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Synthesis of attitude control for statically unstable hypersonic vehicle with low-frequency aero-servo-elastic effect

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ABSTRACT

In this paper, an integrated attitude control scheme is proposed for a statically unstable hypersonic vehicle (HSV) with low-frequency aero-servo-elastic effect. Linear active disturbance rejection control (LADRC) is designed for the pitch angle to address the strong uncertainties and coupling effects. For the particular aero-servo-elastic effect with low frequency, a hybrid phase and gain stabilization technique is embedded into the LADRC framework to suppress the structural modes, which can reduce the phase loss around the crossover frequency. To achieve satisfactory tracking performance and robustness, a non-smooth H_∞ optimization approach is applied to tune the controller gains, which simplifies the tuning and gain scheduling process. Monte Carlo simulation results demonstrate the effectiveness of the proposed control scheme.

1. Introduction

The demands of high flight velocity and exploitation in near space are driving the development of hypersonic vehicle (HSV). In the 1960's, National aeronautics and space administration (NASA) started the research of the scramjet propulsion system, which is the key technique of hypersonic flight. With the success of the scramjet-powered Mach 7 and 10 flights of X-43A in 2004 [1], the possibility of a reliable and affordable access to the space and global reaching has brought a resurgence to the HSV research.

Different from conventional flight vehicles, there are three main challenges in the control of the air-breathing HSV:

(1) It is extremely difficult to get an accurate model of the HSV due to the intricate aero-thermo-elastic-propulsion interactions [2], and besides that the aerodynamic and environmental characteristic parameters have large variations during the hypersonic flight. Thus, the control-oriented model suffers from strong modeling errors, aerodynamic parameter uncertainties and external environmental disturbances, wherein a highly robust controller is required.
(2) The longitudinal dynamics of the HSV may be statically unstable due to the propulsion/airframe integration design, and a high-bandwidth controller is necessary for the stabilization of the unstable short-period modes. However, the low-frequency aero-servo-elastic modes, which are caused by the slender configuration and lightweight airframe, can be excited by such a high-bandwidth controller and the stability may be violated [3]. Therefore, notch filters are designed to restrain structural modes in the traditional method, while large phase lag around the crossover frequency is introduced and the robustness is degraded. Consequently, an integrated control strategy that can achieve robust output tracking and low-frequency aero-servo-elastic mode suppression is urgently needed.
(3) The HSV has fast time-varying dynamics within a wide flight envelope. The controller is required to realize satisfactory performance over the entire range of operating points, which makes the design process even more complicated and time-consuming [4]. An efficient approach is needed to reduce the design cost as well.

Regarding the aforementioned challenges, many methods have been proposed. Linear parameter varying control [5,6], fixed-order robust control [7], linear quadratic regulator [8] and linear active disturbance rejection control (LADRC) [9,10] have been studied within the linear control framework; and adaptive control [11–14],

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sliding mode control [15–18], neural network control [19–22] are the main nonlinear control methods for HSV. Among these control methods, the research focus of HSV is the robust tracking control under diverse uncertainties and aero-elastic effect. The servo-elastic problem was rarely considered [3,5,6,23]. However, the servo-elastic issue due to the flexible deformation at the sensor position is actually more significant than the aero-elastic problem in practice. Ignoring the servo-elastic effect may underestimate the impact of structural dynamics to a great extent, and then the flexible modes may be excited which could destroy the closed-loop stability. Consequently, the servo-elastic problem must be taken into account together with the aero-elastic problem during controller design. Gain stabilization [24–26] and phase stabilization [3,6,23,27,28] are the major approaches to handle the aero-servo-elastic problem. Gain stabilization refers to the passive suppression approach of designing notch filter, which is widely used in practice. However, the phase lag around the crossover frequency produced by the filter will degrade the phase margin greatly for the unstable HSV with low-frequency structural modes. To solve this problem, the phase stabilization, which is an active suppression technique and can be used to stabilize and damp the structural modes by optimizing the sensor position, was proposed. This method avoids the loss of phase margin and is more robust to the uncertainties of the structural dynamics compared with the gain stabilization. However, the phase stabilization can not be applied to nonlinear control methods and is only employed with a few linear controllers possessing simple structures like the proportional derivative (PD) controller [3,6,27] and the dynamic compensator [23].

Motivated by the challenges and the analysis mentioned above, an integrated attitude control scheme, which incorporates LADRC, hybrid phase and gain stabilization and non-smooth H_∞ synthesis technique is proposed in this paper to solve the aforementioned three control challenges. Active disturbance rejection control (ADRC), which is a novel control philosophy to attenuate uncertainties, was proposed by Han [29] and then simplified into LADRC by Gao [30]. LADRC can handle the strong uncertainties, nonlinearities and coupling effects of the HSV in a simple and effective way by regarding all these effects as a total disturbance and estimating it through the extended state observer (ESO). Little model information is required in the controller design. Besides, frequency analysis, which is required especially for the flexible mode suppression issue, can be performed under the LADRC framework. Thus, LADRC is applied to the HSV attitude control in this paper. Owing to the straightforward structure of LADRC, the phase stabilization can be embedded into LADRC framework to deal with the low-frequency aero-servo-elastic problem, and the condition under which the flexible modes can be stabilized actively is presented accordingly. The integration of phase stabilization into LADRC can avoid the loss of phase margin and thus improve the dynamic performance and robustness, which is more advantageous than the previous LADRC scheme for flexible mode suppression wherein notch filters are designed to suppress all the flexible modes without considering the impact of the rate gyro position. The phase stabilization can be employed to stabilize the structural modes, and then traditional notch filters can be designed for the left structural modes that can not be phase stabilized. It should be noted that non-smooth H_∞ synthesis technique [31–33], which is an efficient optimization approach to tune fixed-order linear controller, is utilized for LADRC. The performance requirements are represented in form of the weighed functions designed for the closed-loop transfer functions, and then the controller minimizing the H_∞ norm of the weighed closed-loop transfer functions can be obtained. Thereafter, a proper gain scheduling scheme can be selected to fit the optimization results.

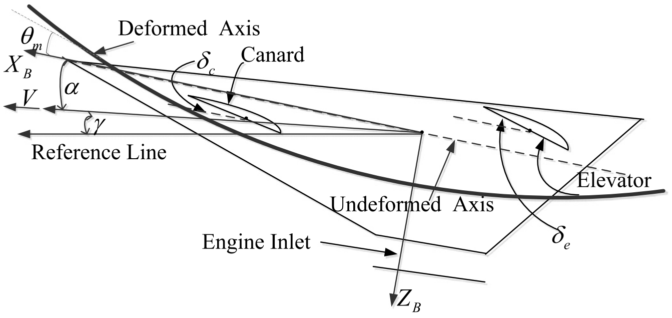

Fig. 1. Configuration of the flexible hypersonic vehicle.

The remainder of the paper is organized as follows. The HSV model and the corresponding control problem are formulated in Section 2. The integrated attitude control scheme is proposed in Section 3. Section 4 illustrates the parameter tuning procedure. The optimization results within the entire designed flight envelope and the Monte Carlo simulation results are provided in Section 5. Finally, concluding remarks are given in Section 6.

2. Problem formulation

The HSV model studied in this paper is a curve fitted control-oriented model proposed by [34], wherein the flexible HSV was modeled as a traditional free beam to eliminate the initial coupling in [35]. A redundant canard is added in this model to improve flight path angle dynamics and stabilize the structural dynamics [36,37]. The sketch of the flexible HSV is shown in Fig. 1. Assuming a flat earth and unit vehicle depth, the motion equation of the longitudinal dynamics can be written as

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

This model consists of five rigid-body states $\boldsymbol{x} = [V, h, \gamma, \alpha, Q]^T$, which represent the velocity, altitude, flight path angle, angle of attack and pitch angular rate, respectively; $\boldsymbol{\eta} = [\eta_1, \dot{\eta}_1, \eta_2, \dot{\eta}_2, \eta_3, \dot{\eta}_3]^T$ are the six flexible states, which are the mass-normalized generalized coordinate η_i and its time-derivative $\dot{\eta}_i$ of the first three structural modes; ω_i and ζ_i are the natural frequency and the damping ratio of the flexible modes, respectively; m and I_{yy} are the mass and the moment of initial. The thrust T, the lift L, the drag D, the pitching moment M and the generalized force N_i are expressed as

$$\begin{aligned} T &= \bar{q}S\left[C_{T,\Phi}(\alpha)\,\Phi + C_T(\alpha) + \boldsymbol{C}_T^{\boldsymbol{\eta}}\boldsymbol{\eta}\right] + \Delta T \\ L &= \bar{q}SC_L(\alpha, \delta_e, \delta_c, \boldsymbol{\eta}) + \Delta L \\ D &= \bar{q}SC_D(\alpha, \delta_e, \delta_c, \boldsymbol{\eta}) + \Delta D \\ M &= z_T T + \bar{q}S\bar{c}C_M(\alpha, \delta_e, \delta_c, \boldsymbol{\eta}) + \Delta M \\ N_i &= \bar{q}S\left(N_i^{\alpha^2}\alpha^2 + N_i^{\alpha}\alpha + N_i^{\delta_e}\delta_e + N_i^{\delta_c}\delta_c + N_i^0 + \boldsymbol{N}_i^{\boldsymbol{\eta}}\boldsymbol{\eta}\right) \\ &\quad + \Delta N_i \end{aligned} \tag{2}$$