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Special Focus on Advanced Nonlinear Control of Hypersonic Flight Vehicles

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An overview on flight dynamics and control approaches for hypersonic vehicles

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Abstract With the capability of high speed flying, a more reliable and cost efficient way to access space is provided by hypersonic flight vehicles. Controller design, as key technology to make hypersonic flight feasible and efficient, has numerous challenges stemming from large flight envelope with extreme range of operation conditions, strong interactions between elastic airframe, the propulsion system and the structural dynamics. This paper briefly presents several commonly studied hypersonic flight dynamics such as winged-cone model, truth model, curve-fitted model, control oriented model and re-entry motion. In view of different schemes such as linearizing at the trim state, input-output linearization, characteristic modeling, and back-stepping, the recent research on hypersonic flight control is reviewed and the comparison is presented. To show the challenges for hypersonic flight control, some specific characteristics of hypersonic flight are discussed and the potential future research is addressed with dealing with actuator dynamics, aerodynamic/reaction-jet control, flexible effects, non-minimum phase problem and dynamics interaction.

Keywords hypersonic flight vehicle, linearizing at the trim state, input-output linearization, back-stepping, non-minimum phase

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Nomenclature

$C_D^{\alpha^i}$= ith order coefficient of α contribution to drag
$C_D^{\delta_e{}^i}$= ith order coefficient of δ_e contribution to drag
$C_L^{\alpha^i}$= ith order coefficient of α contribution to lift
$C_L^{\delta_e}$= coefficient of δ_e contribution to lift
$C_M^{\delta_e}$= coefficient of δ_e contribution to moment
$C_M^{\alpha^i}$= ith order coefficient of α contribution to moment
$\bar{c}$=mean aerodynamic chord
D= drag
g= acceleration due to gravity
h= altitude
h_r= reference altitude
h_0= nominal altitude for air density approximation

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I_{yy}= moment of inertia axis
L= lift
$L_{()}$= length of subscripted component
M_c=control torque vector
M_d=external disturbance torque
M_{yy}= pitching moment
m=mass
$\hat{m}_f$=the mass densities of the forebody
$\hat{m}_a$=the mass densities of the aftbody
N_i=ith generalized force
$N_i^{\alpha^j}$=jth order contribution of α to N_i
p= roll rate
q= pitch rate
$\bar{q}$=dynamic pressure
r=yaw rate
r_E=radial distance from the center of Earth
R_E=radius of the Earth
S=reference area
T= thrust
V=velocity
z_T=thrust to moment coupling coefficient
α=the attack angle
β=slideslip
$\beta_1\left(h,\bar{q}\right),\ldots,\beta_8\left(h,\bar{q}\right)$=thrust fit parameters
δ_e =elevator deflection
ϕ=bank
γ= flight path angle
γ_d= desired flight path angle
ρ=air density
ρ_0=nominal air density for air density approximation
θ_p=pitch angle
ω_i=the natural frequency of the elastic mode η_i
Φ= fuel equivalence ratio
ϕ_f=the mode shapes for the forebody
ϕ_a=the mode shapes for the aftbody
$\hat{\psi}_i$=constrained beam coupling constant for η_i
ε_i=filter parameter
ζ_i=damping ratio for elastic mode η_i
$1/h_s$=air density decay rate

1 Introduction

Near space is above where airliners fly but below orbiting satellites with the region of Earth's atmosphere that lies between 65,000 and 325,000–350,000 feet (20 to 100 km) above sea level, encompassing the stratosphere, mesosphere, and the lower thermosphere. The area is of interest for military surveillance purposes, as well as to commercial interests for communications. The resistance and energy consumption upon an aerocraft are relatively low when it carries out a hypersonic flight in this airspace. Hypersonic flight vehicles (HFVs) refer to the vehicles at speeds of Mach 5 and above. At such kind of speed, a reliable and more cost efficient way to access space can be presented. Also quick response and global attack became possible with the hypersonic flight technique. Accordingly, many developed countries have keenly taken up the hypersonic vehicle research that is full of challenges. The success of NASA's X-43A experimental airplane has affirmed the feasibility of this technology. In 2011, the contact was lost when the unmanned Falcon hypersonic test vehicle (HTV) was performing ‘glide phase’ maneuvers to test its aerodynamics. On May 1, 2013, an experimental hypersonic aircraft was launched on its swan song test flight accelerating the craft to more than five times the speed of sound. The Air Force’s X-51A Waverider reached a top speed of Mach 5.1 during the test flight, traveling more than 230 nautical miles in just over six minutes before crashing into the Pacific Ocean off the California coast as planned. On August 25, 2014, the early morning test of the Advanced Hypersonic Weapon was terminated for safety reasons four seconds after its launch when an anomaly was detected near the launch pad at the state-run Kodiak Launch Complex.

At the beginning of hypersonic research, the focus is on the development of engines to provide hypersonic flight speeds or wide speed ranges in subsonic, supersonic, and hypersonic regimes. However, the studies pursued by the National Aerospace Plane (NASP) and the Hyper-X programs have shown that there are other key technologies that need to be addressed to make hypersonic transportation feasible and efficient. A noteworthy issue is the control design where the unique characteristics of HFV should be carefully considered in comparison with typical aircraft. Unlike conventional aircraft, air-breathing hypersonic vehicles require that the propulsion system should be highly integrated into the airframe. The capture and compression of the flow through the inlet is determined by the properties of the bow shock wave under the vehicle fore-body, which are determined by the angle of attack (AOA) and the dynamic pressure as well as the free stream characteristics [1]. The AOA and the dynamic pressure also effect the combustion kinetics and the exhaust flow/free stream shear layer.

The majority of the hypersonic flight dynamics only consider the longitudinal dynamics of HFV which is known to be unstable, non-minimum phase with respect to the regulated output, and affected significantly by model uncertainty. Therefore HFVs are extremely sensitive to changes in atmospheric conditions as well as physical and aerodynamic parameters. In [1], the brief history is reviewed and the flight dynamics for different configuration is discussed. In [2], the control problems of HFVs are classified into the cruising control of the air-breathing HFV and the re-entry control of the non-power HFV. The dynamics and the control of the winged-cone accelerator configuration, the X-30 configuration, and the re-entry mode are respectively reviewed. In [3], the robustness, reconfigurable control allocation, intelligent control and integrated control design are pointed out as the challenging issues.

Different HFV controllers have been analyzed such as linear quadratic regulator (LQR), robust sum-of-squares method [4], sliding mode control [5], fuzzy control [6], Gauss pseudospectral method (GPM) [7] while many control problems are considered such as actuator saturation [8], aerothermoelastic effects [9] and fault tolerant control [10] using different models such as winged-cone model [11], longitudinal dynamics [12], the control oriented model [13] and the six degree of freedom (DOF) rigid-body model [14].

Controller design is crucial in making hypersonic vehicles feasible. Stability, performance and robustness are three main concerns for the design of guidance and control systems. H_∞ design and μ-synthesis methods [15] and the adaptive control [16,17] are designed based on linear control theory by linearizing the model at the trim state and are widely studied. In [18], a coupled linear parameter varying (LPV) guidance approach with flatness design is proposed to solve the hypersonic guidance problem. Recently nonlinear control is intensively considered with the sliding mode control [5,19] using Lie derivative notation and robust control [20,21] employing the genetic algorithm to search a design parameter space of the nonlinear-dynamic-inversion structure. Back-stepping controller design [22] or dynamic surface control (DSC) [23] can be implemented by taking advantage of the cascade structure of HFV dynamics. Also there exist some control application results by using characteristic model [24], Takagi-Sugeno (T-S) fuzzy model [10] or fuzzy singularly perturbed model [25]. While most of the controller designs are in continuous-time domain, given the widespread use of digital computers and microprocessors for controls applications, the discrete-time case is certainly warranted [26]. Based on Euler approximation model, discrete controllers are investigated on hypersonic vehicle dynamics by considering system uncertainty [27] and actuator saturation [28].

This paper is organized as follows. In Section 2, the recent developed HFV models are listed and the related expression is presented. Section 3 describes recent control approaches based on different modeling methods. Furthermore, the challenging issue for controller design towards the unique characteristics of HFV will be discussed in Section 4. Finally, Section 5 presents several comments and final remarks.

2 Hypersonic flight dynamics

In literature, there have been several papers discussing the modeling of hypersonic flight dynamics [1,2,12,29]. In [1,2] the winged-cone accelerator configuration and the X-30 one are analyzed in detail as such it will not be discussed in detail here. The readers could refer to [12,29,30] for more details. However, to show how the control approaches in Section 3 are developed, several kinds of the widely studied nonlinear hypersonic flight dynamics with aerodynamic parameters are presented in this section.

2.1 Winged-cone model

A widely used longitudinal model is the rigid-body model in [11] for the winged-cone accelerator configuration. In [20], the nonlinear longitudinal dynamics is developed and numerical values for the aerodynamic coefficients are representative from [11]. The winged-cone model is presented as

$$\begin{aligned}
\dot{V} &= \frac{T\cos\alpha - D}{m} - \frac{\mu\sin\gamma}{r_E^2},\\
\dot{h} &= V\sin\gamma,\\
\dot{\gamma} &= \frac{L + T\sin\alpha}{mV} - \frac{(\mu - V^2 r_E)\cos\gamma}{V r_E^2},\\
\dot{\alpha} &= q - \dot{\gamma},\\
\dot{q} &= \frac{M_{yy}}{I_{yy}}.
\end{aligned}$$

This model includes five state variables $X_h = [V, h, \alpha, \gamma, q]^{\mathrm{T}}$ and two control inputs $U_c = [\delta_e, \Phi]^{\mathrm{T}}$. The related definitions of the HFV dynamics in [5] at Mach 15 and 110,000 feet are given as: $r_E = h + R_E$, $\bar{q} = \frac{1}{2}\rho V^2$, $L = \bar{q}SC_L$, $D = \bar{q}SC_D$, $T = \bar{q}SC_T$, $M_{yy} = \bar{q}S\bar{c}\,[C_M(\alpha) + C_M(\delta e) + C_M(q)]$, $C_L = 0.6203\alpha$, $C_D = 0.6450\alpha^2 + 0.0043378\alpha + 0.003772$, $C_M(\alpha) = -0.035\alpha^2 + 0.036617\alpha + 5.3261\times 10^{-6}$, $C_M(q) = (\bar{c}/2V)q(-6.796\alpha^2 + 0.3015\alpha - 0.2289)$.

The control inputs related definition is as

$$\begin{aligned}
C_T &= \begin{cases} 0.02576\Phi, & \text{if } \Phi < 1,\\ 0.0224 + 0.00336\Phi, & \text{otherwise;} \end{cases}\\
C_M(\delta e) &= 0.0292(\delta e - \alpha),
\end{aligned}$$

where $C_x, x = L, D, T, M$ are the force and moment coefficients.

2.2 Truth model and curve-fitted model

The truth model (TM) [13] was developed by Bolender and Doman [31] and Groves [32]. The model was derived using compressive flow theory as an attempt to extend earlier work done by Chavez and Schmidt [29]. A derivation based on Lagrange's equations yields the equations of motion of the longitudinal dynamics given by

$$\begin{aligned}
\dot{V} &= \frac{T\cos\alpha - D}{m} - g\sin\gamma,\\
\dot{h} &= V\sin\gamma,\\
\dot{\gamma} &= \frac{L + T\sin\alpha}{mV} - \frac{g\cos\gamma}{V},
\end{aligned}$$

$$
\begin{aligned}
\dot{\alpha} &= q - \dot{\gamma},\\
\dot{q} &= \frac{M_{yy}}{I_{yy}} + \frac{\tilde{\psi}_1 \ddot{\eta}_1}{I_{yy}} + \frac{\tilde{\psi}_2 \ddot{\eta}_2}{I_{yy}},\\
k_{1TM}\ddot{\eta}_1 &= -2\zeta_1\omega_1\dot{\eta}_1 - \omega_1^2\eta_1 + N_1 - \tilde{\psi}_1\frac{M_{yy}}{I_{yy}} - \tilde{\psi}_1\tilde{\psi}_2\frac{\ddot{\eta}_1}{I_{yy}},\\
k_{2TM}\ddot{\eta}_2 &= -2\zeta_2\omega_2\dot{\eta}_2 - \omega_2^2\eta_2 + N_2 - \tilde{\psi}_2\frac{M_{yy}}{I_{yy}} - \tilde{\psi}_1\tilde{\psi}_2\frac{\ddot{\eta}_2}{I_{yy}},
\end{aligned}
$$

where

$$
\begin{aligned}
k_{1TM} &= 1 + \frac{\tilde{\psi}_1}{I_{yy}},\\
k_{2TM} &= 1 + \frac{\tilde{\psi}_2}{I_{yy}},\\
\tilde{\psi}_1 &= \int_{-L_f}^{0} \hat{m}_f \varepsilon \phi_f(\varepsilon)\mathrm{d}\varepsilon,\\
\tilde{\psi}_2 &= \int_{0}^{-L_a} \hat{m}_a \varepsilon \phi_a(\varepsilon)\mathrm{d}\varepsilon.
\end{aligned}
$$

The curve-fitted model (CFM) is a simplified, closed-form model that retains the essential characteristics of the TM. The following approximations are adopted in the study [13]:

$$
\begin{aligned}
T &\approx T_{\Phi}(\alpha)\Phi + T_0(\alpha)\\
&= [\beta_1(h,\bar{q})\Phi + \beta_2(h,\bar{q})]\alpha^3 + [\beta_3(h,\bar{q})\Phi + \beta_4(h,\bar{q})]\alpha^2 + [\beta_5(h,\bar{q})\Phi\\
&\quad + \beta_6(h,\bar{q})]\alpha + [\beta_7(h,\bar{q})\Phi + \beta_8(h,\bar{q})],\\
D &\approx \bar{q}S\left(C_D^{\alpha^2}\alpha^2 + C_D^{\alpha}\alpha + C_D^{\delta_e^2}\delta_e^2 + C_D^{\delta_e}\delta_e + C_D^0\right),\\
L &\approx L_0 + L_\alpha\alpha + L_{\delta_e}\delta_e = \bar{q}S\left(C_L^0 + C_L^{\alpha}\alpha + C_L^{\delta_e}\delta_e\right),\\
M_{yy} &\approx M_T + M_0(\alpha) + M_{\delta_e}\delta_e\\
&= z_T T + \bar{q}S\bar{c}\left(C_M^{\alpha^2}\alpha^2 + C_M^{\alpha}\alpha + C_M^0\right) + \bar{q}S\bar{c}C_M^{\delta_e}\delta_e,\\
N_1 &\approx N_1^{\alpha^2}\alpha^2 + N_1^{\alpha}\alpha + N_1^0,\\
N_2 &\approx N_2^{\alpha^2}\alpha^2 + N_2^{\alpha}\alpha + N_2^{\delta_e}\delta_e + N_2^0,\\
\bar{q} &= \frac{1}{2}\rho V^2,\\
\rho &= l\rho_0\exp\left[-\frac{h-h_0}{h_s}\right].
\end{aligned}
$$

The relevant parameters are listed in Tables S1–S7 (See Supplement material).

In some studies, the weak couplings $\tilde{\psi}_1$ and $\tilde{\psi}_2$ between the rigid mode and flexible mode can be eliminated, then the flexible hypersonic flight model [30,33] can be derived as

$$
\begin{aligned}
\dot{V} &= \frac{T\cos\alpha - D}{m} - g\sin\gamma,\\
\dot{h} &= V\sin\gamma,\\
\dot{\gamma} &= \frac{L + T\sin\alpha}{mV} - \frac{g\cos\gamma}{V},\\
\dot{\alpha} &= q - \dot{\gamma},\\
\dot{q} &= \frac{M_{yy}}{I_{yy}},\\
\ddot{\eta}_i &= -2\zeta_i\omega_i\dot{\eta}_i - \omega_i^2\eta_i + N_i, i = 1,2,3.
\end{aligned}
$$

2.3 Control oriented model

As summarized in [13], the control oriented model (COM) is obtained from the CFM by removing the altitude and flexible states and setting the weak elevator couplings to zero. The dynamics is presented as follows:

$$\begin{aligned}
\dot{V} &= \frac{T\cos\alpha - D}{m} - g\sin\gamma,\\
\dot{h} &= V\sin\gamma,\\
\dot{\gamma} &= \frac{L + T\sin\alpha}{mV} - \frac{g\cos\gamma}{V},\\
\dot{\alpha} &= q - \dot{\gamma},\\
\dot{q} &= \frac{M_{yy}}{I_{yy}},
\end{aligned}$$

where

$$\begin{aligned}
T &\approx T_{\Phi}(\alpha)\Phi + T_0(\alpha)\\
&= [\beta_1(h,\bar{q})\Phi + \beta_2(h,\bar{q})]\alpha^3 + [\beta_3(h,\bar{q})\Phi + \beta_4(h,\bar{q})]\alpha^2 + [\beta_5(h,\bar{q})\Phi\\
&\quad + \beta_6(h,\bar{q})]\alpha + [\beta_7(h,\bar{q})\Phi + \beta_8(h,\bar{q})],\\
D &\approx \bar{q}S(C_D^{\alpha^2}\alpha^2 + C_D^{\alpha}\alpha + C_D^0),\\
L &\approx L_0 + L_{\alpha}\alpha = \bar{q}SC_L^0 + \bar{q}SC_L^{\alpha}\alpha,\\
M_{yy} &\approx M_T + M_0(\alpha) + M_{\delta_e}\delta_e\\
&= z_T T + \bar{q}S\bar{c}(C_M^{\alpha^2}\alpha^2 + C_M^{\alpha}\alpha + C_M^0) + \bar{q}S\bar{c}C_M^{\delta_e}\delta_e,\\
\bar{q} &= \frac{1}{2}\rho V^2,\\
\rho &= \rho_0 \exp\left[-\frac{h - h_0}{h_s}\right].
\end{aligned}$$

2.4 Re-entry motion

The dynamic equations of rotational motion of the X-33 vehicle re-entry modes are given by the Euler equation [34]

$$Jw = -\Omega J w + M_c + M_d,$$

where J is the symmetric, positive definite moment of inertia tensor, $w = [p, q, r]^{\mathrm{T}}$ is the angular rate (roll, pitch, and yaw rate respectively) vector, $M_c \in R^3$ is the control torque vector, and a vector $M_d \in R^3$ contains any external disturbance torque.

The skew symmetric matrix Ω is given by:

$$\Omega = \begin{bmatrix} 0 & -w_3 & w_2 \\ w_3 & 0 & -w_1 \\ -w_2 & w_1 & 0 \end{bmatrix}.$$

The evolution of the X-33 vehicle orientation is described in terms of the mission angle vector γ_0 by the kinematics equation

$$\dot{\gamma}_0 = R(\cdot)\, w,$$

where $\gamma_0 = [\phi, \beta, \alpha]^{\mathrm{T}}$, ϕ, β, α are the bank, slideslip, and AOA respectively and parameters of the kinematics equation are defined as follows:

$$R(\cdot) = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha \\ \sin\alpha & 0 & -\cos\alpha \\ 0 & 1 & 0 \end{bmatrix}. \tag{1}$$

2.5 Comparison of different models

Unlike winged-cone model, the TM includes the coupling between rigid-body accelerations and flexible body dynamics. Since the TM is complex, CFM writes the expression in closed-form. The expression of M_{yy} in CFM contains the additional term $z_T T$, where z_T is a known quantity to account for the pitching moment produced by the underslung scramjet engine in the model [12].

As stated in [13], the nonminimum phase behavior results from the momentary loss of lift that occurs when the elevator is actuated to initiate a climb and the additional effector can be used to compensate for the undesirable contribution of the elevator to lift. The canard is placed near the nose of the aircraft, forward of the center of gravity. The $C_L^{\delta_e}$ item is absent in the expression of lift force for the COM because the deflection of the canard will be ganged with the elevator deflection using a negative gain and the $C_L^{\delta_e}$ item can be safely ignored while $C_M^{\delta_e}$ becomes larger.

The re-entry motion is composed of inner loop (angular rates) and outer loop (mission angles). The vector of control torque M_c is generated by the aerodynamic surfaces, described as $M_c = D_0(\cdot)\delta$ where $D_0(\cdot) \in R^{3\times 6}$ is sensitivity matrix calculated in real time on the basis of table lookup data, $\delta \in R^6$ is the vector of aerodynamic surface deflections. The mission for cruise and re-entry is different. For the cruise phase, the longitudinal dynamics is considered with control goal to steer system altitude and velocity from a given set of initial values to desired trim conditions with the tracking reference while the scamjet engine provides power for acceleration. For the re-entry motion, the goal is to follow the predefined angular which is governed by the aerodynamic surface without scamjet engine so that the vehicle could track the desired trajectory.

3 Hypersonic flight control

For hypersonic flight control, numerous designs have been proposed on linear controller, robust controller, adaptive controller and intelligent controller. The focus is mainly on how to deal with the system uncertainty and guarantee the stability of the closed-loop system. For example, to deal with the uncertainty, one can employ the upper bound to construct the robust design. Also considering that the uncertainty can be written into linearly parameterized form, adaptive control with parameter estimation could be studied. Furthermore, the intelligent control could be designed in case the uncertainty is the function of system states. In this paper, for exhaustive analysis, the recent progress in hypersonic flight control will be surveyed based on different way dealing with the dynamics instead of directly towards controller design.

3.1 Controllers based on small perturbation method

Small perturbation method or small-signal linearization is widely employed for controller design by linearizing the nonlinear system at trim state. In this way, the nonlinear model is approximated as linear model and then linear control techniques could be employed. Since the method is easy to implement, it is commonly used in engineering applications.

In [35], the classic and multivariable linear control is designed by Schmidt for the longitudinal model of the flight dynamics developed in [29,36]. In [37], the robust linear output feedback control reposes upon robust servomechanism theory and a novel internal model design is employed. In [32], a linearized model is obtained from the nonlinear dynamics at a specific trim condition and the linear quadratic regulator controller is developed with implicit model following method. In the adaptive controller design [17], the hypersonic cruise vehicle is subjected to center-of-gravity movements, aerodynamic uncertainties, actuator saturation, failures, and time-delays. On the basis of a linearized model of the underlying rigid body dynamics and explicitly accommodates for all uncertainties, the control architecture is presented. Considering the system uncertainty, neural network (NN) is employed during the design [38]. In case of the external disturbances, the disturbance observer is designed [39]. The problem of reference output tracking control is addressed in [40] and the problem of guaranteed cost control with pole assignment is studied in [41]. While most research is on trajectory following, in [42], the design of guidance laws for hypersonic missiles incorporates the terminal conditions to maximize target penetration.

3.2 Controllers based on input-output linearization

Feedback linearization is a commonly used approach to eliminate the nonlinear characteristics of the system. Through a change of variables and a suitable control input, the approach includes a transformation of the nonlinear system into an equivalent linear system. Input-output linearization uses full state feedback to globally linearize the nonlinear dynamics of selected controlled outputs.

To deal with the system uncertainty, the sliding controller is designed with adaptive parameter estimation and it is extended to the case that does not require full state measurement [5]. Similarly, the high gain observer is employed for state estimation while NN is used for uncertainty approximation [43]. In [21], the probability of instability and probabilities of violations of 38 performance criteria, subject to the variations of the uncertain system parameters, are used to characterize the system robustness. Using a genetic algorithm to search a design parameter space of the nonlinear-dynamic-inversion structure, the control system is designed.

The nonlinear-disturbance-observer-based control (NDOBC) approach is proposed in [44] to enhance the disturbance rejection performance of the longitudinal dynamics. In [45], a linearized uncertainty model for the hypersonic longitudinal motion dynamics is derived, based on which a robust minimax LQR controller is designed. In [46], by introducing finite time integral sliding mode manifolds, a finite time control method is designed for the hypersonic dynamics with disturbance observer.

3.3 Controller based on “intermedium” model

Since directly constructing a nonlinear controller is not available, “intermedium” model based controller design is gaining increasing attention. Here “intermedium” model refers to the design using approximate dynamics representing the original nonlinear dynamics via certain assumptions. Currently T-S model [47] and characteristic modeling [48] based controller design is widely studied. There already exit numerous theoretical results on the control methods developed on “intermedium” model. Thus the controller design for the nonlinear dynamics could be simplified to the analysis on the “intermedium” model.

In the past two decades, increasing attention has been on the stability analysis for T-S fuzzy systems. The great advantage of a T-S fuzzy system is its universal approximation of any smooth nonlinear function by a “blending” of some local linear models, which greatly facilitates the analysis and synthesis of the complex nonlinear system. Since local linear models are used for T-S fuzzy model, linear matrix inequalities (LMIs) design is employed for stability criteria of T-S fuzzy systems. In [49], fuzzy T-S model described by fuzzy If-Then rules is used to represent the longitudinal dynamics of flexible air-breathing hypersonic vehicles. Furthermore, by considering the disturbances and the faults, the fuzzy reliable tracking problem is proposed, and the tracking control problem is transformed into a stabilization problem. In [10], the attitude dynamics are formulated into the T-S fuzzy model and an adaptive fault-tolerant tracking-control scheme is proposed based on the online estimation of actuator faults. In [47], the fast dynamics are transformed into a regular form and then the fuzzy T-S model is established.

The characteristic modeling is to build up a model for target system by analyzing the dynamic feature of that system, emphasizing the requirement of controller. Generally, a characteristic model is described by the second-order differential equation. In [24], the multi-input-multi-output (MIMO) characteristic model is established for a 6-DOF X-20 analogous hypersonic vehicle dynamic model during its unpowered cruising phase. To get the parameters, the adaptive online algorithm is used. So for the characteristic modeling, it is not necessary to know the exact analytic model in advance. However, in order to approach the system, enough samples are required and the differential equation should be slowly time-varying. In [50], by dividing the whole restriction range into several subspaces the fuzzy logic is introduced into the characteristic modeling. In [51], with fuzzy dynamic characteristic model, the controlled model is described as a slowly time-varying fuzzy system, wherein the parameters are estimated online by using recursive Least-Squares algorithm. In [48], the characteristic model with prominent practical privileges is introduced to the attitude dynamics using the golden-section adaptive control law and the H_2 and H_∞ performances are guaranteed by determining the parameter using LMI based criterions.

3.4 Controllers based on back-stepping

Back-stepping design [22] is powerful tool for the design of controllers of nonlinear system in or transformable to parameter strict-feedback form. The idea of back-stepping is to design a controller recursively by considering some of the state variables as "virtual controls" and designing for them intermediate control laws. The design procedure is to start with a system which is stabilizable with a known feedback law for a known Lyapunov function, and then to add to its input an integrator [22]. For the augmented system a new stabilizing feedback law is explicitly designed and shown to be stabilizing for a new Lyapunov function, and so on. For hypersonic flight control, back-stepping is widely studied since the dynamics is in cascade form.

To deal with the uncertainty, typically there are several ways such as NN or fuzzy logic system (FLS) approximation [6,52,53], linearized parameter based dynamic inversion design [8,30] and nominal feedback with robust design. Considering the HFV dynamics, for the altitude subsystem it is with cascade structure. In [6], the subsystem was transformed into the strict-feedback form.

Take winged-cone model for example.

Assumption 1. Since γ is quite small during the cruise phase, we take $\sin\gamma \approx \gamma$ in (1) for simplification. The thrust term $T\sin\alpha$ in $\gamma - \theta$ equation can be neglected because it is generally much smaller than L.

For $h - \gamma$ subsystem, the tracking error of the altitude is defined as $\tilde{h} = h - h_r$ and the flight path command is chosen as

$$\gamma_d = \arcsin\left[\frac{-k_h\,(h-h_r) - k_I\int(h-h_r)\,dt + \dot{h}_r}{V}\right]. \tag{2}$$

if $k_h > 0$ and $k_I > 0$ are chosen and the flight path angle is controlled to follow γ_d, the altitude tracking error is regulated to zero exponentially [54].

Remark 1. With time-scale decomposition [4], the velocity and altitude are considered to be invariant during the controller design of $\gamma - \theta_p - q$ subsystem.

Define $X = [x_1, x_2, x_3]^{\mathrm{T}}$, $x_1 = \gamma$, $x_2 = \theta_p$, $x_3 = q$, $\theta_p = \alpha + \gamma$.

With Assumptions 1, the dynamics can be written as the strict-feedback form:

$$\begin{aligned}
\dot{x}_1 &= f_1(x_1) + g_1(x_1)x_2,\\
\dot{x}_2 &= f_2(x_1,x_2) + g_2(x_1,x_2)x_3,\\
\dot{x}_3 &= f_3(x_1,x_2,x_3) + g_3(x_1,x_2,x_3)\delta_e,\\
y_A &= x_1.
\end{aligned} \tag{3}$$

The velocity subsystem can be rewritten as

$$\begin{aligned}
\dot{V} &= f_v + g_v u_v,\\
u_v &= \Phi.
\end{aligned} \tag{4}$$

Definition for nonlinear function f_i and g_i, $i = 1, 2, 3, v$ is as follows:

$f_1 = -(\mu - V^2 r_E)\cos\gamma/(V r_E^2) - 0.6203\bar{q}S\gamma/(mV)$, $g_1 = 0.6203\bar{q}S/(mV)$, $f_2 = 0$, $g_2 = 1$, $f_3 = \bar{q}S\bar{c}[C_M(\alpha) + C_M(q) - 0.0292\alpha]/I_{yy}$, $g_3 = 0.0292\bar{q}S\bar{c}/I_{yy}$.

If $\Phi > 1$, $f_v = -(D/m + \mu\sin\gamma/r_E^2) + 0.0224\bar{q}S\cos\alpha/m$, $g_v = 0.00336\bar{q}S\cos\alpha/m$. Otherwise $f_v = -(D/m + \mu\sin\gamma/r_E^2)$, $g_v = 0.02576\bar{q}S\cos\alpha/m$.

Remark 2. Using the derived strict-feedback form of the dynamics, many control methods [55–57] could be implemented on the system.

In [58], the dynamic inversion control is designed with FLS approximating the uncertainty. However, implementation of adaptive back-stepping controllers requires analytic calculation of the partial derivatives of certain stabilizing functions. As the order of a nonlinear system increases, analytic calculation

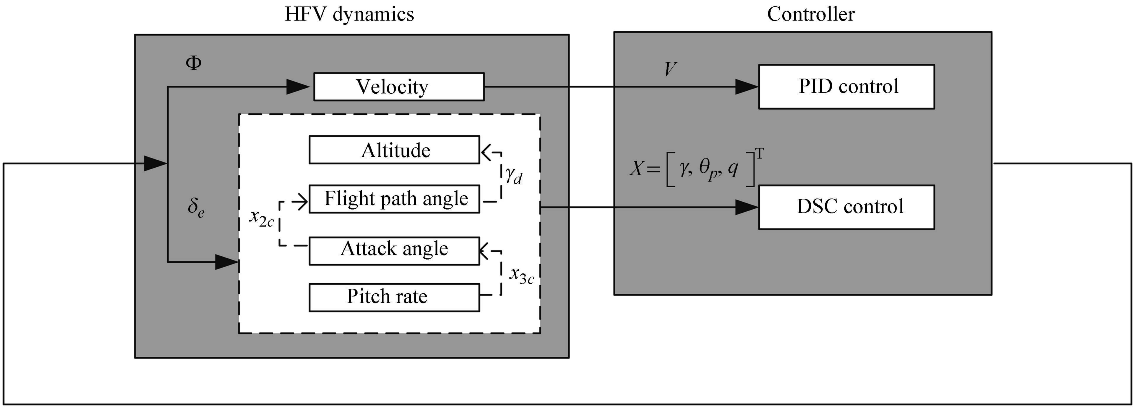

Figure 1 Scheme of DSC.

of these derivatives becomes prohibitive and it is the so-called "explosion of complexity". In [6], the first-order filter is incorporated into the design to eliminate the problem.

To clearly show the idea of DSC design, the scheme is shown in Figure 1.

We consider the case that the f_i and g_i of the strict-feedback system is known. For system (3), define $\tilde{x}_1 = x_1 - x_{1d}$.

Take θ_p as virtual control and design x_{2c} as

$$g_1 x_{2c} = -k_1 \tilde{x}_1 - f_1 + \dot{x}_{1d}, \tag{5}$$

where $k_1 > 0$ is the design parameter.

Introduce a new state variable x_{2d}, which can be obtained by the following first-order filter

$$\varepsilon_2 \dot{x}_{2d} + x_{2d} = x_{2c}, x_{2d}(0) = x_{2c}(0). \tag{6}$$

Take q as virtual control and design x_{3c} as

$$x_{3c} = -k_2 \tilde{x}_2 + \dot{x}_{2d}, \tag{7}$$

where $k_2 > 0$ is the design parameter.

Introduce a new state variable x_{3d}, which can be obtained by the following first-order filter

$$\varepsilon_3 \dot{x}_{3d} + x_{3d} = x_{3c}, x_{3d}(0) = x_{3c}(0). \tag{8}$$

Design the elevator deflection δ_e as

$$g_3 \delta_e = -k_3 \tilde{x}_3 - f_3 + \dot{x}_{3d}, \tag{9}$$

where $k_3 > 0$ is the design parameter. Furthermore, the command filter design can be applied by constructing the compensated tracking error [59].

In [60], to efficiently handle the time-varying disturbance and the system uncertainty, the disturbance observer is employed to estimate them. The back-stepping controller is designed with disturbance observer [61] for the attitude control model of near space vehicle. Similar design with guaranteed transient performance is studied in [62].

The sequential loop closure controller design [30,63] is based on the decomposition of the equations into functional subsystems. The methods [8,30,63] are based on the linearly parameterized form of the original dynamics.

Take the COM for example. Define $\tilde{h} = h - h_r$, $x_1 = \gamma, x_2 = \theta_p, x_3 = q$, $\theta_p = \alpha + \gamma$, $u = \delta_e$. The reference of flight path angle is the same as (2).

The following attitude dynamics can be derived

$$\dot{x}_1 = g_1 x_2 + f_1 - \frac{g}{V}\cos x_1,$$

$$\begin{aligned}\dot{x}_2 &= x_3,\\ \dot{x}_3 &= g_3 u + f_3,\end{aligned}\tag{10}$$

where

$$\begin{aligned}f_1 &= \frac{L_0 - L_\alpha \gamma + T\sin\alpha}{mV} = \omega_{f1}^T \theta_{f1},\\ g_1 &= \frac{L_\alpha}{mV} = \omega_{g1}^T \theta_{g1},\\ f_3 &= \frac{M_T + M_0(\alpha)}{I_{yy}} = \omega_{f3}^T \theta_{f3},\\ g_3 &= \frac{M_{\delta_e}}{I_{yy}} = \omega_{g3}^T \theta_{g3},\end{aligned}$$

with

$$\begin{aligned}\omega_{f1} &= \frac{\bar{q}S}{V}\begin{bmatrix} 1, -\gamma, \alpha^3\Phi\sin\alpha, \alpha^2\Phi\sin\alpha, \alpha\Phi\sin\alpha,\\ \Phi\sin\alpha, \alpha^3\sin\alpha, \alpha^2\sin\alpha, \alpha\sin\alpha, \sin\alpha \end{bmatrix}^{\mathrm{T}},\\ \theta_{f1} &= \frac{1}{m}\begin{bmatrix} C_L^0, C_L^\alpha, C_{T\Phi}^{\alpha^3}, C_{T\Phi}^{\alpha^2}, C_{T\Phi}^{\alpha}, C_{T\Phi}^{0},\\ C_T^{\alpha^3}, C_T^{\alpha^2}, C_T^{\alpha}, C_T^{0} \end{bmatrix}^{\mathrm{T}},\\ \omega_{g1} &= \frac{\bar{q}S}{V},\\ \theta_{g1} &= \frac{1}{m}C_L^\alpha,\\ \omega_{f3} &= \bar{q}S\left[\alpha^3\Phi, \alpha^2\Phi, \alpha\Phi, \Phi, \alpha^3, \alpha^2, \alpha, 1, \alpha^2, \alpha, 1\right]^{\mathrm{T}},\\ \theta_{f3} &= \frac{1}{I_{yy}}\begin{bmatrix} z_T\left(C_{T\Phi}^{\alpha^3}, C_{T\Phi}^{\alpha^2}, C_{T\Phi}^{\alpha}, C_{T\Phi}^{0}\right),\\ z_T\left(C_T^{\alpha^3}, C_T^{\alpha^2}, C_T^{\alpha}, C_T^{0}\right),\\ \bar{c}\left(C_M^{\alpha^2}, C_M^{\alpha}, C_M^{0}\right) \end{bmatrix}^{\mathrm{T}},\\ \omega_{g3} &= \bar{q}S,\\ \theta_{g3} &= \frac{1}{I_{yy}}\bar{c}C_M^{\delta_e}.\end{aligned}$$

In practice, due to physical constraint, there exist limitations on the control input and its change rate. Since the thrust system is tightly coupled with the elastic states, large deflection will stir up the elastic change which destroy the stability. Currently, different methods are applied on the dynamics, however little attention is focused on the saturation problem. In [8], the DSC is employed to deal with the case of actuator saturation with auxiliary signal. In [28], with time-scale decomposition by analyzing the slow and fast dynamics, the controller is designed for three subsystems and the constraint of throttle setting is studied. In [64], the robust DSC is designed for the flexible hypersonic flight dynamics with dead-zone input nonlinearity. Furthermore, the state constraint is considered and the adaptive command filter back-stepping design is proposed.

Nonlinear robust controller for a non-minimum phase model of an air-breathing hypersonic vehicle can be found in [65]. In [66], by solving a system of linear algebraic equations, the controllers and the external reference trajectories are simultaneously obtained. In [67], the pure-feedback form is derived and the DSC is applied. In [68], the output feedback back-stepping control via small-gain theorem is analyzed for a generic hypersonic vehicle. Considering the variable structure near space vehicle, the robust attitude tracking control is proposed based on switched nonlinear systems [69].

For the control of flight vehicle and spacecraft, controller on the basis of continuous system is usually implemented by a digital computer with a certain sampling interval [70–73]. The use of digital computers and samplers in the control circuitry has made the use of discrete-time system representation more justifiable for controller design than continuous-time representation. In [74], the discrete model is derived by Euler approximation and NN is employed to deal with the system uncertainty [55].

Take winged-cone model for example. By Euler approximation [71] with sampling period T_s, systems (3) can be expressed by a discrete-time model as

$$\begin{aligned} x_i\left(k+1\right) &= F_i\left(\bar{x}_i\left(k\right)\right) + G_i\left(\bar{x}_i\left(k\right)\right) x_{i+1}\left(k\right) = F_{3,i}^c\left(\bar{x}_{i+1}\left(k\right)\right), \\ x_3\left(k+1\right) &= F_3^c\left(\bar{x}_3\left(k\right)\right) + G_3^c\left(\bar{x}_3\left(k\right)\right)\delta_e\left(k\right), \\ y\left(k\right) &= x_1\left(k\right), i=1,2, \end{aligned} \tag{11}$$

where $\bar{x}_i\left(k\right) = \left[x_1\left(k\right), x_2\left(k\right), \ldots, x_i\left(k\right)\right]^{\mathrm{T}}$ are the state variables, $F_j\left(\bar{x}_j\left(k\right)\right) = x_j\left(k\right) + T_s f_j\left(k\right)$, $G_j(\bar{x}_j\left(k\right)) = T_s g_j\left(k\right)$, $j=1,2$. $F_3^c\left(\bar{x}_3\left(k\right)\right) = F_3\left(\bar{x}_3\left(k\right)\right)$, $G_3^c\left(\bar{x}_3\left(k\right)\right) = G_3\left(\bar{x}_3\left(k\right)\right)$.

By Euler approximation with sampling period T_s, discrete velocity subsystem (4) can be derived as

$$V(k+1) = V(k) + T_s[f_v(k) + g_v(k)u_v(k)]. \tag{12}$$

In [75], the desired controller is approximated by NN and the robust back-stepping controller design is presented. By describing the uncertainty as the realizations of Gaussian random functions, the adaptive Kriging control is designed for the discrete strict-feedback hypersonic model [27]. In [76], the equivalent prediction model is analyzed and the neural back-stepping controller is compared with the Euler model based design [74] to show the effectiveness.

In real-time application, intelligent control with back-stepping design might lead to increased computation load. Two simple ideas could be implemented. The first one considers the burden of online parameter update (NN weights updating). In [52,77], the norm of the NN weights vector is estimated and the novel controller is constructed. The other is to lessen the complexity of the controller design. In [54], the normal output feedback form is derived and high gain observer is used to estimate the newly defined variables. In this way, only one NN is needed so that the controller is much simpler compared with the back-stepping design. Similar to the idea in [54], the prediction model in discrete-time is derived by continuously looking ahead [78] and the universal Kriging controller [79] is designed with NN and Kriging estimation simultaneously. In this way, the controller is simplified.

3.5 Comparison of different control methods

From the above analysis, the controller design on the hypersonic flight model could not be directly constructed since the dynamics is complex. Several attempts simplifying the design are introduced based on different starting points. For small perturbation method and input-output linearization, the linear model is obtained. For the T-S fuzzy model, it borrows the advantage of fuzzy system and linear model while a characteristic model is described by the second-order differential equation.

For small perturbation method, the linear model is approximate, even relative to the model and the linear control theory could be easily implemented on the linearized model. Since the linear model is on certain operation point, with large flight envelope, it requires gain scheduling around several trim conditions of interest. The disadvantage is that it requires precise knowledge of the model. Otherwise, the derived model cannot represent the features of the original dynamics.

For the input-output linearization, the model is exactly linearized using feedback control signal. The relative degree should be calculated and the nonlinearity becomes really complex as order increases. When the dynamics is known, feedback linearization could be accomplished and the dynamic inversion design could be applied. However, uncertainty and disturbance exist and the exact model is unavailable. As a result, additional robust design and adaptive item should be included in the control to make sure of system stability.

For the "intermedium" model, the controller is implemented based on the good characteristics provided by the "intermedium" model. For example, the LMI based results for the T-S fuzzy model could be employed. Also the characteristic model represents the nonlinear dynamics with the second-order differential equation, based on which the controller is easy to be constructed. For the two methods, "intermedium" model is approximated as the original dynamics but the difference between nonlinear dynamics and "intermedium" model is rarely analyzed. For example, the precision of T-S fuzzy model is dependant on the rules. However deciding the rules for nonlinear dynamics with predefined precision is still an open problem.

For the back-stepping scheme, it does not transform the dynamics into linear model and the controller could be designed step by step with robust and adaptive design. With back-stepping design, it is easy to consider different constrains since the virtual control is developed for each equation. To some extent, the design is directly towards the nonlinear system. Several attempts are tried using "predictor" without back-stepping [54,79] towards the asymptotic stability of the closed-loop system. Since the "predictor" indicates the trajectory of future output under current control input and it does not present any information of system states, it is difficult to include the factor of states constraint. So for complex control purpose there must be tradeoff between the control goal and the dynamics transformation.

4 Potential future research

From the aforementioned survey, we see that both linear and nonlinear methods have been intensively studied on hypersonic flight control. However, current controller is proposed according to the structure of HFV dynamics. To some extent, the idea is almost close to the conventional aircraft control. This is the main problem lying in current hypersonic control applications and more specific characteristics of hypersonic flight dynamics should be taken into consideration for controller design. So there are fundamental and essential issues that are worth probing further. In view of the capability for the controller, it should be robust to unknown environment and adapt fast with system change. Also for the problem lying in hypersonic flight with large flight envelope, actuator saturation, aerothermoelastic effect and dynamics interaction should draw more attention.

4.1 Robustness and adaptation

Currently the controller is often proposed with only simple control goal that the closed-loop system is stable. The HFV is flying with fast speed and the dynamics is sensitive to environment and parameter uncertainty. So the controller should be robust to the unknown dynamics to make sure of system safety. Meanwhile, to achieve better tracking, the controller should be on adaption to learn the information. In view of this, numerous papers designed the adaptive controllers but only a few have focused on designing the controller with the characteristics of fast adaption. For example, the intelligent controller is highly dependant on the learning speed of NN or FLS. In this way, the adaption speed for learning is crucial for the adaptive controller and useful machine learning [80] might provide new way. Disturbance is another great factor and the controller design should consider disturbance rejection. However, most of the methods do not consider active and direct disturbance rejection. Though there are already some results on disturbance observer based control which provides active estimation, one main existent problem is to model the disturbance according to the flight environment instead of the mathematical analysis by Lyapunov approach only. Also more research should be on the analysis of the characteristics of the disturbance in principle since it will provide effective way of signal processing for further controller design.

4.2 Large flight envelope

Compared with other aircrafts, the dynamic characteristics of HFV vary much more over the flight envelope due to the extremely wide range of operating conditions and rapid change of mass distributions. Hypersonic flight includes the ascent, the cruise and the reentry of the vehicle, but it is lack of adequate flight data which results in the little knowledge about the aerodynamic parameters. Once the dynamics is well known, the multi-phase model could be established on different states and the gain schedule method could be implemented. However, current re-entry analysis is only on certain condition and the characteristic of large flight envelope is not seriously considered. So for the study of large flight envelope, the controller should be designed for fast changing states. Meanwhile, it is important to analyze the switching mechanism for multi-model design with system uncertainty and unknown disturbance. Also the guidance scheme and the flight control system need to be highly integrated in order to provide a robust stable high performance fight.

4.3 Actuator dynamics

For X-30 or X-43A, the primary lift to generate surface is the body itself due to inefficiency of using a thin wing. So during the flight, requirement of large lift force may result in unaffordable elevator deflection. Also the sudden environmental disturbance may cause the instantaneous saturation of the elevator deflection and it will deteriorate the performance or even make the system unstable. Dead-zone input nonlinearity is a non-differentiable function that characterizes certain non-sensitivity for small control inputs. The presence of such a nonlinearity in feedback control systems may cause severe deterioration of the system performances.

HFV is one kind of unmanned aircraft and the controller is implemented by digital computer. It is important to analyze how the system uncertainty would affect the control performance since the error could be cumulated with the system order. The derivation of discrete controller with back-stepping design may result in the requirement of a really large control input. This is not reasonable for real application and it is crucial for the controller to be equipped with the capability of “looking ahead and prediction”. Though the controllers have been proved to make the system stable, sometimes the control input is subjected to high frequency oscillation. In real life the oscillation may lead to instability of the vehicle and thus the controllers cannot be employed.

From the above analysis, to make the flight control efficient, the actuator dynamics should be taken into consideration to improve safety, reliability, maintainability of the flight task for hypersonic vehicle.

4.4 Aerodynamic/reaction-jet controller

Re-entry is challenging since the flight envelope is comparable to fighter airplane executing demanding maneuvers. Guidance Navigation and Control system is vital for the successful accomplishment of the re-entry mission. Flight control of the X-33 vehicle during re-entry involves attitude maneuvers through a wide range of flight conditions [34]. The control design process is complicated since the control channels are highly coupled, there exist wind disturbances and aerodynamic qualities are poorly understood.

Though in [10,34,60], different controllers are designed for the attitude dynamics, little research is on the aerodynamic/reaction-jet controller for the re-entry phase. At the beginning of re-entry, the air density is thin and the aerodynamic surfaces cannot provide sufficient control input. Thus two kinds of actuators are used during the re-entry phase: the reaction control system (RCS) and the aerodynamic surfaces. To make sure of the re-entry performance, efficient control of dynamics with aerodynamic/reaction-jet is important.

4.5 Aerothermoelastic effect

To achieve hypersonic speeds, the scramjet engine should work in high dynamic pressure. As a consequence, it caused an increase in aerodynamic heating. A test of Hypersonic Technology Vehicle-2 or HTV-2 was conducted by Defense Advanced Research Projects Agency (DARPA), however the mission failed. Since then DARPA has been investigating possible causes for the issue, and the agency suspects that unexpectedly large pieces of the hypersonic aircraft’s skin peeled off. DARPA says that some of the skin was expected to wear down due to the extreme heat and speed of the aircraft. Also the conclusion achieved by an independent review board emphasized that “unexpected aeroshell degradation, creating multiple upsets of increasing severity that ultimately activated the Flight Safety System was the most likely cause for the failure. The result of these findings is a profound advancement in understanding the areas we need to focus on to advance aerothermal structures for future hypersonic vehicles. So in the controller design, the aerothermoelastic effect should be considered to achieve satisfied performance [81].

4.6 Non-minimum phase characteristic

In [12], the nonlinear model of the longitudinal dynamics for an air-breathing hypersonic vehicle is developed. The authors point out that the equations of motion capture inertial coupling effects between the pitch and normal accelerations of the aircraft and the structural dynamics. The linearized aircraft dynamics are found to be unstable and non-minimum phase behavior is exhibited in most cases. Also it indicates that a natural frequency more than twice the frequency of the fuselage bending mode exist in an aeroelastic mode. The short-period mode and the bending mode of the fuselage are strongly coupled.

Currently, most studies consider using canard deflection [13] to eliminate the non-minimum phase phenomenon. However, with the help of this additional control surface the rigid-body model has the full relative degree. The presence of a canard, while beneficial for controllability, may negatively impact the design of the thermal protection system, as this additional control surface must withstand a significant thermal stress [63]. So the great feature should be studied in order to make the vehicle with high performance. The non-minimum phase characteristic can exhibit extreme difficulties in the control system design. The difficulty is mainly due to that the existence of unstable zero-dynamics can cause conventional feedback controller to run into trouble. So how to well control such a non-minimum phase hypersonic vehicle is challenging.

4.7 Dynamics interactions and transient performance

The aerodynamic effects of the elastic airframe, propulsion system, and structural dynamics are highly interactive and the related characteristics remain uncertain and hard to predict due to lack of sufficient tests and inadequacy of ground test facilities [1]. The flexible states appear in the dynamics and are coupled with the pitch rate. Currently the controllers either ignore the flexible states or consider it as disturbance. Though simulations show the feasibility under certain condition, more principal analysis should be paid on the decoupling of different time-scale states. Also flexible change of the shape alters conditions for working of scramjet engine. Furthermore, the perturbation of propulsion system indirectly impacts the longitudinal dynamics, the elastic mode variations. So the elastic airframe, propulsion system, and structural dynamics interact on each other strongly. However, for controller design, the factor of coupling between propulsion system and vehicle body was not “seriously” analyzed.

It is known that the dynamics are unstable, highly coupled and affected by significant model uncertainty. The hypersonic vehicles fly at such a high speed and little knowledge on the aerodynamics exists. Thus if the transient performance is bad, then the system might go unstable. So further research should aim at analyzing the transient performance to assure the safe and efficient running of the system.

5 Conclusion

Recently, the control of HFV is gaining more and more attention and numerous methods are studied on different control problems in view of different modeling such as small perturbation method, input-output linearization, “intermedium” model and back-stepping scheme. This paper presented the commonly used hypersonic flight model for controller design and then reviewed the recent progress in the related domain. The potential challenge is discussed for future research of large flight envelope, actuator dynamics, aerothermoelastic effect, non-minimum phase, dynamics decomposition and so on.

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Supporting information Tables S1–S7.
The supporting information is available online at info.scichina.com and link.springer.com. The supporting ma-

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