{w}}^T \tilde{\boldsymbol{\theta}} \\
&= - \left(l_1 - 2b_M - \frac{1}{4} \right) z_1^2 + \frac{1}{4} b_M z_2^2 + \frac{1}{4} b_M S_2^2 + \frac{1}{4_1} \delta_2^2 + \tilde{b}_m z_1 \alpha_1 + z_1 \bar{\mathbf{w}}^T \tilde{\boldsymbol{\theta}}, \tag{15}
\end{aligned}$$

则式 (15) 可进一步写为

$$\begin{aligned}
\dot{V}_1 &= z_1 \dot{z}_1 - \bar{\boldsymbol{\theta}}^T \mu_1^{-1} \dot{\bar{\boldsymbol{\theta}}} - \frac{1}{\mu_2} \tilde{\kappa} \dot{\tilde{\kappa}} + \frac{1}{2d} \|\boldsymbol{\delta}\|^2 \\
&\leq b_M \left(z_1^2 + \frac{1}{4} z_2^2 \right) + b_M \left(z_1^2 + \frac{1}{4} S_2^2 \right) - l_1 z_1^2 + z_1^2 + \frac{1}{4_1} \delta_2^2 + \frac{1}{2d} \|\boldsymbol{\delta}\|^2 \\
&= - \left(l_1 - 2b_M - \frac{1}{4} \right) z_1^2 + \frac{1}{4} b_M z_2^2 + \frac{1}{4} b_M S_2^2 + \frac{1}{4_1} \delta_2^2 + \frac{1}{2d} \|\boldsymbol{\delta}\|^2. \tag{16}
\end{aligned}$$

定义误差微分方程 $\dot{S}_2 = -S_2/\varepsilon_2 - \alpha_1$, 则 $\dot{S}_2 = \dot{\chi}_2 - \dot{\alpha}_1 = -S_2/\varepsilon_2 - \dot{\kappa}(-l_1 z_1 - \eta_2 + \varphi_{0,1}(y) - \bar{\mathbf{w}}^T \hat{\boldsymbol{\theta}} - \bar{\mathbf{w}}^T \tilde{\boldsymbol{\theta}} + \dot{y}_d)$. 由式 (10), 假设 z_1 有界, 可得存在有界函数 B , 使得

$$\left| \dot{S}_2 + \frac{S_2}{\varepsilon_2} \right| \leq B_2(z_1, z_2, \dots, z_n, S_2, \hat{\boldsymbol{\theta}}, b_m, y_d, \dot{y}_d, \ddot{y}_d), \tag{17}$$

其中, $B_2(z_1, z_2, \dots, z_n, S_2, \hat{\boldsymbol{\theta}}, b_m, y_d, \dot{y}_d, \ddot{y}_d)$ 为有界函数.

可得

$$S_2 \dot{S}_2 \leq -\frac{S_2^2}{\varepsilon_2} + B_2 |S_2| \leq -\frac{S_2^2}{\varepsilon_2} + S_2^2 + \frac{1}{4} B_2^2. \tag{18}$$

由动态面 $z_2 = v_{m,2} - \chi_2$, 得出

$$\dot{z}_2 = \dot{v}_{m,2} - \dot{\chi}_2 = v_{m,3} - k_2 v_{m,1} - \dot{\chi}_2.$$

设计虚拟控制 α_2 如下:

$$\alpha_2 = -\hat{b}_m z_1 - l_2 z_2 + k_1 v_{m,1} + \dot{\chi}_2, \tag{19}$$

其中, l_2 为正的设计参数. 这里我们增加了一个 $-\hat{b}_m z_1$ 补偿项, $\hat{b}_m$ 表示 b_m 在 t 时刻的估计值. 以 α_2 为输入, 引入新的状态变量 χ_3 , 定义如下一阶滤波器

$$\varepsilon_3 \dot{\chi}_3 + \chi_3 = \alpha_2, \quad \chi_3(0) = \alpha_2(0), \tag{20}$$

其中时间常数 $\varepsilon_3 > 0$ 待设计.

令 $S_3 = \chi_3 - \alpha_2$, 则 $\dot{\chi}_3 = -S_3/\varepsilon_3$. 由于 $v_{m,3} = z_3 + \chi_3 = z_3 + S_3 + \alpha_2$, 并利用 Young 不等式可得

$$\dot{z}_2 z_2 = z_2 (z_3 + S_3 + \alpha_2 - k_2 v_{m,1} - \dot{\chi}_2) \leq \frac{1}{2} z_1^2 - \left(l_2 - \frac{1}{2} b_M - 2 \right) z_2^2 + \frac{1}{4} z_3^2 + \frac{1}{4} S_3^2. \tag{21}$$

求误差微分方程 $\dot{S}_3 = -S_3/\varepsilon_3 - \alpha_2$, 则

$$\dot{S}_3 = \dot{\chi}_3 - \dot{\alpha}_2 = -\frac{S_3}{\varepsilon_3} - (-\hat{b}_m z_1 - l_2 \dot{z}_2 + k_2 \dot{v}_{m,1} + \ddot{\chi}_2). \tag{22}$$

同理可得

$$\left| \dot{S}_3 + \frac{S_3}{\varepsilon_3} \right| \leq B_3(z_1, z_2, \dots, z_n, S_2, S_3, \hat{\theta}, \hat{b}_m, y_d, \dot{y}_d, \ddot{y}_d),$$

其中, $B_3(z_1, z_2, \dots, z_n, S_2, S_3, \hat{\theta}, \hat{b}_m, y_d, \dot{y}_d, \ddot{y}_d)$ 是有界函数.

$$S_3 \dot{S}_3 \leq -\frac{S_3^2}{\varepsilon_3} + B_3 |S_3| \leq -\frac{S_3^2}{\varepsilon_3} + S_3^2 + \frac{1}{4} B_3^2. \quad (23)$$

步骤 i $i = 3, 4, \dots, \rho$, 设第 i 个动态面 $z_i = v_{m,i} - \chi_i$, 则

$$\dot{z}_i = \dot{v}_{m,i} - \dot{\omega}_i = v_{m,i+1} - k_i v_{m,1} - \dot{\chi}_i. \quad (24)$$

选取虚拟控制 α_i 如下

$$\alpha_i = -z_{i-1} - l_i z_i + k_i v_{m,1} + \dot{\chi}_i, \quad (25)$$

其中 l_i 为正的设计参数.

以 α_i 为输入, 引入新的状态变量 χ_{i+1} , 定义如下一阶滤波器

$$\varepsilon_{i+1} \dot{\chi}_{i+1} + \chi_{i+1} = \alpha_i, \quad \chi_{i+1}(0) = \alpha_i(0). \quad (26)$$

由于 $v_{m,i+1} = z_{i+1} + \chi_{i+1} = z_{i+1} + S_{i+1} + \alpha_i$, 可得

$$\dot{z}_i z_i \leq \frac{1}{2} z_{i-1}^2 - (l_i - 2) z_i^2 + \frac{1}{2} z_{i+1}^2 + \frac{1}{4} S_{i+1}^2. \quad (27)$$

步骤 n 定义动态面 $z_n = v_{m,n} - \chi_n$, 则

$$\dot{z}_n = \dot{v}_{m,n} - \dot{\omega}_n = \sigma_0(y)u + v_{m,n+1} - k_n v_{m,1} - \dot{\chi}_n. \quad (28)$$

选取如下的控制律

$$u = -\frac{1}{\sigma_0(y)}(-l_n z_n - v_{m,n+1} + k_n v_{m,1} + \dot{\chi}_n), \quad (29)$$

其中 l_n 为正的设计参数; 选取如下的自适应律 $\dot{\hat{\theta}} = \mu_1 \bar{\omega} z_1$, $\dot{\hat{\kappa}} = \mu_2 z_1 \bar{\alpha}_1$, $\bar{\alpha}_1 = l_1 z_1 + \eta_2 + \varphi_{0,1}(y) + \bar{\omega}^T \hat{\theta} - \dot{y}_d$, 其中 μ_1, μ_2 为正常数. 则闭环控制系统所有信号将半全局一致终结有界, 且选取适当的参数, 跟踪误差会收敛到原点的一个邻域内.

2.3 稳定性分析

考虑如下的 Lyapunov 函数

$$V = \frac{1}{2} \sum_{i=1}^n z_i^2 + \frac{1}{2d} \sum_{i=1}^n \delta^T P \delta + \frac{1}{2\mu_1} \bar{\theta}^T \bar{\theta} + \frac{1}{2\mu_2} \bar{\kappa}^T \bar{\kappa} + \frac{1}{2} S_i^2, \quad (30)$$

其中 $z = [z_1, z_2, \dots, z_n]^T$. 设有界函数 $B_i < M_i, M_i > 0, i = 2, \dots, n$.

将 $V(t)$ 对时间 t 求导, 同时将控制律以及自适应律代入式 (30), 并利用 Young 不等式, 整理得

$$\dot{V} \leq -\left(l_1 - 2b_M - \frac{3}{4}\right) z_1^2 - \left(l_2 - \frac{3}{4}b_M - \frac{5}{2}\right) z_2^2 - \sum_{i=3}^{n-1} \left(l_i - \frac{5}{2}\right) z_i^2 - \left(l_n - \frac{1}{2}\right) z_n^2 - \left(\frac{1}{2d} - \frac{1}{4}\right) \sum_{i=1}^n \|\delta_i\|^2$$

$$-\left(\frac{1}{\varepsilon_2} - \frac{1}{4}b_M - 1\right)S_2^2 - \sum_{i=3}^n \left(\frac{1}{\varepsilon_i} - 1\frac{1}{4}\right)S_i^2 + \frac{1}{4}\sum_{i=2}^n M_i^2. \quad (31)$$

由以上假设可知 $v = \frac{1}{4}\sum_{i=2}^n M_i^2$ 有界, 所以如果选择 l_i 足够大 ε_i 足够小, 各参数选取合理时, 可以实现 $\dot{V}(t) \leq -cV(t) + v$, $c > 0$, 上式两边同乘以 e^{ct} 得

$$\frac{d}{dt}(V(t)e^{ct}) \leq e^{ct}v. \quad (32)$$

对上式求定积分得

$$0 \leq V(t) \leq \frac{v}{c} + \left[V(0) - \frac{v}{c}\right]e^{-ct} \leq \frac{v}{c} + V(0) = v_0. \quad (33)$$

由 v_0 有界可得 $V(t)$ 有界. 由式 (30) 可得

$$\|\tilde{\theta}\|^2 \leq \frac{2\mu_1 v}{c}, \quad z_i^2 \leq \frac{2v}{c}, \quad \|\delta\|^2 \leq \frac{2dv}{c\lambda_{\min}(\mathbf{P})}, \quad \tilde{\kappa}^2 \leq \frac{2\mu_2 v}{c}, \quad S_i^2 \leq \frac{2v}{c}, \quad i = 1, 2,$$

所以 $\tilde{\theta}$, z_i , δ , κ , S_i 都是有界的, 可选取较大的 c 值使得 v/c 充分小, 从而使跟踪误差 z_1 在有限时间后变得适当小, 从而实现跟踪误差 z_i 收敛到原点的一个小领域内. 同样可实现经过有限时间后 $\delta \rightarrow 0$, 实现观测器误差的收敛性.

3 高超声速飞行器自适应容错控制设计

高超声速飞行器是强耦合强非线性系统, 通道间解耦较难, 所以在此寻求可直接使用的纵向通道模型. 由于高超声速飞行器 Winged-Cone 的气动参数已公开, 同时 Langley 研究中心还公开了 Winged-Cone 在平衡巡航条件下的纵向动力学模型^[14].

假设 3 在本文讨论的平衡巡航阶段, 飞行器的速度保持恒定不变.

假设 4 忽略发动机动态, 只考虑舵偏角 δ_e 做输入的飞行器控制情况.

假设 5 假设纵向角速率信号不能得到, 即系统状态向量不完全可测量.

则可得到高超声速飞行器的纵向通道动力学模型

$$\begin{cases} \dot{\alpha} = q - \dot{\gamma}, \\ \dot{q} = M_{yy}/I_{yy}, \\ \dot{\gamma} = \frac{L + T \sin \alpha}{mv} - \frac{(\mu_g - v^2 r) \cos \gamma}{vr^2}, \end{cases} \quad (34)$$

式中, $L = 0.5\rho v^2 S C_L$, $T = 0.5\rho v^2 S C_T$, $M_{yy} = 0.5\rho v^2 S c[C_M(\alpha) + C_M(\delta_e) + C_M(q)]$, $r = h + R_e$, $C_L = 0.6203\alpha$,

$$C_T = \begin{cases} 0.025768\beta_0, & \beta_0 < 1, \\ 0.0224 + 0.00336\beta_0, & \beta_0 > 1, \end{cases}$$

$$C_M(\alpha) = -0.035\alpha^2 + 0.036617\alpha + 5.3261 \times 10^{-6}C_M(q) = (c/2v)q(-6.796\alpha^2 + 0.3015\alpha - 0.2289),$$

$$C_M(\delta_e) = c_e(\delta_e - \alpha),$$

其中 v, γ, h, α, q 分别表示飞行器的速度、航迹倾斜角、高度、迎角和纵向角速率. T, D, L 和 M_{yy} 分别表示推力、阻力、升力和纵向转动动力矩, m, I_{yy}, S, μ_g 和 R_e 分别表示飞行器的质量、纵向转动惯量、参考气动面积、重力常数和地球半径, c 和 c_e 为常数. 控制输入量为舵偏角 δ_e 和燃气流设置 β_0 . 其他参数说明参见文献 [15].

3.1 纵向动力学系统建模

将航迹倾斜角 γ 方程代入迎角 α 方程中, 由于航迹倾斜角 γ 比较小, 所以在此近似为 $\cos \gamma \approx 1$, 从而减少一个状态变量. 设 $x_1 = \alpha$, $x_2 = q$, $u_1 = \beta_0$, $u_2 = \delta_e$, 假设纵向角速率 q 不能测量得到, 以迎角 α 作为输出, 则高超声速飞行器的纵向动力学模型可表示为

$$\begin{cases} \dot{x}_1 = x_2 + f_1(x_1), \\ \dot{x}_2 = f_2(x_1, x_2) + g_1(x_1)u_1 + g_2u_2, \\ y = x_1, \end{cases} \quad (35)$$

式中

$$f_1(x_1) = c_1(0.6203\alpha + 0.02318 \sin \alpha) + \frac{\mu - v^2 r}{vr^2}, \quad c_1 = \frac{0.5\rho v^2 S}{mv}, \quad c_2 = \frac{0.5\rho v^2 S c}{I_{yy}},$$

$$f_2(x_1, x_2) = c_1[-0.035\alpha^2 + (0.036617 - c_e)\alpha] + (c/2v)q(-6.796\alpha^2 + 0.3015\alpha - 0.2289) + c_2 5.3261 \times 10^{-6},$$

$$g_2 = c_1 c_e, \text{ 其中 } m = 9375, I_{yy} = 7, S = 3603, c = 80, c_e = 0.0292, \rho = 0.24325, g_1(x_1)u_1 = 0.5\rho v S C_T \sin \alpha / m.$$

设作动器故障发生在燃气流设置 β_0 环节 ($u_1 = \bar{u}$), 由故障产生的输入系数 a_1, b_2 未知, 舵偏角 δ_e 正常工作 ($u_2 = u$). 则式 (35) 可进一步表示为

$$\begin{cases} \dot{x}_1 = x_2 + f_1(x_1), \\ \dot{x}_2 = f_2(x_1, x_2) + \sigma(x_1)a_1 + b_2 g_2 u, \\ y = x_1. \end{cases} \quad (36)$$

式中,

$$\sigma(x_1) = \frac{0.5\rho v S}{m} \cdot \sin \alpha.$$

3.2 仿真结果

采用本文所提算法, 设计滤波器为

$$\dot{\eta} = A_0 \eta + K_0 y + \varphi(y), \quad \dot{\xi} = A_0 \xi + H(y), \quad \dot{\lambda} = A_0 \lambda + e_2 \sigma(y)u,$$

其中, $\varphi(y) = [f_1(x_1) \quad f_2(x_1, x_2)]^T$, $a = [0 \quad a_1]^T$, $b = b_2$, $H(y) = \begin{bmatrix} 0 & 0 \\ 0 & \sigma(x_1) \end{bmatrix}$, $v_0 = \lambda$, $k_1 = 3$, $k_2 = 2$, $l_1 = 7$, $\varepsilon_2 = 0.2$, $\sigma_0(y) = g_2$ 为常值. 状态跟踪值为 $x_{1d} = 2$, 仿真初始条件为飞行速度 $v = 15 \text{ Ma}$, 高度 $h = 30 \text{ km}$. 仿真结果如图 1~4 所示. 图中 x_1 为迎角 α , x_2 为航迹倾斜角 γ , 图 3 和 4 为向量 α 和 q 的误差输出曲线. 图 1 中迎角 α 的输出有微小的跃变, 这主要是由于虚拟控制量 α_1 的设计中存在待调试的自适应参数造成的, 而且跃变的幅度较小, 在允许的误差范围内, 收敛速度较快, 因此可以认为正常. 总体来说从仿真结果可以看出系统跟踪误差具有良好的收敛性.

4 结语

本文对高超声速飞行器飞行过程中遇到部分作动器故障问题, 提出了一类观测器设计方法, 推导出相应的数学表达形式, 将该问题转化为一类最小相位系统输出反馈控制问题, 在状态变量不能够完

图 1 x_1, x_2 仿真曲线Figure 1 Simulation curve of x_1, x_2 图 2 u 仿真曲线Figure 2 Simulation curve of u 图 3 e_α 仿真曲线Figure 3 Simulation curve of e_α 图 4 e_q 仿真曲线Figure 4 Simulation curve of e_q

全测量情况下, 采用基于动态面技术的自适应反演控制方法, 解决了部分作动器故障带来的系统参数未知问题, 提出一种新颖的基于 K -滤波器理论的观测器和控制器一体化设计思路, 并利用高超声速飞行器纵向通道动力学模型进行仿真实证。

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Hypersonic aircraft adaptive fault-tolerant controller design

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Abstract The hypersonic aircraft control system design must deal with the extra prominent dynamics characteristics: highly coupled, strongly nonlinear, time variational and so on. Thus, during the course of control system study and design for the hypersonic aircraft, the following factors must be considered: plant elastic deformation, multi-inputs multi-outputs, uncertain aerodynamic parameters, sensors and actuator failures, which is differ from the traditional aircrafts control system design. To solve the failure problem of the actuator in the course of the hypersonic aircraft flight, one kind of adaptive backstepping fault-tolerant control method based on the observer and controller designed synthetically is brought up. At first, we develop the research model based on a SISO output feedback nonlinear unobserved minimum phase system under the condition of single channel actuator failure of the hypersonic aircraft, then adopt K -filter to reconstruct state vectors. When only the output is measurable, the dissertation designs one new observer to estimate convergence state vector and design the adaptive control law to guarantee the system boundedness. In the course of adaptive backstepping design, the dissertation employs the dynamic surface control strategy to eliminate the explosion of terms by introducing a series of first order filters to obtain the differentiation of the virtual control inputs. Lyapunov stability theorem guarantees the error uniformly bound. Both theory analysis and simulation verification show the simplicity and effectiveness of this method. At last the pitch channel of hypersonic aircraft is studied as an example to validate the above theory.

Keywords hypersonic aircraft, observer, K -filter, dynamic surface adaptive backstepping, fault-tolerant control

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