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Modeling and nonlinear control for air-breathing hypersonic vehicle with variable geometry inlet

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Abstract

This paper develops a control method for an air-breathing hypersonic vehicle with variable geometry inlet (AHV-VGI). For the AHV-VGI, a movable translating cowl is used to track the shock on lip conditions to capture enough air mass flow, which can ensure a more powerful thrust. Compared with traditional air-breathing hypersonic vehicle with fixed geometry inlet (AHV-FGI), this AHV-VGI extends the velocity range, which is favorable to the acceleration and maneuvering flight. However, the VGI causes the unknown changes of the aerodynamic forces, moment and the thrust in the meanwhile. Therefore, we firstly establish a longitudinal dynamic for AHV-VGI, which includes the uncertain changes induced by VGI. A conception of the optimal elongation distance of translating cowl is introduced, and its estimated value is obtained by curve fitted approximation. And then, the control process for AHV-VGI is divided into two subsystems. For each subsystem, a sliding mode controller is designed, and interval type-2 fuzzy logic systems (FLSs) are adopted to approximate nonlinear parts including the uncertain changes induced by VGI. Furthermore, uniformly stability of the whole system is proved by Lyapunov approach. Finally, simulation results demonstrate that AHV have a better control performance under the condition of VGI compared to the FGI.

Keywords: hypersonic vehicle, variable geometry inlet, movable translating cowl, type-2 fuzzy system, sliding mode control

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1. Introduction

In recent years, air-breathing hypersonic vehicle (AHV) have attracted a great deal of attention, mainly because of reliable, affordable, routine access to space and prompt global reach [1][2][3]. Both of the technical advantages have commercial as well as military implications, as witnessed by the success of NASA's scramjet-powered X-43A and X-51A[4][5]. This type of vehicle has a unique design, incorporating a supersonic combustion scramjet engine located beneath the fuselage. This configuration can exhibit good performance in the range of Mach 4-7, but it causes severe aero-propulsion interactions and uncertainties, which result in highly nonlinear, strongly coupling, and fast time varying, with a great amount of parameter uncertainties as well as unknown external disturbances [6][7]. Therefore, the dynamics modeling and flight control design of AHV become one of the most challenging problems.

For modeling of hypersonic vehicle for control design, generally, there are three kinds of dynamics models in the open literature. The first model is Winged-Cone configurature called the generic hypersonic vehicle (GHV)[8]. The GHV model was developed to support NASA funded conceptual design studies of hypersonic flight vehicles. The aerodynamic characteristics of the vehicle were developed using a CFD-based study conducted jointly at NASA Langley and Rockwell International[9][10]. Based on the aerodynamic data, A model for the longitudinal dynamics of GHV was presented and dynamic inversion was adopted to design nonlinear robust controller[11][12]. The second dynamics model of hypersonic vehicle is a plane symmetrical configurature AHV. The model is the first analytical aeropropulsive/aeroelastic AHV model. In this model, a two-dimensional hypersonic aerodynamic analysis using Newtonian theory was used, coupled with a one-dimensional aerothermodynamic analysis of the flow within a scramjet-type propulsion system[13]. Subsequently, some dynamic and robustness analysis were given based on this model[14][15]. The third model of AHV was developed by U.S. Air Force Research Laboratory (AFRL) engineers. This model captures many of the complex interactions between the propulsion system, the aerodynamics, and the structural dynamics, resulting in a more accurate and substantially more complex model[16]. Subsequently, for reducing the difficulty for nonlinear control of AHV, Parker established a rigid body/elastic body coupling model of hypersonic vehicle oriented for control. This model includes the coupling between the engine and flight mechanics, the coupling between compliant modes and rigid modes and the influence of these couplings on design of the control system [17]. Whatever the model is, steering the state to a desired trim condition along some reference trajectories is the main problem for AHV. Many of control methods and techniques have been applied to flight control design of AHV, such as linear quadratic regulator control[18], robust control[19], adaptive control[20], sequential loop closure controller design[21], slid-

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