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Nonlinear robust control of hypersonic aircrafts with interactions between flight dynamics and propulsion systems

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ABSTRACT

This paper addresses the nonlinear robust tracking controller design problem for hypersonic vehicles. This problem is challenging due to strong coupling between the aerodynamics and the propulsion system, and the uncertainties involved in the vehicle dynamics including parametric uncertainties, unmodeled model uncertainties, and external disturbances. By utilizing the feedback linearization technique, a linear tracking error system is established with prescribed references. For the linear model, a robust controller is proposed based on the signal compensation theory to guarantee that the tracking error dynamics is robustly stable. Numerical simulation results are given to show the advantages of the proposed nonlinear robust control method, compared to the robust loop-shaping control approach.

1. Introduction

Hypersonic vehicles (HVs) are intended to serve as reliable and cost-efficient space platforms to get access to the near space by reducing the flight time [1]. The feasibility of these new vehicles has been confirmed by the successful experimental flight tests of the NASA's X-43A airplane [2]. The glide phase maneuver mission of the unmanned Falcon hypersonic test vehicle was failed in 2011. The robust controller design of these vehicles is one of the key challenges to make HVs feasible and reliable. Furthermore, the robust control laws should guarantee the stability and the tracking control performances of the closed-loop control systems for HVs.

The special characteristics of the HVs' dynamics, however, pose a challenge for their robust tracking controller design. The longitudinal model of the HVs' dynamics involves high nonlinearity and strong coupling between the flight dynamics and the propulsion systems [3,4], as well as large model mismatches. Furthermore, HVs are very sensitive to the aerodynamic parameter variations and the external atmospheric disturbances. All these dynamic features may seriously affect the tracking control performances of the designed closed-loop control systems. Actually, the vehicle dynamics involves nonlinearities, couplings, and multiple uncertainties including parametric uncertainties, model mismatch uncertainties, and external disturbances simultaneously. Therefore, the robustness properties of the designed closed-loop control system are hard to be guaranteed. Fuzzy controllers were designed for the hypersonic vehicles in [5] to achieve the robust flight. In [6], based on the guaranteed cost control algorithm and the poles assignment technique, an admissible controller was designed to guarantee the prescribed tracking performance costs. But, the effects of the uncertainties on the control system were not further discussed in the stability analysis in [5,6]. Adaptive based control strategies were studied in [7–11] to enhance the robustness properties of the closed-loop control system against nonlinear and coupling dynamics, as well as uncertainties including parametric uncertainties. However, a transient period is required for the adaptive based control approaches to estimate the actual values of the uncertain parameters and thereby the dynamic tracking performances of the proposed control system cannot be specified. Nonlinear disturbance observers were introduced to design robust control controllers in [12,13] to reduce the effects of several uncertainties. In [14–16], parameter-varying modeling and control methods were studied. Several factors including uncertain parameters and external disturbances were discussed for the designed closed-loop control system, but further discussions on other uncertainties were ignored in the further stability proof.

Conventionally, the HVs' trajectory tracking control problems at the trim states can be addressed by the linear robust control methods such as H_∞ control approach, loop-shaping control scheme, and μ-synthesis (see, for example, [3] to mention a few).

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In this case, the parameter variations and nonlinear and coupling dynamics are usually considered as uncertainties in their controller design, which may result in the conservation problem of the robust linear controller design. Furthermore, back-stepping based strategies for the longitudinal motion of near space vehicles were presented in [17,18]. By these techniques, the known information on the nonlinear and coupling dynamics can be used and thus the conservation of the robust controller design can be reduced. However, the designed closed-loop control system only by the back-stepping control method is hard to be robust against multiple uncertainties. An alternative choice is to combine the back-stepping technique and the robust loop-shaping control approach to achieve the robust flight for HVs. But, the influences of the uncertainties on the control systems cannot be restrained in the whole frequency range by this control method.

This paper is aimed to propose a nonlinear robust controller for the longitudinal dynamics of the HVs. The proposed robust controller consists of a feedback linearization controller and a linear robust controller. The feedback linearization technique is firstly applied to achieve output/input linearization for the longitudinal model, which leads to a linear error model of the HVs. The linear model is considered as a nominal linear model with equivalent disturbances, which do not satisfy the matching conditions. The equivalent disturbances include parametric uncertainties, model mismatch uncertainties, external disturbances, and nonlinear dynamics, which cannot be counteracted accurately by the feedback linearization method. Then, a linear robust controller consisting of a nominal controller and a robust compensator is designed for the obtained linearized model. The nominal controller based on the pole assignment scheme is applied to guarantee that the outputs of nominal linear systems can track the desired velocity and height references; the robust compensator is introduced to restrain the effects of the uncertainties mentioned above on the closed-loop control system.

Compared to previous researches on the robust controller design for uncertain HVs, the results shown in this paper have the following features simultaneously:

First, the effects of the known nonlinear and coupling dynamics and equivalent disturbances including parametric uncertainties, model mismatch uncertainties, external disturbances, and unknown nonlinear dynamics on the control systems can be restrained. The equivalent disturbances can be dissatisfied with the matching conditions.

Second, the conservation of the robust controller design can be reduced. Actually, for the traditional robust linear controller design, the nonlinear and coupling dynamics are considered as uncertainties and included in the uncertainty terms, which may lead to an increase of the upper norm-bounds of the uncertainty terms and the conservation problem. In this paper, the information on the known nonlinear and coupling dynamics is used in the nonlinear controller design and their effects on the closed-loop control systems can be counteracted by the feedback linearization technique, which would result in the conservation reduction of the robust controller design.

Third, the velocity and height tracking errors are proven to be guaranteed to converge into a priori set neighborhood of the origin in a finite time. Compared to the mixed-sensitivity loop-shaping control approach, the effects of the uncertainties can be restrained as small as desired in the whole frequency range by the proposed control method.

This paper is organized as follows: in Section 2, the longitudinal dynamic model of the HSVs is briefly introduced; the nonlinear robust control method is proposed in Section 3; the robust stability and the robust tracking properties are proven in Section 4; the simulation comparisons are shown in Section 5 and conclusions are drawn in Section 6.

2. Hypersonic vehicle model

The control-oriented model of the longitudinal dynamics of generic hypersonic vehicles presented in this paper is originally developed by NASA Langley Research Center, as shown in [18]. This vehicle model includes five state variables $(V, h, \gamma, \alpha, q)$, where V represents the velocity, h the altitude, γ the flight path angle, α the attack angle, and q the pitch rate. The mathematical descriptions of the longitudinal dynamics for HVs can be obtained via Lagrange's equations as follows:

$$\begin{aligned}
\dot{V} &= (T\cos\alpha - D)/m - \mu\sin\gamma/r^2 + d_V,\\
\dot{h} &= V\sin\gamma + d_h,\\
\dot{\gamma} &= (L + T\sin\alpha)/m/V - \left(\mu - V^2 r\right)\cos\gamma/V/r^2 + d_\gamma,\\
\dot{\alpha} &= q - \dot{\gamma} + d_\alpha,\\
\dot{q} &= M_y/I_y + d_q,
\end{aligned} \tag{1}$$

where m, μ, and I_y are the mass, gravitational constant, and moment of inertia, respectively. $r = h + r_e$, where r_e is radius of the Earth. $d_i\ (i = V, \gamma, q, \alpha, h)$ are external bounded time-varying atmospheric disturbances. T, L, D, and M_y represent the thrust force, lift force, drag force, and pitching moment satisfying that

$$\begin{aligned}
T &= \rho V^2 S C_T/2,\\
L &= \rho V^2 S C_L/2,\\
D &= \rho V^2 S C_D/2,\\
M_y &= \rho V^2 S\bar{c}\left(C_{M\alpha} + C_{M\delta e} + C_{Mq}\right)/2,
\end{aligned} \tag{2}$$

where ρ, S, and $\bar{c}$ denote the air density, reference area, and mean aerodynamic chord, respectively. As shown in [13], C_T, C_L, C_D, $C_{M\alpha}$, $C_{M\delta e}$, and C_{Mq} are coefficients of thrusts and moments, which can be determined by the following equations:

$$\begin{aligned}
C_T &= \begin{cases} 0.02576\beta + d_1 & \beta < 1,\\ 0.02440 + 0.00336\beta + d_2 & \beta > 1,\end{cases}\\
C_L &= 0.6203\alpha + d_3,\\
C_D &= 0.6405\alpha^2 + 0.0043378\alpha + 0.003772 + d_4,\\
C_{M\alpha} &= -0.035\alpha^2 + 0.036617\alpha + 5.3261\times 10^{-6} + d_5,\\
C_{M\delta e} &= 0.0292\left(\delta_e - \alpha + d_6\right).\\
C_{Mq} &= \left(0.5\bar{c}q/V\right)\left(-6.796\alpha^2 + 0.3015\alpha - 0.2289 + d_7\right),
\end{aligned} \tag{3}$$

where β is the throttle setting, δ_e is the elevator deflection, and $d_i\ (i = 1, 2, \ldots, 7)$ are model uncertainties representing the mismatches between the truth model and the control-oriented model, which are considered as additive perturbations and assumed to be norm bounded. The scramjet engine model can be described by a second order system as follows:

$$\ddot{\beta} = -2\xi_n\omega_n\dot{\beta} - \omega_n^2\beta + \omega_n^2\beta_c + d_\beta, \tag{4}$$

where β_c, ω_n, and ξ represent the throttle setting command, natural frequency for the β dynamics, and damping ratio for the β dynamics, respectively, and d_β represents the external bounded disturbance.

From the longitudinal dynamics described by Eqs. (1)–(4), one can see that there exist serious couplings between the velocity and height channels, especially the interactions between the flight dynamics and propulsion systems. Besides, it is obvious that the vehicle systems are highly nonlinear, which pose a challenge for their controller design.

For the longitudinal model, the velocity V and the altitude h are chosen as the outputs and required to track the prescribed given commands, which are devoted by V_c and h_c, respectively. The aim of the paper is to achieve robust tracking properties of the closed-loop systems under the influences of highly nonlinearity and uncertainties, by designing a nonlinear robust controller.