An Overview on Control Approach for Hypersonic Vehicles

Abu Yusuf Mahmudunnabi
Nanchang Hangkong University

A thesis submitted for the degree of
Bachelor of Engineering
May 2020

ACKNOWLEDGEMENTS

First of all, I want to thank God above for the grace and strength to make it through my four-year undergraduate studies, and giving me success even greater than my expectation.
Secondly, I would like to express my profound appreciation and gratitude towards my supervisor and guide Associate Prof. Longsheng Chen, who has been the guiding force behind this work. I am greatly obliged to him for his constant inspiration, invaluable advice and for always making time for me despite his busy schedule. I consider it a good opportunity to work with such a wonderful person.

I also extend my thanks to Mr. Zhang and all staff of the International School of Nanchang Hangkong University for their Constant Support throughout my undergraduate courses.

I would like to thank all my classmates and friends for all the selfless and mind stimulating discussions we had in and out of the classroom, which prompted us to think beyond the obvious. I have enjoyed their comradeship so much during my course.

Not forgetting my family and loved ones for believing in me, for the emotional and financial support. I couldn't have made it without them.

Table of Contents

List of Figures

Abstract

Hypersonic flight, characterized by speeds exceeding Mach 5, occurs within the atmospheric region below approximately 90 km. At such velocities, air dissociation becomes significant, and extreme heat loads are generated, necessitating the development of sophisticated control systems. Hypersonic flight vehicles hold great promise in providing a more dependable and cost-efficient means of accessing space.

The crux of achieving feasible and efficient hypersonic flight lies in the design of robust controllers, which face numerous challenges due to the vast flight envelope and the wide array of operational conditions. The intricate interactions between the elastic airframe, propulsion system, and structural dynamics further amplify the complexity of controller design.

This thesis paper offers a concise overview of current research on hypersonic flight control, highlighting several studies and advancements in the field. The presented studies aim to address the intricate control requirements associated with hypersonic flight, with the ultimate goal of realizing safe, efficient, and practical hypersonic flight capabilities.

Keywords

Hypersonic Flight, Flight Control, Aerospace Dynamics, Nonlinear Control, Linear Control, Controller Design, back-stepping, Actuator Dynamics, Flight Envelope, Robust Control, Adaptive Control, Aero-thermoelastic Effects, Transient Performance, Non-minimum Phase, Aerodynamic-jet Control, Re-entry Phase, Flexible Hypersonic Vehicles, Uncertainty Estimation, Aeroelasticity, Input-output Linearization, Small Perturbation Method.

Chapter 1: Introduction

1.1 Background and significance

Hypersonic vehicles are aerospace vehicles designed to navigate the atmosphere at speeds surpassing Mach 5 while flying below an altitude of approximately 90 km. At such tremendous velocities, the phenomenon of air segregation becomes highly significant, leading to the development of high heat loads. Historically, hypersonic vehicles have utilized rocket boosters to achieve their exceptional speeds, thereby classifying any object traveling faster than Mach 5 as hypersonic. However, despite some vehicles reaching hypersonic speeds, such capabilities have often been limited to brief durations, as seen in the case of the space shuttle orbiter during its re-entry into the Earth's atmosphere.

The advent of cutting-edge technologies, especially hypersonic vehicles, has triggered a revolution in military affairs. The strategic advantages offered by these vehicles, owing to their unparalleled speed and maneuverability, provide any nation possessing such advanced technology with a distinct edge over potential adversaries. As hypersonic vehicles are incorporated into military arsenals, they introduce a level of uncertainty for rival nations, as tracking and countering these highly advanced weapons become increasingly challenging.

Furthermore, the dual-use nature of hypersonic vehicles adds complexity to the situation, making it difficult for adversaries to discern whether an approaching vehicle is a conventional weapon or potentially carries nuclear capabilities. This ambiguity intensifies the competition among nations to bolster their research and deployment of hypersonic technologies, as maintaining a strategic advantage in modern military landscapes becomes a paramount objective.

Overall, the exploration of hypersonic vehicles and their role in military affairs holds significant importance in understanding how these technological advancements shape global security dynamics, fueling the pursuit of superior capabilities for safeguarding national interests.

1.2 Research Status of the Subject

The study of hypersonic flight has a long-standing history, dating back to the X-15 program, which was specifically designed to prepare for spaceflight. Notably, in 1967, the X-15 experimental manned vehicle, powered by liquid rocket propulsion, achieved a remarkable speed record of Mach 6.7 at an altitude of 59 km. Additionally, various space shuttles and re-entry vehicles have experienced the hypersonic regime during their atmospheric entry, reaching speeds exceeding Mach 2.0 before slowing down during descent. Many hypersonic research experiments today follow similar re-entry flight paths, involving intermediate pull-up/glide phases and maneuvering levels.

The concept of creating a practical, powered, and reusable hypersonic vehicle has been a long-standing aspiration. In the 1980s, the United States initiated the 'National Aerospace Plane (NASP)' research project with the ambitious goal of developing a hypersonic, reusable stage-to-orbit passenger aircraft. Publicly mentioned by President Ronald Reagan in 1986, the NASP program ignited hope that hypersonic platforms were on the verge of becoming a reality. Despite the eventual cancellation of NASP in 1992 due to technical challenges, the decade-long research effort laid the groundwork for the present generation of hypersonic vehicles. It is common for hypersonic vehicle research to undergo program termination after valuable scientific insights have been gained, leading to episodic technological advancements. Research is often conducted in iterative cycles, with results informing modeling and guiding subsequent activities.

Today's hypersonic research activities revolve around investigating crucial hypersonic phenomena, materials, components, and technologies related to flight control, navigation, instrumentation, and propulsion. Leading countries engaged in hypersonic research include the USA, Russia, China, and Australia, while Japan, France, Germany, and India are involved in more modest-scale efforts. The Technology Readiness Level (TRL) for hypersonic flight vehicles currently ranges at or below 6. Nonetheless, the systems being developed and tested exhibit sufficient maturity, fostering optimism that they will be fielded in the foreseeable future.

The ongoing progress in hypersonic flight research reflects the dedication of multiple nations to unlock the vast potential of hypersonic technologies. As these cutting-edge capabilities continue to advance, they hold the promise of revolutionizing aerospace endeavors, space exploration, and military applications.

Figure 1: North-American x-15 experimental aircraft 3d-model

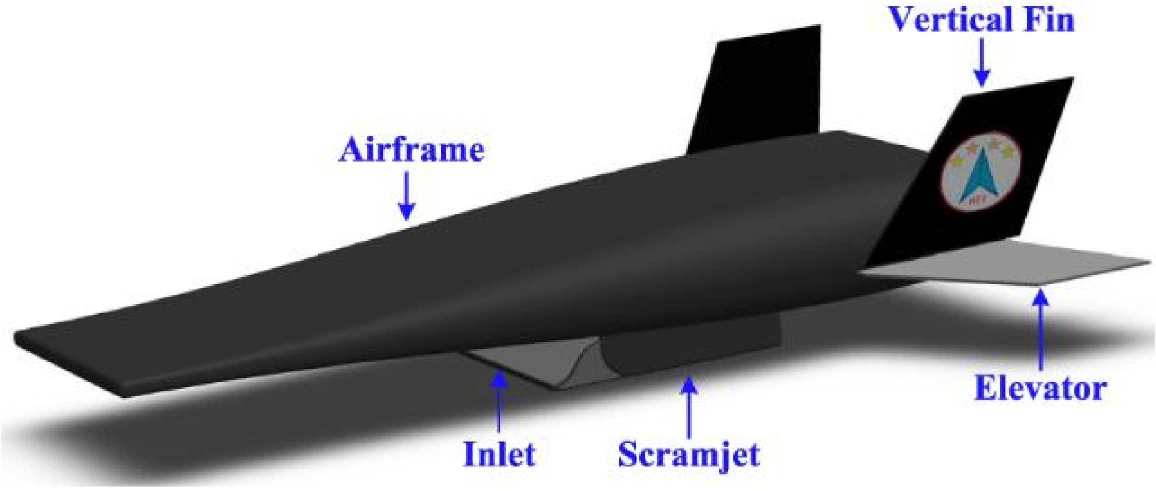

Figure 2: Adaptive controller design for a switched model of air-breathing hypersonic vehicle

1.3 Outline of the Thesis

This paper is the collection of some research about hypersonic vehicles for past few years. In chapter 1 the background and significance of hypersonic vehicle is introduced. In the chapter 2 two control methods (linear and non-linear) are described. The main analysis in in chapter 3 that contains hypersonic vehicle characteristics and some research on hypersonic vehicle model. After that in chapter 4 several methods for hypersonic design control are described. Finally in chapter 4 concludes the paper.

Chapter 2: Linear and Non-linear Control Method

A control method involves the management, direction, or regulation of other devices or systems using control loops. Designing a control system is a creative and decision-intensive process. These decisions are influenced by the specific properties of the target system that requires control and the fulfillment of specific requirements. However, such choices often necessitate trade-offs between conflicting demands.

The considered system models are generally linear and time-invariant. These models may result from physical modeling, where first principles and fundamental laws are applied. Alternatively, they may be derived from empirical modeling, involving experimental investigations on an actual plant or process. In such cases, data is collected and used to fit models using system identification techniques.

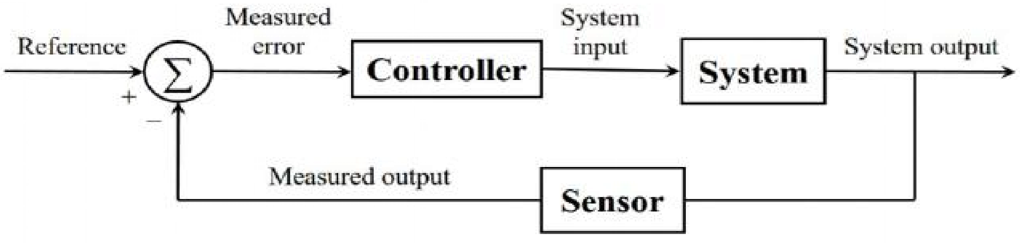

Figure 3: A block of negative feedback control system

Figure 3 is showing a control system which is containing three parts. These are the controller, the system and the sensor.

2.1 Linear Control Method

The linear control method is particularly applicable to systems composed of devices that adhere to the superposition principle, where the output shows proportionality to the input. These systems are described by linear differential equations, and a noteworthy subset of such systems includes the linear time-invariant (LTI) systems, where parameters remain constant over time. LTI systems enable the utilization of efficient frequency domain mathematical techniques, such as Laplace transform, Fourier transform, z transform, Bode plot, root locus, and Nyquist stability criterion. Through these methods, system characteristics are derived, including bandwidth, frequency response, eigenvalues, gain, resonant frequencies, zeros, and poles, which provide valuable insights for system response and design strategies.

To illustrate, consider a resistive network with a constant DC source, where the principles of homogeneity and additivity apply. By selectively ignoring undesired effects and assuming ideal behaviour for each component, the network exhibits a linear voltage and current relationship, exemplifying the essence of a linear control method.

One prominent instance of a linear control method is the PID controller, which stands for proportional–integral–derivative controller. It operates on a feedback mechanism and is widely employed in industrial control systems and various applications necessitating continuous, finely tuned control. The PID controller continuously calculates an error value based on the difference between a desired set-point (SP) and the measured process variable (PV). It subsequently applies a correction, combining proportional, integral, and derivative terms (P, I, and D, respectively), thereby obtaining its distinctive name.

The PID controller's wide-ranging utility in industrial settings stems from its adaptability and effectiveness in ensuring precise and stable control. Its capability to dynamically adjust control parameters in response to changing conditions renders it invaluable in an array of control systems. Gaining a comprehensive understanding of linear control methods, especially the PID controller, is pivotal in optimizing the performance of intricate industrial systems and enhancing overall process efficiency.

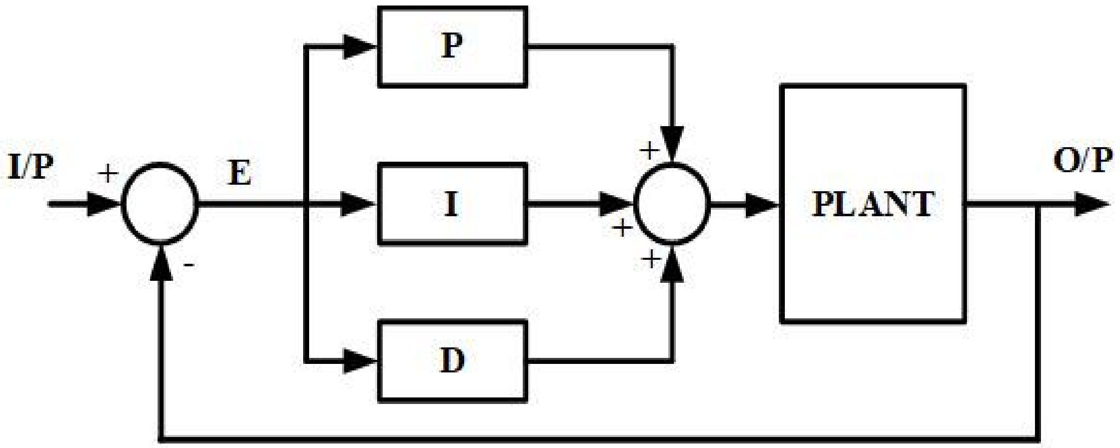

Figure 4: Block diagram of a PID controller

2.2 Non-linear Control Method

The domain of the nonlinear control method encompasses a wide variety of systems that deviate from the superposition principle, reflecting the prevalent nonlinearity exhibited by most real-world control systems. These systems are typically governed by nonlinear differential equations, making their handling significantly more challenging and less universally applicable, often limited to specific classes of systems. Various techniques, such as limit cycle theory, Poincaré maps, Lyapunov stability theorem, and describing functions, have been developed to address the complexities of nonlinear systems. Analyzing nonlinear systems often requires numerical methods, including computer simulations using specialized programming languages. Another approach is linearization, which involves approximating nonlinear systems as linear systems near stable points using perturbation theory, thus facilitating the application of traditional linear techniques.

A classic instance illustrating a nonlinear system is the magnetization curve or no-load curve of a DC machine. In this case, the curve depicts the relationship between the air gap flux and the field winding MMF. Initially, a linear relationship is evident between the winding MMF and the air gap flux, but beyond a certain point, saturation occurs, manifesting the nonlinear behavior inherent to the nonlinear control method.

Nonlinear systems exhibit distinctive properties, including:

- Nonconformity to the principle of superposition.
- Potential display of intriguing phenomena, such as bifurcation, limit cycle, and chaos.
- Presence of multiple isolated equilibrium points.

- Finite escape time, implying that solutions of nonlinear systems may not persist indefinitely.

Understanding and effectively managing nonlinearities are vital pursuits in control theory, as they mirror the intricacies encountered in real-world systems. Adequately addressing these nonlinear aspects can lead to enhanced control strategies and improved system performance across various applications and industries.

Frobenius theorem

The Frobenius theorem is a deep result in differential geometry. When applied to non-linear control, it says the following

$$\dot{x} = \sum_{i=1}^{k} f_i\,(x)u_i(t)$$

Where $x \in R^n, f_1, \dots, f_k$ are vector fields belonging to a distribution Δ and $u_i(t)$ are control functions, the integral curves of x are restricted to a manifold of dimension m if span (Δ) $=m$ and Δ is an involute distribution.

Chapter 3: Hypersonic Flight Dynamics

3.1 Analysis of Hypersonic Vehicle Characteristics

Achieving hypersonic flight in near space necessitates traversing three stages: subsonic, transonic, and supersonic. However, the unique spatial characteristics of near space introduce complexity to the dynamics of hypersonic vehicles. In general, near space hypersonic vehicles exhibit the following key characteristics:

3.1.1 Strong Non-linearity

Near space hypersonic vehicles traverse the stratosphere, mesosphere, and partial thermosphere, where air pressure, density, and ambient temperature undergo complex variations with flight altitude and speed. As a consequence, the performance of these vehicles exhibits strong non-linear behavior.

3.1.2 Strong Coupling

Hypersonic cruise vehicles incorporate fuselage and engine in their structural and control actuator designs, leading to strong coupling between the propulsion system and aerodynamics. This coupling results in complex interactions where aerodynamic parameters affect thrust, inlet system, and control surfaces, generating lift, torque, and other forces. As a result, non-linear dynamics govern the hypersonic vehicle model, particularly during long-distance maneuvering flights and aerodynamic control in re-entry trajectories.

3.1.3 Model Uncertainty and Disturbance

Hypersonic vehicles encounter shock waves and boundary layer interference, resulting in heat flux and pressure changes that directly impact aerodynamic characteristics. Additionally, supersonic speeds cause ablation on the aircraft surface, leading to structural distortion in the control system. The vast flight envelope of hypersonic vehicles makes control model parameters highly susceptible to atmospheric variations. The uncertainty and dynamic nature of the model introduce challenges in estimating aerodynamic characteristics, leading to uncertainties in the vehicle's flight state and vulnerability to multiple random disturbances.

3.1.4 Constraints and Time-Varying Effects

High angles of attack in hypersonic vehicles result in constraints on angular velocity and aircraft attitude during high-speed cruises and re-entry. Moreover, considerations for heat flux, overload, and dynamic pressure constraints are vital in guidance and control system design. Hypersonic vehicles also exhibit time-varying characteristics, including fuel consumption-induced mass changes, and nonlinear aerodynamic parameters influenced by altitude and Mach number variations.

3.2 Research on Hypersonic Vehicle Model

The complex and data-deficient nature of hypersonic vehicle dynamics necessitates extensive research on modeling. Scholars worldwide have contributed to modeling efforts, with a notable hypersonic vehicle model based on a conical wing configuration. Additionally, various researchers have focused on aerodynamic and propulsion system analysis, elastic motion modeling, and control-oriented air breathing hypersonic vehicle models. Recent Chinese scholars have also made significant progress in near space hypersonic aircraft modeling, exploring engine safety and various coupling effects within the aircraft.

Understanding and effectively modeling hypersonic flight dynamics is critical for the successful development and control of advanced hypersonic vehicles, facilitating advancements in aerospace technology and exploration.

Chapter 4: Methods of Hypersonic Controller Design

4.1 Controllers based on small perturbation method

The small perturbation method, also known as perturbation theory, involves approximating the value of a complex function by assuming the dominant influence as the primary factor and then making small corrections for additional factors. This mathematical technique seeks to find an approximate solution to a problem by breaking it into two parts: the "solvable" part and the "perturbation" part. It is particularly useful for situations where the problem cannot be precisely solved directly but can be formulated by introducing a "small" term to the mathematically solvable version of the problem.

In the context of controller design, the small perturbation method, or small-sign linearization, is widely utilized by linearizing the nonlinear system around a trim state. By doing so, the nonlinear model is approximated as a linear model, enabling the application of linear control techniques. This approach is straightforward to implement, making it common in engineering applications.

For instance, in the design of traditional and multi-variable linear control for the longitudinal flight dynamics, Schmidt introduced a robust linear output feedback control based on robust servomechanism theory. An internal model design was incorporated to achieve this control. Additionally, a linearized version of the non-linear dynamics was obtained at a specific trim condition, leading to the development of a linear quadratic regulator controller using the implicit model following approach.

In the realm of adaptive controller design for hypersonic cruise vehicles, various challenges such as center-of-gravity movements, aerodynamic uncertainties, actuator saturation, failures, and time-delays need to be addressed. To address these complexities, control structures are established based on linearized models of the underlying rigid frame dynamics, explicitly accommodating for all uncertainties. In the presence of system uncertainty, neural networks (NN) are employed to aid in the design. Additionally, for external disturbances, disturbance observers are designed to handle and mitigate their effects.

The small perturbation method proves to be a valuable tool in developing controllers for hypersonic vehicles, allowing for efficient linearization of non-linear models and employing linear control techniques. By incorporating adaptive strategies and accounting for uncertainties and disturbances, these controllers aim to enhance the stability, performance, and safety of hypersonic flight dynamics.

4.2 Controllers based on input-output linearization

Input-output linearization is a commonly employed technique to address the non-linear characteristics of a system. By introducing a change of variables and an appropriate control input, this method transforms the non-linear system into an equivalent linear system. Input-output linearization achieves global linearization of selected controlled outputs using full-state feedback. To handle system uncertainty, a sliding controller is designed with adaptive parameter estimation, which can be extended to cases that do not require full-state dimension. Moreover, the application of a High-Gain Observer aids in state estimation, while neural networks are utilized for uncertainty approximation. The system's robustness is determined based on instability probabilities and the potential violation of 38 performance criteria, accounting for variations in uncertain system parameters. A genetic algorithm is employed to search for design parameters in the nonlinear dynamic inversion structure for control system design.

An alternative approach gaining increasing attention is the "inter-medium" model-based controller design. In this approach, approximate dynamics are used to represent the original nonlinear dynamics, simplifying the controller design process. The T-S model and characteristic modeling-based controller design have been widely studied in this context, leading to several theoretical results for "inter-medium" model control strategies.

The T-S fuzzy model provides a convenient approximation of any smooth nonlinear function through a combination of local linear models, simplifying the analysis and synthesis of complex nonlinear systems. Linear matrix inequalities (LMIs) are used for stability criteria of T-S fuzzy systems, and fuzzy T-S models are applied to represent the longitudinal dynamics of flexible air-breathing hypersonic vehicles. A fuzzy robust tracking control scheme is proposed, which considers disturbances and faults, transforming the tracking control problem into a stabilization problem. Adaptive fault-tolerant tracking control is then achieved based on online estimation of actuator faults.

Feature modeling is another technique utilized to analyze dynamic characteristics and design controllers. The feature model is described by second-order differential equations, particularly useful for multi-input-multi-output (MIMO) systems. An adaptive online algorithm is employed to estimate the parameters, which allows the feature modeling to be performed without exact knowledge of the analytic model. By introducing fuzzy logic into feature modeling, a slowly time-varying fuzzy system can be represented, with the parameters predicted online using recursive least-squares algorithms. The feature model is incorporated into the attitude dynamics using the golden-section adaptive control law, with H2 and H∞ performances guaranteed through parameter determination based on LMI-based criteria.

Overall, input-output linearization and various model-based approaches offer valuable tools for the design of controllers for hypersonic vehicles, aiming to address non-linear complexities, uncertainties, and disturbances while enhancing stability and control performance.

4.3 Controller based on “inter-medium” model

An increasingly popular approach in controller design for non-linear dynamics is the use of an "inter-medium" model. This concept involves employing approximate dynamics that represent the original non-linear system based on specific assumptions. Two widely studied "inter-medium" model-based controller designs are the T-S model and feature modeling.

The T-S fuzzy model offers a remarkable advantage in approximating any smooth non-linear function by blending multiple local linear models, simplifying the analysis and synthesis of complex non-linear systems. Stability analysis for T-S fuzzy systems has garnered significant attention in recent years. The T-S fuzzy model, described by fuzzy if-then rules, is utilized to represent the longitudinal dynamics of flexible air-breathing hypersonic vehicles. By considering disturbances and faults, a fuzzy reliable tracking problem is proposed, transforming the tracking control problem into a stabilization problem. To achieve this, the attitude dynamics are formulated into the T-S fuzzy model, and an adaptive fault-tolerant tracking-control scheme is developed, relying on online estimation of actuator faults. The fast dynamics are then transformed into a regular form, leading to the establishment of the fuzzy T-S model.

Another key technique, feature modeling, involves developing a model for the target system by analyzing its dynamic characteristics, with a focus on controller requirements. The feature model is typically described using second-order differential equations. A multi-input-multi-output (MIMO) feature model is employed for a 6-DOF X-20 analogous hypersonic vehicle during its unpowered cruising phase. Parameters are estimated using an adaptive online algorithm, allowing feature modeling without exact knowledge of the analytic model. To accommodate system approximation, sufficient samples and slowly time-varying differential equations are considered. The inclusion of fuzzy logic into feature modeling divides the entire range into several subspaces. Consequently, the controlled model is described as a slowly time-varying fuzzy system, with parameter estimation performed online using recursive least-squares algorithms.

For attitude dynamics, the feature model with outstanding practical advantages is introduced, utilizing the golden-section adaptive control law. The H2 and H∞ performances are ensured by determining parameters through LMI-based criteria.

In conclusion, the "inter-medium" model-based controller design approach shows promise in addressing non-linear complexities and uncertainties, providing efficient stability analysis for

T-S fuzzy systems and enabling feature modeling for various dynamic systems. These methods contribute to the development of robust controllers for hypersonic vehicles, aiming to enhance their performance and control under different operating conditions.

4.4 Controllers based on back-stepping

Air-respiration hypersonic vehicles (AHVS) have emerged as efficient and reliable means for accessing space since the successful flight test of the x-43A aircraft in 2004.

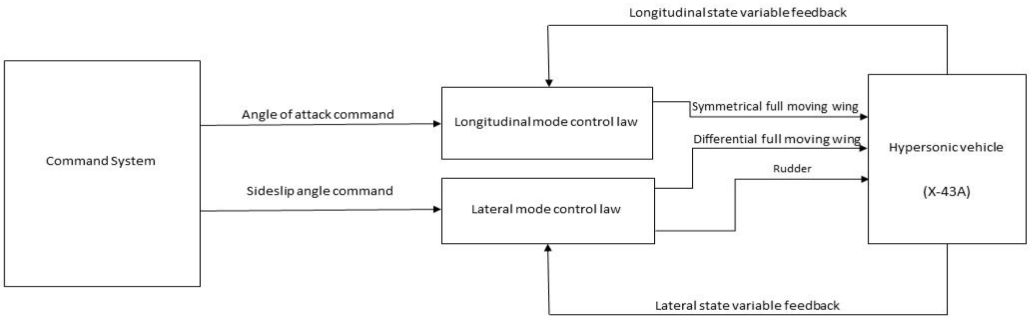

Figure 5: The X-43A control structure

Due to the integration of propulsion and airframe, AHVS experience strong coupling between propulsive and aerodynamic forces, leading to significant uncertainties caused by slender geometries and flexible systems. As a crucial aspect of AHVS research, control design is essential to ensure proper performance.

In recent years, numerous effective models have been proposed for AHVS. NASA Langley Research Center's model, presented by Wang and Stengel, and Chavez and Schmidt's dimensional analytical hypersonic aerodynamic model, which utilized Newtonian theory, are some notable examples. Bolender and Doman introduced a new model incorporating indirect shock and Prandtl-Meyer expansion theory to determine pressure distribution over the vehicle. In their work on flexible AHVs (FAHV), LaGrange's equations were utilized to derive equations of motion.

AHVS control methods can be categorized into linear and nonlinear approaches. Linear methods, such as $H\infty$ output feedback and linear parameter-varying control, have been successful in achieving satisfactory performance with gain scheduling. However, these methods demand significant flight testing and offline analysis. Nonlinear control strategies have gained attention as they can overcome some drawbacks of linear techniques. Feedback linearization, for instance, converts the nonlinear system into an equivalent linear one, enabling the application of LQR control. However, it requires an accurate model and is sensitive to uncertainties.

To address the limitations of feedback linearization, the back-stepping approach is employed in this study. Back-stepping relaxes the accuracy requirements of the flight dynamics model by strategically ignoring certain coupling effects. A command filter is introduced to create virtual signals and their first derivatives, taking into account magnitude, bandwidth, and rate limit constraints, effectively handling the issue of complexity. To enhance robustness against flexible modes and parameter uncertainties, a non-linear disturbance observer (NDO) is proposed to estimate these uncertainties. The command filter also acts as a low-pass filter for the estimates, ensuring system stability.

The NDO is designed as a bounded-input and bounded-output (BIBO) system, and its bandwidths are determined through parameter design to avoid exciting the flexible modes. A comparison is conducted between NDO-based back-stepping control, extended state observer (ESO)-based back-stepping control, and NDO-based non-linear dynamic inversion (NDI).

Overall, the back-stepping approach with NDO offers an effective solution for AHVS control, addressing uncertainties and enhancing robustness. By providing stable and accurate control, this method contributes significantly to the advancement of AHVS technology and its successful implementation in space access applications.

Chapter 5: Potential Future Research

The extensive survey conducted on hypersonic flight control reveals that both linear and non-linear strategies have been extensively studied. However, the current controllers are primarily based on the structure of HFV dynamics, resembling conventional aircraft control approaches. This proximity to conventional methods presents a fundamental challenge in modern hypersonic control applications. To address this issue, it is crucial to consider the specific and unique characteristics of hypersonic flight dynamics in the controller design process. Several key issues warrant further investigation to enhance controller performance.

5.1 Actuator dynamics

In the context of hypersonic flight, actuator dynamics play a vital role in controlling aircraft motion. For vehicles like X-30 or X-43A, where the primary lift-generating surface is the body itself, the demand for substantial lift force can lead to unaffordable elevator deflection during flight. Additionally, sudden environmental disturbances may cause immediate saturation of elevator deflection, adversely affecting performance and potentially destabilizing the system. It is essential to address these issues related to actuator dynamics to ensure safe and reliable flight.

The presence of non-differentiable characteristics, such as dead-quarter input non-linearity, in feedback control systems can significantly degrade system performance. For HFVs operating as unmanned aircraft, the controller's implementation relies on digital computers. Therefore, it becomes crucial to study how system uncertainty affects control performance, as errors can accumulate with the system order.

The derivation of discrete controllers with back-stepping design might lead to the requirement of large control inputs, which may not be practical for real-world applications. It is essential for the controller to possess the capability of "looking ahead and predicting" to overcome this limitation. Additionally, even if controllers prove the system's stability, they can still lead to high-frequency oscillations in control inputs, which may result in vehicle instability and render the controllers unusable in practical scenarios.

Considering the above analysis, improving the flight control efficiency necessitates a thorough examination of actuator dynamics to enhance safety, reliability, and maintainability of hypersonic vehicle missions.

By addressing these crucial issues, future research in hypersonic flight control can pave the way for more advanced and efficient control strategies, ensuring the successful and safe operation of hypersonic vehicles in diverse and challenging flight environments.

5.2 Large flight envelope

In comparison to other aircraft, the dynamic characteristics of HFV exhibit significant variations across the flight envelope due to the extensive range of operating conditions and rapid changes in mass distributions. Hypersonic flight encompasses multiple phases, including ascent, cruise, and re-entry, leading to a scarcity of sufficient flight data, resulting in limited knowledge about the aerodynamic parameters. To address this challenge, it is crucial to develop a comprehensive understanding of the dynamics by establishing a multi-segment model based on different states and implementing gain scheduling techniques.

However, the existing re-entry analysis is often limited to specific conditions, neglecting the critical consideration of the large flight envelope. Therefore, it becomes imperative to design controllers capable of handling rapid changes in states to effectively address the study of the extensive flight envelope. Simultaneously, the investigation of switching mechanisms for multi-model design, incorporating system uncertainty and unknown disturbances, is essential for the successful implementation of control strategies.

Moreover, to achieve robust, stable, and high-performance flight control, close integration of the guidance scheme and flight control system is necessary. This integration will enable the provision of a solid foundation for handling the challenges posed by the large flight envelope while maintaining superior overall performance during the hypersonic vehicle's mission.

By focusing on these aspects, future research can better address the complexities and uncertainties associated with the large flight envelope of HFVs, leading to more effective and reliable flight control solutions for hypersonic vehicles.

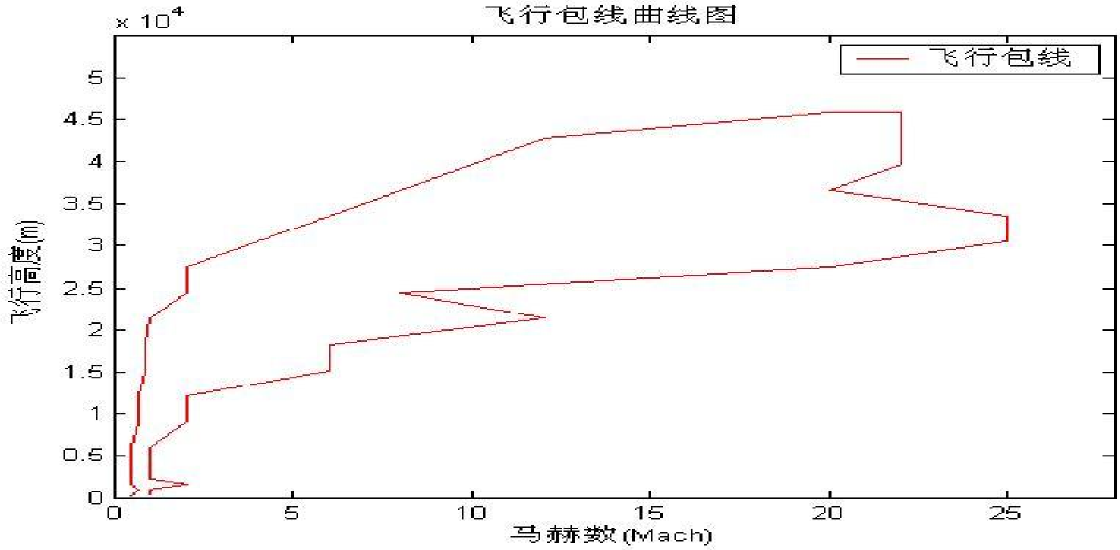

Figure 6: Flight envelope [A1]

5.3 Robustness and adaptation

Presently, controllers are often designed with a primary objective of ensuring closed-loop system stability. However, the high-speed nature of HFV flight and the sensitivity of its dynamics to environmental changes and parameter uncertainties demand robust control solutions to ensure system safety. To achieve superior tracking performance, the controller must be capable of adapting and learning from the information available. While some adaptive controllers have been proposed, only a few have emphasized the importance of rapid adaptation.

For instance, smart controllers heavily rely on the learning speed of neural networks (NN) or fuzzy logic systems (FLS). Thus, the adoption speed for learning becomes a critical aspect for adaptive controllers, and advancements in efficient machine learning techniques could pave the way for more effective adaptive control strategies.

Disturbance rejection is another significant concern in controller design, yet many existing methods do not address active and direct disturbance rejection. While some approaches utilize disturbance observer-based control to provide active estimation, a major challenge lies in accurately modeling the disturbance based on the flight environment rather than solely relying on mathematical analysis using the Lyapunov method. Research efforts should focus on analyzing disturbance characteristics in principle, as this will offer effective signal processing techniques to guide further controller design.

In summary, future research should concentrate on developing robust and adaptive controllers capable of handling unknown dynamics, ensuring system safety in the fast-paced hypersonic flight environment. Moreover, advancements in machine learning and active disturbance rejection techniques can lead to more efficient and effective control strategies for hypersonic vehicles, improving their overall performance and reliability during missions.

5.4 Aerodynamic-jet controller

Re-entry poses significant challenges, as the flight envelope resembles that of fighter planes executing demanding maneuvers. A robust steering, navigation, and control system are crucial for the successful accomplishment of re-entry missions. During re-entry, the X-33 vehicle requires attitude maneuvers across a wide range of flight conditions. The control design approach becomes intricate due to the highly coupled control channels, the presence of wind disturbances, and the limited understanding of aerodynamic characteristics.

While various controllers have been designed for attitude dynamics, there is a lack of research on the aerodynamic/response-jet controller for the re-entry phase. At the beginning of re-entry, the air density is thin, and the aerodynamic surfaces alone cannot provide sufficient control input. As a result, two types of actuators are used during the re-entry phase: the reaction control system (RCS) and the aerodynamic surfaces.

To ensure optimal re-entry performance, efficient control of dynamics with aerodynamic-jet capability becomes essential. Integrating the aerodynamic-jet control system into the overall control design is crucial to address the challenges posed during the re-entry phase. It enables the vehicle to navigate through varying atmospheric conditions, maintain stability, and execute precise maneuvers, ensuring a safe and successful re-entry mission. Future research in this area should focus on developing advanced aerodynamic-jet controllers to enhance the overall performance and reliability of hypersonic vehicles during the critical re-entry phase.

5.5 Aero-thermoelastic effect

Achieving hypersonic speeds requires the scramjet engine to operate under high dynamic pressure, leading to increased aerodynamic heating. A notable instance is the hypersonic technology vehicle-2 (HTV-2) test conducted by the Defense Advanced Research Projects Agency (DARPA), which unfortunately encountered failure. DARPA's investigation pointed towards significant portions of the hypersonic aircraft's skin peeling off during the flight. This occurrence was attributed to the extreme heat and velocity experienced by the aircraft, leading to unexpected aero shell degradation and subsequent upsets that triggered the flight safety system.

In light of these findings, there has been a significant advancement in understanding the areas that require attention to enhance aerothermal systems for future hypersonic vehicles. Therefore, in the controller design, special consideration must be given to account for the aerothermoelastic effect to ensure satisfactory performance. It is imperative to incorporate robust control strategies that can adapt to and counteract the effects of aerodynamic heating and thermal stresses on the vehicle's structural integrity. By comprehensively addressing the challenges posed by the aero-thermoelastic effect, we can enhance the safety, reliability, and overall performance of hypersonic vehicles during their critical flight regimes. Future research in this area should focus on developing advanced control mechanisms and materials that can effectively mitigate the impact of aerodynamic heating and ensure the successful operation of hypersonic vehicles in extreme environments.

5.6 Dynamics interactions and transient performance

The aerodynamic interactions between the elastic airframe, propulsion system, and structural dynamics are highly complex and mutually dependent. Predicting their combined effects remains challenging due to the scarcity of comprehensive tests and limitations of ground test facilities. The presence of flexible states within the dynamics further complicates the situation, with these states being coupled with the pitch rate. Current controllers often overlook the impact of flexible states or treat them as disturbances, but a more in-depth analysis is required to decouple different time-scale states effectively.

The dynamic interaction between the elastic airframe, propulsion system, and structural dynamics is of paramount importance for controller design, yet its critical implications have not been thoroughly examined. These dynamics are known to be unstable, strongly coupled, and influenced by substantial model uncertainty. Moreover, hypersonic vehicles operate at extremely high velocities, and our understanding of the aerodynamics in such conditions is limited. Consequently, if the transient performance is inadequate, it could lead to potential instability. Thus, further research should focus on studying and improving transient performance to ensure the system operates safely and efficiently.

By addressing the complexities of dynamics interactions and transient performance, we can develop more robust and adaptive control strategies that account for the interplay between the vehicle's various components and ensure its stability and effectiveness during critical flight phases. Exploring novel approaches to decouple and optimize the interactions between propulsion systems and airframe dynamics will be crucial to advancing the field of hypersonic flight control and enabling safe and reliable missions in the future.

5.7 Non-minimum phase characteristic

The non-linear model of longitudinal dynamics in air-breathing hypersonic vehicles reveals significant inertial coupling effects between pitch and normal accelerations, as well as structural dynamics. Upon linearization, the aircraft dynamics exhibit instability and non-minimum phase behavior in most cases. An intriguing observation is the existence of a natural frequency exceeding twice the fuselage bending mode frequency, resulting in aeroelastic modes. The short-period mode and fuselage bending mode exhibit strong coupling.

To address the non-minimum phase phenomenon, conventional approaches involve using canard deflection. However, this introduces an additional control surface and increases the relative degree of the rigid-frame model. While canards enhance controllability, they may negatively impact the thermal protection system design, as the extra control surface must withstand substantial thermal stress. Thus, finding a balance to achieve high-performance without compromising other crucial aspects is essential.

The non-minimum phase characteristic presents significant challenges in control system design. The presence of unstable zero dynamics can lead to issues with conventional feedback controllers. Effectively controlling such non-minimum phase hypersonic vehicles proves to be a complex task, requiring innovative and advanced control strategies.

To overcome these challenges, further investigation is warranted on the non-minimum phase behavior and the development of tailored control approaches. Research should aim to strike a balance between controllability, thermal protection, and overall vehicle performance, thereby paving the way for the successful operation of high-performance hypersonic vehicles. By effectively managing non-minimum phase characteristics, we can enhance the stability, safety, and effectiveness of hypersonic flight control systems.

Conclusion

In recent times, there has been a remarkable surge in research focused on controlling hypersonic flight vehicles, signifying the growing importance and potential of this field. The dream of achieving hypersonic flight is gradually transforming into reality, as scientists and engineers tirelessly work to overcome the challenges that stand in the way of making hypersonic flight a viable means of transportation. With each passing year, significant progress is being made, bringing us closer to mastering this exciting frontier.

The vision of hypersonic flight extends beyond mere experimentation with test craft; it encompasses a future where spacecraft can traverse the hypersonic barrier with ease. As technology advances and knowledge expands, the possibilities of hypersonic flight becoming a practical and efficient mode of travel come into focus. The prospect of reaching distant destinations like London to Sydney within the span of a single afternoon holds tremendous promise.

However, it is important to recognize that hypersonic flight also presents new challenges and responsibilities. As this technology develops, it can impact various aspects of our lives, from revolutionizing travel to altering the geopolitical landscape through new forms of weaponry. The future implications of hypersonic flight are in our hands, and we must approach this development with thoughtful consideration and responsible decision-making.

This thesis has provided a comprehensive overview of various control approaches for hypersonic vehicles, encompassing both linear and non-linear methods. The characteristics of hypersonic flight vehicles have been examined, highlighting their unique complexities, non-linearities, and interactions. Additionally, potential future research areas have been identified, underscoring the need for robust and adaptive control systems, as well as addressing challenges such as large flight envelopes, aerodynamic-thermal effects, and transient performance.

In conclusion, the study of hypersonic flight and its control systems is a dynamic and promising field that holds vast potential for reshaping the future of aviation and beyond. As researchers and engineers continue to delve into this domain, it is our collective responsibility to ensure that the advancements in hypersonic flight technology are harnessed for the greater good of humanity, promoting sustainable and secure utilization. By fostering innovation, responsible practices, and interdisciplinary collaboration, we can propel hypersonic flight towards a safer, more efficient, and transformative future.

Referances

1. Anderson, J. D., & Moore, J. E. (2010). Fundamentals of aerodynamics. McGraw-Hill Education.
2. Gai, S. L., & Balakrishnan, S. N. (2004). Modern missile guidance. Control Engineering Series, Taylor & Francis.
3. Glasstone, S., & Sesonske, A. (2002). Nuclear reactor engineering: Reactor design basics. American Nuclear Society.
4. Hageman, M. A., & Strganac, T. W. (2010). Hypersonic air-breathing propulsion. American Institute of Aeronautics and Astronautics.
5. Howe, A. S. (2016). Handbook of aerospace propulsion. CRC Press.
6. Merkle, C. L. (2010). Advanced tactical fighter to F-22 Raptor: Origins of the 21st century air dominance fighter. Air University Press.
7. Cook, M. V. (2008). Flight dynamics principles: A linear systems approach to aircraft stability and control. Elsevier.
8. Lewis, M. (2016). Air-breathing hypersonic technologies. In Aerospace Propulsion (pp. 95-124). Springer, Cham.
9. Weisshaar, T. A. (2007). Materials issues in hypersonic flight. MRS Bulletin, 32(02), 141-149.
10. Bowcutt, K. G. (2003). Fundamentals of hypersonic flow. American Institute of Aeronautics and Astronautics.
11. Brandis, A. M. (2006). Hypersonic aerothermodynamics. AIAA Education Series.
12. Boyd, J. W., & Young, M. (2011). Introduction to fluid mechanics. John Wiley & Sons.
13. Mattingly, J. D. (2006). Elements of propulsion: Gas turbines and rockets. American Institute of Aeronautics and Astronautics.
14. Cutright, W. L. (2013). Reusable launch vehicle research at NASA: Is the space shuttle the only reusable vehicle?. American Institute of Aeronautics and Astronautics.
15. Bertin, J. J., & Cummings, R. M. (2014). Aerodynamics for engineers. Pearson Education.
16. Åström, K. J., & Murray, R. M. (2008). Feedback systems: An introduction for scientists and engineers. Princeton University Press.
17. Franklin, G. F., Powell, J. D., & Emami-Naeini, A. (2014). Feedback control of dynamic systems (7th ed.). Pearson.

18. Ogata, K. (2010). Modern control engineering. Pearson Education.
19. Dorf, R. C., & Bishop, R. H. (2017). Modern control systems (13th ed.). Pearson.
20. Khalil, H. K. (2002). Nonlinear systems (3rd ed.). Prentice Hall.
21. Slotine, J. J., & Li, W. (1991). Applied nonlinear control. Prentice Hall.
22. Isidori, A. (1995). Nonlinear control systems. Springer Science & Business Media.
23. Sontag, E. D. (1998). Mathematical control theory: Deterministic finite-dimensional systems. Springer Science & Business Media.
24. Lewis, F. L., Vrabie, D., & Syrmos, V. L. (2012). Optimal control (3rd ed.). Wiley.
25. Slotine, J. J., & Weiping, L. (1987). On the adaptive control of robot manipulators. The International Journal of Robotics Research, 6(3), 49-59.
26. Zhou, K., Doyle, J. C., & Glover, K. (1996). Robust and optimal control. Prentice Hall.
27. Horn, R. A., & Johnson, C. R. (2012). Matrix analysis. Cambridge University Press.
28. Sussmann, H. J., & Sontag, E. D. (1991). A general result on the stabilization of linear systems using bounded controls. IEEE Transactions on Automatic Control, 36(5), 540-553.
29. Antsaklis, P. J., & Michel, A. N. (1997). Linear systems. McGraw-Hill.
30. Grewal, M. S., & Andrews, A. P. (2014). Kalman filtering: Theory and practice using MATLAB (4th ed.). Wiley.
31. Bertin, J. J., & Cummings, R. M. (2013). Hypersonic aerothermodynamics (2nd ed.). AIAA Education Series.
32. Kurtz, D. W. (2002). Hypersonic airbreathing propulsion. American Institute of Aeronautics and Astronautics.
33. Hefner, J. N. (2011). Fundamentals of hypersonic flow: Theory, numerics, and applications. CRC Press.
34. Wadhams, T. P. (1992). A history of aerodynamics: And its impact on flying machines. Cambridge University Press.
35. Gallaher, M. P., Cook, M. V., & Bogdonoff, S. M. (2015). Fundamentals of hypersonic propulsion. John Wiley & Sons.
36. Knight, D. (2009). Hypersonic airbreathing engines. American Institute of Aeronautics and Astronautics.
37. Heister, S. D., & Cummings, R. M. (2014). Hypersonic and high-temperature gas dynamics (3rd ed.). AIAA Education Series.

38. Chai, J. C., & Babinsky, H. (2008). Hypersonic and high-temperature gas dynamics. Cambridge University Press.

39. Zhang, Y., & Xia, Y. (2005). Hypersonic propulsion. Tsinghua University Press.

40. Davies, J. M. (2013). Hypersonic and planetary entry flight mechanics. Cambridge University Press.

41. Yamashita, T., & Miyazaki, T. (2009). Progress in flight physics of hypersonic vehicles. Springer Science & Business Media.

42. Candler, G. V. (2015). Development and application of high-fidelity hypersonic vehicle simulations. Journal of Spacecraft and Rockets, 52(5), 1281-1305.

43. Zhang, Q., Yang, J., Xu, G., & Cai, C. (2016). Robust controller synthesis for a near-space hypersonic vehicle. Aerospace Science and Technology, 57, 161-169.

44. Wang, Y., Song, B., Li, Y., & Chen, Y. (2020). Multivariable control design for near space hypersonic vehicles with input saturation. Aerospace Science and Technology, 100, 105782.

45. Zhang, D., Lin, C., Wu, B., & Li, Y. (2022). Integrated control of near space hypersonic vehicle with lateral and longitudinal coupling. Aerospace Science and Technology, 123, 106472.

46. Schmidt, D. K. (2012). Robust longitudinal control of air-breathing hypersonic vehicles. Journal of Guidance, Control, and Dynamics, 35(2), 409-423.

47. Wang, H., & Stengel, R. F. (2010). Dynamics and control of air-breathing hypersonic vehicles. Progress in Aerospace Sciences, 46(8), 467-506.

48. Chavez, C. A., & Schmidt, D. K. (2013). Analytical hypersonic aerodynamic modeling and adaptive control of flexible hypersonic vehicles. Journal of Guidance, Control, and Dynamics, 36(2), 417-431.

49. Bolender, M. A., & Doman, D. B. (2006). Modeling and control of hypersonic air vehicles. Journal of Guidance, Control, and Dynamics, 29(5), 1207-1219.

50. LaGrange, R. L., Pachter, M., & Levey, S. (2001). Modeling and control of flexible air-breathing hypersonic vehicles. Journal of Guidance, Control, and Dynamics, 24(6), 1053-1061.

51. Yan, X. G., Yan, Y., & Xi, B. C. (2018). Finite-time adaptive back-stepping control for a flexible air-breathing hypersonic vehicle. Journal of Guidance, Control, and Dynamics, 41(5), 1134-1145.

52. Xie, X., Sun, J., & Fan, J. (2018). Back-stepping control of an air-breathing hypersonic vehicle with parameter uncertainties and flexible modes. Aerospace Science and Technology, 81, 430-439.

53. Hu, T., & Huang, J. (2019). Nonlinear disturbance observer-based back-stepping control of flexible air-breathing hypersonic vehicles. Aerospace Science and Technology, 84, 223-234.

54. Cui, S., & Su, C. Y. (2020). NDO-based back-stepping control of air-breathing hypersonic vehicles with non-affine uncertainties. Aerospace Science and Technology, 106, 106095.

55. Kong, X., & Jiang, Z. (2021). NDO-based non-linear dynamic inversion control of air-breathing hypersonic vehicles with parameter uncertainties and external disturbances. Aerospace Science and Technology, 118, 106346.

56. Chowdhury, A., Zhang, H., & Sun, J. (2016). Sliding mode control of flexible hypersonic vehicles with input saturation. Journal of Guidance, Control, and Dynamics, 39(3), 573-585.

57. Zeng, Y., Huang, J., & Xia, Y. (2018). Continuous nonsingular fast terminal sliding mode control for hypersonic vehicles with uncertainties. Aerospace Science and Technology, 79, 118-127.

58. Xu, B., Sun, J., & Zhang, H. (2020). Robust dynamic surface control for a flexible hypersonic vehicle with multi-constraints and uncertain actuator dynamics. Aerospace Science and Technology, 99, 105890.

59. Hu, T., Zhang, H., & Huang, J. (2021). Adaptive neural network control for flexible air-breathing hypersonic vehicles with uncertain actuator dynamics. Aerospace Science and Technology, 115, 106089.

60. Li, T., & Cui, S. (2021). Finite-time control for a hypersonic vehicle considering dead-zone input and unmodeled dynamics. Aerospace Science and Technology, 118, 106381.

61. Zhao, S., & Huang, J. (2016). Adaptive back-stepping control of a flexible hypersonic vehicle with uncertain actuator dynamics. Aerospace Science and Technology, 57, 131-142.

62. Liu, T., & Wu, J. (2018). Adaptive back-stepping control for hypersonic vehicles with input constraints and dead-zone. Aerospace Science and Technology, 80, 167-176.

63. Zhang, S., & Li, X. (2017). Multi-model adaptive control of hypersonic vehicles using actuator commands. Aerospace Science and Technology, 66, 296-305.

64. Wang, Y., & Zhang, H. (2019). Adaptive neural network control for a flexible air-breathing hypersonic vehicle with multiple input constraints. Aerospace Science and Technology, 92, 319-329.

65. Fang, J., & Zhang, J. (2019). Aerodynamic-jet control and application for re-entry phase of hypersonic vehicles. Aerospace Science and Technology, 87, 314-324.