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REVIEW

Recent research progress on airbreathing aero-engine control algorithm

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Abstract Airbreathing aero-engines are regarded as excellent propulsion devices from ground takeoff to hypersonic flight, and require control systems to ensure their efficient and safe operation. Therefore, the present paper aims to provide a summary report of recent research progress on airbreathing aero-engine control to help researchers working on this topic. First, five control problems of airbreathing aero-engines are classified: uncertainty problem, multi-objective and multivariable control, fault-tolerant control, distributed control system, and airframe/propulsion integrated control system. Subsequently, the research progress of aircraft gas turbine engine modelling, linear control, nonlinear control, and intelligent control is reviewed, and the advantages and disadvantages of various advanced control algorithms in aircraft gas turbine engines is discussed. Third, several typical hypersonic flight tests are investigated, and the modelling and control issues of dual-mode scramjet are examined. Fourth, modelling, mode transition control and thrust pinch control for turbine-based combined cycle engines are introduced. Followed, significant hypersonic airframe/propulsion integrated system control is analysed. Finally, the study provides specific control research topics that require attention on airbreathing aero-engines.

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Abbreviation

1-D	one-dimensional
2-D	two-dimensional
BRL	bounded real lemma
CFD	computational fluid dynamics
DCS	distributed control system
DOF	3-degree of freedom
EKF	extended Kalman filter
EME	equilibrium manifold expansion
GTE	gas turbine engine
LMPC	linear model predictive control
LPV	linear parameter varying
MIMO	multiple-input multiple-output
MPC	model predictive control
MRAC	model reference adaptive control
NCL	nonlinear component-level
NMPC	nonlinear model predictive control
NN	neural network
q-LPV	quasi-linear parameter varying
RBCC	rock-based combined cycle
RBF	radical basis function
SISO	single-in single-out
SMC	sliding mode control
TBCC	turbine-based combined cycle
TRRE	turbo-aided rock-augmented ramjet combined cycle engine
TSM	terminal sliding mode

1. Introduction

The permanent human desire for higher flight speeds is a motivation for the continuous development of aviation science. From subsonic to transonic and supersonic speeds, and finally to hypersonic speed, airbreathing aero-engines are the most important propulsion devices of aviation aircrafts. To pursue higher cruising speeds, airbreathing aeroengines need to maintain high specific impulse performance in high-speed flight conditions. Figure 1 shows the performance comparison of airbreathing aero-engines. When the flying speed is low, a turbo or turbofan engine is enough; when the flying speed exceeds Mach 3, ramjet inlet instead of a compressor is used to reduce the considerable total pressure loss caused by the blade. Turbine engines and ramjets are two typical air-breathing engine systems, and there are various combinations of power systems based on these two engines. Turbofan engines provide sufficient power for civil airliners and military fighter jets [1]. A scramjet is considered one of the most effective propulsion devices to achieve hypersonic flight [2], and has the advantages of long flight distance, high specific impulse, high Mach cruise and single-stage orbit [3,4]. A variety of combined power systems, such as turbine-based combined cycle (TBCC) engines that consist of different airbreathing aero-engines, enable aircrafts to fly over a wide range of speeds and airspaces [5]. Compared with rockets that need to carry many oxidants during flight, airbreathing aero-engines make full use of oxygen in the atmosphere, which is significant to increase their payload, and makes them one of the most important propulsion devices for near-space vehicles.

Control is one of the key technologies for air-breathing aeroengines, which must work through feedback control [7]. Unlike intake, exhaust, combustion chamber, thermal protection and fuel technologies, control technology does not seem to belong to the engine, but it is indeed important to improve engine performance. For example, NASA [8] used multivariable control to solve the special flight missions of F-35 aircraft in short takeoff and vertical landing. Broadly speaking, the purpose of the control system is to achieve good thrust response capability and maintain important engine output within safe limits. Even for a linear model with known parameters, designing a controller that can meet the above objectives is a challenging task. The nonlinear, multivariable, and time-varying characteristics of actual airbreathing aero-engines add more complexity to the control system. Because the research time is longer than that of other airbreathing engines, the control of aircraft gas turbine engines (GTEs) is more mature. In 1987, the integrated high performance turbo engine technology (IHPTET) program was launched to double the engine's thrust-to-weight ratio and increase the combustor temperature by 222 °C [9]. This plan proposed a revolutionary engine model-based control mode, namely intelligent engine control [10−12], to improve the problems of sensor-based control [13]. Model-based control requires an airborne model that can accurately estimate unmeasurable parameters such as engine thrust and surge margin in real time to achieve closed-loop control of performance parameters. In the beginning of the 21st century, the advanced versatile affordable advanced turbine engines (VAATE) program was launched [9]. VAATE regards smart engines as one of three key research areas, combining a common core engine and embedded technology to enhance engine durability and adaptability [11] and indicates the model-based control system of the aero-engine. This technology mainly transmitts the measurable parameters and model calculation output of the engine to the diagnosis and prediction system, and adjusts the engine

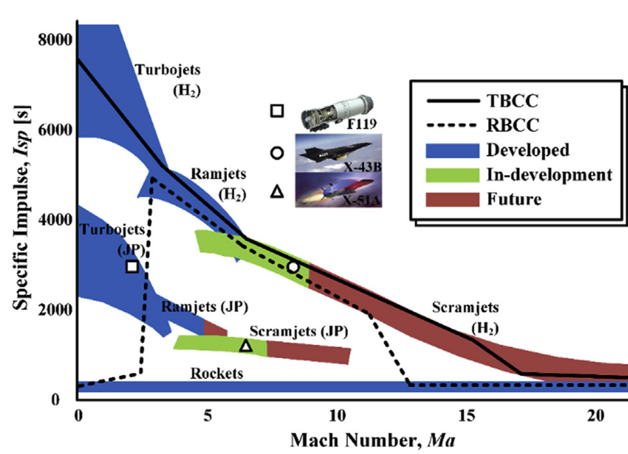


Figure 1 Performance comparison of aero-engines [6].

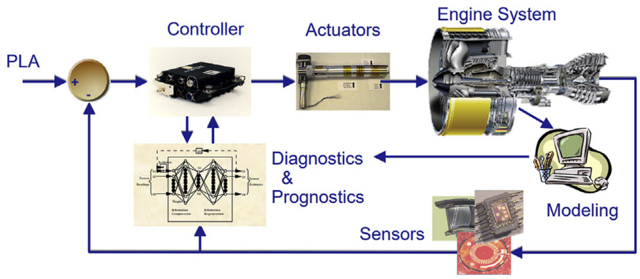


Figure 2 Block diagram of intelligent engine control system [11].

output with the controller [14,15]. Figure 2 indicates the block diagram of intelligent engine control system.

Model-based control methods enable to implement various advanced control algorithms for turbofan engines. In addition to turbofan engines, other types of hypersonic aero-engines also need to perform control system research. For hypersonic airbreathing aero-engines, the current study is mainly focused on the stage of engine design, and there is little publicity about the control aspects. As a military power, the United States started research on hypersonic flight in the 1950s. Figure 3 summarises part of the US airbreathing aero-engine research programs and platforms. Among them, the National Aerospace Plane (NASP) program is representative and can be regarded as a beginning for a new wave of international research on supersonic/hypersonic airbreathing propulsion technology. During the nearly 10 years of NASP, key technologies and theories were rapidly developed in several aspects, such as airframe/propulsion integration, supersonic combustion theory, and dual-mode scramjet, forming a rich technical foundation for subsequent research. The important flight tests include X-43A and X-51A. More details can be found in the first section of Part 4 of this review. In addition, Russia, Japan, China and the European Union have also extensively studied airbreathing aero-engines. makes them one of the most important propulsion devices for near-space vehicles.

To facilitate readers' understanding and search for the content of interest, Figure 4 shows the content block diagram of this review.

2. Significant control issues for airbreathing aero-engine

With the increasing need for stability, high performance, and long-life operation of airbreathing aero-engines, the control system faces a series of important control problems. Owing to the long research time of control system design for aircraft GTEs, we can review and identify the significant challenges of airbreathing aero-engines. In addition, this section will analyse the common features of these control issues for ramjet and combined cycle engines, which are also the topics of interest.

2.1. Uncertainty problem of airbreathing aero-engines control system

System uncertainty is one of the focus of control science [27–29]. Uncertainty is widespread in the real world and often refers to model uncertainty, that is, the mathematical

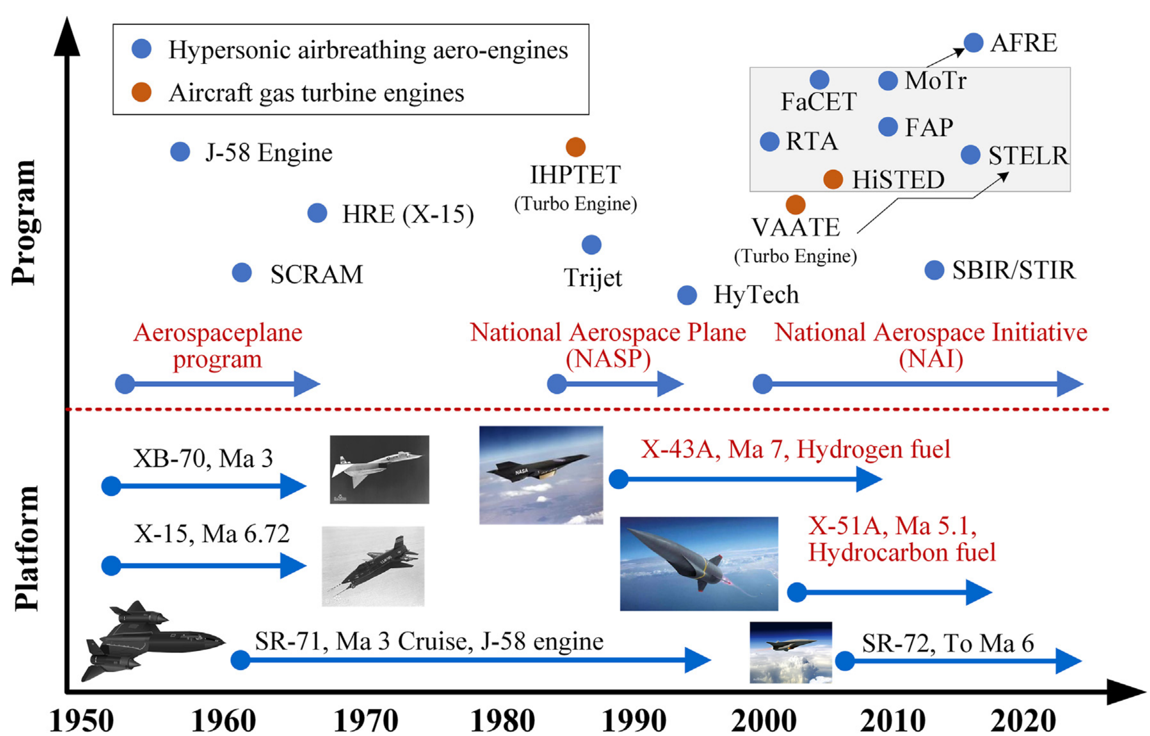


Figure 3 Main US airbreathing aero-engine research program and platform. Literature index of some studies: Aerospaceplane program [16], XB-70 [17], X-15 [18], SR-71&J-58 Engine [19], SCRAM [20], NASP [16], IHPTET [9], Trijet [21], X-43A [22], HyTech [23], NAI [16], VAATE [9], RTA [24], FAP [25], X-51A [26].

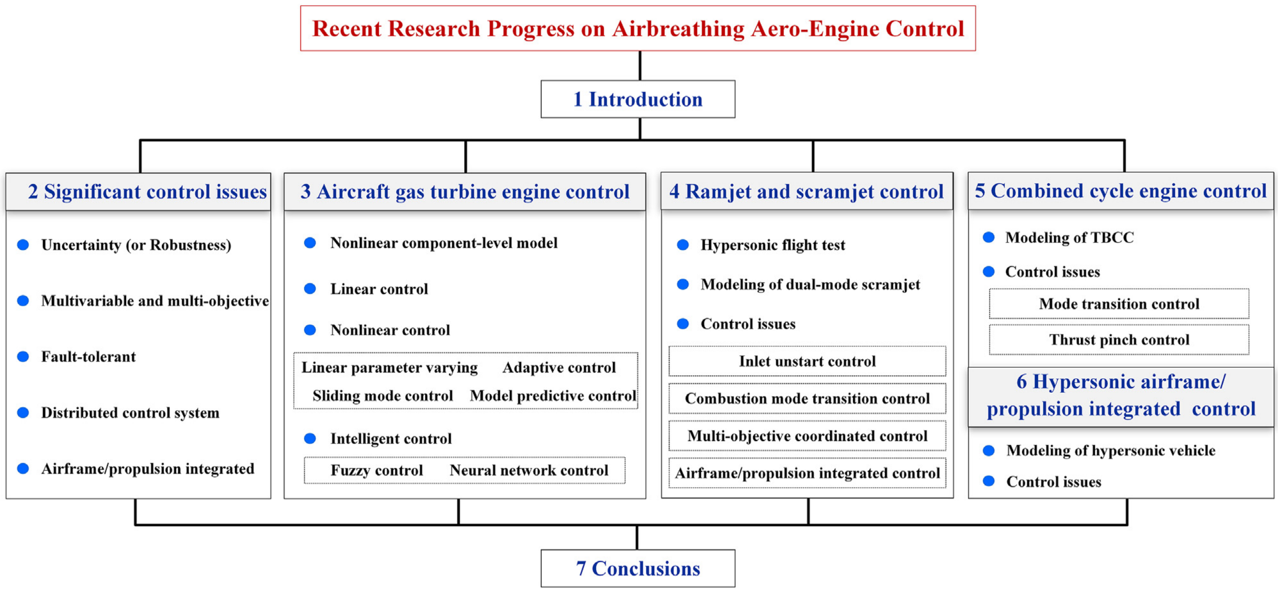


Figure 4 Content block diagram.

model used in the control system design is inconsistent with the real physical system. At the same time, it also contains the uncertainty of the external disturbance, but this can also be reflected in the uncertainty of the external disturbance model at the end. The control system is mostly designed according to the mathematical model, but it will ultimately be realised on the actual physical one. When control theory becomes increasingly rigorous and precise, the contradiction of uncertainty becomes more prominent, which further promotes the development of control theory to application. Uncertainty can also be summarised as a robustness issue, which refers to the controller performance that must be achieved and guaranteed for the actual application of the control system, that is, the ability of the control system to resist various uncertainties.

Owing to the strong nonlinearity, it is difficult to express the airbreathing aero-engine in analytical mathematical form. At present, the mathematical model of airbreathing aero-engines cannot be perfectly replicated with an actual engine, thus it is necessary to consider the uncertainty when designing the control system. The analysis of the uncertainty problem has considerably promoted the development of control science, which is also fully reflected in the control application of airbreathing aero-engines. First, the linear robust control method applies considerable effort to the research of uncertainty. By ensuring the robustness of the airbreathing aero-engine control system, researchers can use a single-point linear model to design a control system that is stable over a wide operating range. In addition, several nonlinear methods have been applied to solve the uncertainty. For example, linear parameter varying (LPV) control provides a more accurate mathematical model of airbreathing aero-engines and is usually combined with robust design to study system uncertainty; sliding mode and adaptive control are self-adjusting research aiming at the uncertainty of the aero-engine; the neural network (NN) control relies on its strong nonlinear approximation ability to solve the control system unknown uncertainty, etc. The application research of the above-mentioned control algorithms in airbreathing aero-engines is provided below for specific engine introduction. In short, uncertainty is an essential problem that must be considered in the control system design of airbreathing aero-engines.

2.2. *Multivariable and multi-objective control for performance and safety*

2.2.1. *Multivariable control*

There are two main purposes for the multivariable control of airbreathing aero-engines. On the one hand, the advanced airbreathing aero-engine adjusts its thermal cycle process by changing the geometry, size, or position of some components while normally adjusting the fuel flow to obtain the engine's high thrust or low fuel consumption. On the other hand, special flight missions such as rapid manoeuvring of aircraft and ultra-high Mach flight introduce new requirements for system control, and multivariable control for special operating conditions has also become a development requirement. Advanced airbreathing aero-engines need to provide higher performance and complete more complicated missions, which leads to the development of multivariable control design and its application for airbreathing aero-engines.

In 2000, NASA Glenn Research Center [8] disclosed its multivariable control methods used in turbofan engines, and provided reasons for the application of multivariable control in aero engines, such as the complexity of variable-cycle engines and high-performance needs of aircrafts. This method can be used to control the special flight process of short takeoff and vertical landing of aircrafts. Robust control was also used to design the multivariable controller for aero-engines. When investigating the multivariable control for the RM12 engine, Härefors et al. [30] proposed that a multivariable control system should serve the specific complex flight mission of the engine. For different flight missions, NASA [1] defined three main missions for aero engines, including military high-performance fighter missions and high-speed civilian transportation missions. The abovementioned missions require multivariable control by adjustment methods other than the main fuel flow. In addition, multivariable control is necessary for ramjets and combined cycle engines, which need to operate in higher Mach and wider airspace and have various means of regulation [31,32].

At present, turbofan engines have different control variables. Fuel flow is the main adjustment method for aero-engine control. Variable geometry nozzles are often used to adjust the pressure ratio in the multivariable control of the engine, particularly in the afterburner process. In addition, variable bleed valves and variable stator vanes are frequently used to avoid surge and stall effects by program control. For ramjet and combined cycle engines, variable geometry inlets and combustors provide new adjustable degrees of control freedom for the wide-range flight of the aircraft. In summary, multivariable control is an important research direction for airbreathing aero-engines.

2.2.2. Multi-objective control

To maximise the performance of the airbreathing aero-engine, it is necessary to release some constraints of the engine such that it runs close to the safety boundary. Thus, the contradictory relationship between safety and high performance is also revealed. Airbreathing aero-engines need to work for a long time in a wide flight envelope. The high performance and safety protection of the engine are undoubtedly complex multi-objective control problems [33].

Airbreathing aero-engines face several limitations. First, Samar et al. [34,35] and Spang et al. [36] proposed the basic control goal of a turbofan engine using the lowest fuel consumption to achieve the required thrust. In addition to meeting high-performance requirements such as takeoff, transonic acceleration, and supersonic cruise, the control system ensures that safety limits such as surge and temperature boundary of the turbine are not exceeded. In the operation process, all types of safety limit conditions often occur during transitional acceleration and deceleration. If extreme acceleration is performed along the surge boundary, the engine is likely to cross the surge and turbine over-temperature boundaries, and it is likely to cross the boundary and flameout while decelerating along the lean blowout boundary. Liu et al. [33,37] designed a switching controller to solve the multi-objective problem of an aircraft engine. In some peculiar conditions, the control system can ensure the stability of the engine. Second, Ma et al. [38] studied the thrust performance and safety protection requirements of dual-mode scramjets in a wide flight envelope. The scramjet control system needs to consider multi-objective tasks, including engine thrust control, inlet steady margin protection control, and combustion chamber over-temperature protection control. Thrust is always an important performance output of an engine and exists in most parts of multi-objective missions. The safety performance protection control, particularly for the problem of inlet unstart and combustor over-temperature, often occurs under different operating conditions. The former appears in the ramjet mode, and the latter generally becomes a prominent issue in the scramjet mode. For combined cycle engines, these limitations become a more complex control problem. In summary, the control targets faced by airbreathing aero-engines in a wide operating range are different, and multi-objective control is necessary.

2.3. Fault-tolerant control for various faults

The so-called fault-tolerant control technology means that the system can still maintain stability and enable the controlled object to work normally when the sensor, actuator or component fails. With the technology development, the performance requirements of airbreathing aero-engines are increasingly high, which also means that the engine system is more complicated. Under such circumstances, it is more necessary for the engine to timely change the control strategy through the fault-tolerant control system to ensure the safe and stable operation of the airbreathing aero-engine. Airbreathing aero-engines are extremely complex and precise devices. When facing a severe and changeable working environment, the engine is prone to various types of faults, such as gas-path faults, sensor faults and performance degradation.

There are several reasons for gas-path failures in engines. For example, a long-term load causes wear and corrosion of mechanical parts inside the engine, which leads to gas-path failure. Inhalation of external material may also cause component damage, leading to failure. After a gas-path failure occurs in the engine, the relationship between the internal parameters of the engine changes, resulting in large changes in the flow and efficiency of the components. The gas-path fault also causes mismatch between the thrust provided by the engine and the required thrust. In this case, the throttle lever needs to be manually adjusted, which increases the flight burden. Focussing on this problem, Li et al. [39] introduced the performance deterioration mitigation control method on a two-spool-mixed-flow-turbo-fan engine.

As an important part of the control system, the sensor is mainly responsible for the acquisition, transmission, and transformation of information, and provides the basis for further decision-making. The accuracy of detection information, timeliness of information transmission, and reliability of operation are of vital importance. If the sensor fails, it transmits the wrong information, which will seriously influence the entire system. Therefore, sensor failure is an important factor affecting the safety of the control system. The engine control system operates in a severe environment of high temperature and strong vibration, which can easily cause sensor signal disconnection, performance ageing, gain attenuation, and other faults. To solve the problem of sensor fault, several researchers have proposed fault tolerant control methods [40–42]. According to Eterno et al. [43], modern fault-tolerant control can be divided into two types: active fault tolerant control and passive fault tolerance control. The latter means that the controller designed in advance can tolerate the failure behaviour without changing the gain parameters and control structure of the controller, thus it is easy to implement and has good real-time performance. However, in active fault tolerant control, this is not enough to guarantee the stability of the system under fault conditions, and other performance indicators, such as robustness, response speed, anti-interference, and control cost, should also be considered. The concept of active fault tolerant control is derived from the fact that active handling of the fault occurs [44,45]. In addition, there are also problems such as information delay, data packet loss, and node failure due to the addition of the data bus [46,47].

2.4. Distributed control system

A distributed control system (DCS) is another important development aspect of aero-engine control. At present, the aero-engine control system is basically a centralised full authority digital electronic control system, and the centralised engine control system structure is shown in Figure 5 [48]. All processing and control functions of the system are executed by full authority digital electronic control, such as processing and calculation of control laws, redundancy management, filtering, and measuring of input/output signals. With the more complex structure of the airbreathing aero-engine, the control system is no longer limited to fuel control, but also to inlet and nozzle control. In response to this, the U.S. Department of Defense, NASA-Glen Research Center, and the U.S. industry established the distributed engine control working group to study the distributed control of aero-engines [49]. Compared with the aero-engine centralised control system, the DCS is very different from the control method, control structure, control, and measurement actuators. Figure 6 shows the distributed engine control architecture. DCS connects any number of control elements through a common and standardised communication interface. It is a fully intelligent distributed structure that uses a highly integrated data bus. In DCS, the complicated wire bundles of a centralised full authority digital electronic control system are almost eliminated by a bus system, which considerably reduces the weight. The DCS used in aero-engine control has the following characteristics and advantages:

- Reduce the complexity and weight of the engine control system and have a higher thrust-to-weight ratio;
- Adopt an open system structure, standardised intelligent devices, and interfaces. Shorten the development cycle and reduce costs;
- Reduce the breakdown and the maintenance cost. Improve the reliability and maintainability of the system;
- Improve the flexibility of control system design and upgrade. Smart devices are independent of each other and can independently adopt advanced technology;
- Use a layered structure to improve work efficiency.

The research on DSCs mainly includes the following. First, the architecture optimisation of the engine DSC was studied, and researchers proposed the application of ring topology and genetic algorithm [50,51]. Second, digital communication networks and bus structures that meet the needs of distributed control communication, reliability, real-time, versatility, economy, and efficiency were discussed [52,53]. Third, the stability and robustness of DCSs for network-induced delay and uncertainty disturbance were studied [54–59]. In addition to time delay control, decentralized control is also an important aspect of DCSs [60,61]. At present, a series of technologies need to be solved before DSCs are widely used. Among them, most key technologies

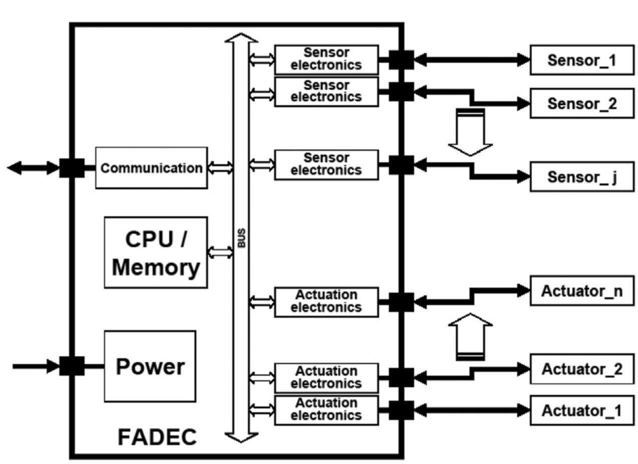


Figure 5 Centralized engine control architecture [48].

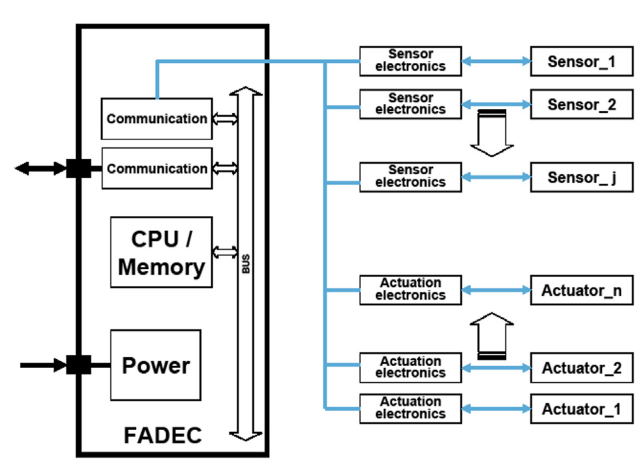


Figure 6 Distributed engine control architecture [48].

include smart sensors and actuators, high-temperature resistant electronic components, reliable and efficient network communication technology, and distributed power systems.

2.5. Airframe/propulsion integrated control system

With increasing flight Mach, the problem of airframe/propulsion integrated system design and control has become increasingly important. For modern fighters and hypersonic vehicles, the power device must be integrated with the vehicle to improve the aerodynamic performance of the entire system. In addition, most hypersonic vehicles with ramjet propulsion adopt the waverider configuration, in which the engine directly becomes a part of the aircraft configuration and needs to participate in aircraft aerodynamic configuration design. Thus, airframe/propulsion integrated control is an important issue for vehicles with airbreathing aero-engines.

Considering that integrated control is a significant problem for both engine and vehicle researchers, we will focus on this issue in the sixth part of this review.

2.6. Summary of control issues

In this section, five important control issues are summarised for airbreathing aero-engines. First, the uncertainty problem widely exists in the complex nonlinear airbreathing aero-engine control system. Second, multi-variable and multi-objective problems introduce the dual requirements of performance guarantee and safety protection for engine control systems. Third, fault-tolerant control is important for ensuring the safety and effectiveness of the control system. Fourth, a DCS is the future development direction of airbreathing aero-engines. Finally, airframe/propulsion integrated control has become particularly important in the research of hypersonic airbreathing aero-engines.

Although control issues can be simply summarised as items, they are not independent. We can simply classify the high-performance requirements and safety guarantees of modern aero-engines into the second control problem. However, those who focus on the third problem can easily refute this view because the engine without fault-tolerant control is difficult to be truly efficient and run for a long time. The same problem may also appear in other categories. Therefore, it is difficult for airbreathing aero-engines to isolate each control method or control problem by a simple classification. We can only provide information to help readers on research of airbreathing engine control.

3. Aircraft gas turbine engine control

Since the advent of the aircraft GTE, it has captured the attention of countries that want to explore aerospace science. In more than half a century, research on GTEs has rapidly developed. With the increasing requirements of engine performance, the control system design becomes more important. However, research on the control system of GTEs did not fundamentally change until the emergence of the full authority digital electronic control system [62].

Nowadays, the control system of GTEs not only needs to ensure operating performance and safety, but also consider important tasks such as reduce the operating cost, increase the fuel consumption rate, and increase the engine life. Therefore, the studies of modern aviation gas turbine systems also follow the increasing system uncertainty, diversification of control variables, intelligent control, etc. [7,63,64]. With the improvement of the real-time performance and accuracy of the engine nonlinear component-level (NCL) model, several advanced control methods of GTEs have been studied. Due to the length of this review and the author's understanding, research on GTE control cannot be exhaustive. In this section, we will start with the engine NCL model and introduce the research of advanced control methods on GTEs in three aspects: linear, nonlinear, and intelligent control.

3.1. Nonlinear component-level model

The establishment of mathematical models of controlled objects is important for control systems, particularly model-based control, which presents high requirements for high-precision GTE's mathematical models. As GTEs are multivariable, nonlinear, and time-varying complex systems, it is very difficult to build an accurate and real-time one for simulation. The NCL model is a simplified aero-thermodynamic system based on the constraints of the input and output of each component. The difficulty in modelling NCL models lies in the accuracy of component characteristics and the speed of model iteration.

GasTurb is a powerful and flexible gas turbine cycle program that is accompanied by additional tools, namely Smooth C, Smooth T, Map Collection, and GasTurb Details. GasTurb has been widely used and recognised in the GTE modelling field due to its friendly man-machine interface, excellent simulation accuracy, complete compressor/turbine characteristic diagram, and other auxiliary tools [65,66]. NASA released the C-MAPSS90k simulation platform, which has a large bypass ratio of the engine and can simulate the performance outputs of a two-rotor turbofan with high accuracy. Based on this platform, researchers have investigated the application of advanced control methods, gas path fault diagnosis, health management, etc. [67]. In addition, GSP [68], Turbomatch [69], PROOSIS [70], etc. are also powerful tools for studying GTE characteristics.

Although researchers continue to simplify GTE models based on components, compressor, and turbine characteristics, still no analytical expressions are available and the results are often presented in tables, with parameters obtained by interpolation. It is almost impossible to design a control system directly on the NCL model. Therefore, a state variable model that can be applied to the design of advanced engine control law, state monitoring, and fault diagnosis was developed [71]. In addition, most control methods require a control-oriented model for this method.

For example, LPV control needs to establish a corresponding LPV model, and fuzzy control needs to establish a T−S fuzzy model. However, most of these control-oriented models are identified by an NCL model. NCL models can also be used to estimate some difficult-to-measure GTE outputs. However, owing to the limitations of experimental conditions and costs, many control studies on GTEs are verified in NCL models.

3.2. *Linear control for aircraft GTE*

GTEs must work through feedback control [7]. With the development of engine control technology and electronic equipment of control systems, the control system of GTEs has changed from single variable control to complex multivariable control. In recent years, research on advanced linear control methods, including robust control, have been applied in GTEs, but they are complicated and have multiple-input multiple-output (MIMO) objects with strong nonlinearity. Robust control has outstanding advantages in solving the uncertainty and multivariable problems of nonlinear objects. The advanced control plan for GTEs started in the 1970s. Control methods including linear quadratic regulator, linear-quadratic Gaussian with loop-transfer recovery, and H_∞ have been studied.

The F100 multivariable control synthesis program, which was a cooperative effort by the Air Force Aero-Propulsion Laboratory and the NASA Lewis Research Center, aimed at using the linear quadratic regulator to design a multivariable control for the F100 turbofan engine [72,73]. However, this method considerably relied on the accuracy of the mathematical model used for controller design and had no good tolerance for system uncertainty. To solve this problem, linear-quadratic Gaussian with loop-transfer recovery introduced Kalman filter technology to enhance the ability of the control system of GTEs to suppress external disturbances. The filter method was used to compensate the recovery gain to a certain extent, such that the entire system had a better response rate and disturbance rejection robustness [74,75]. In addition, the H_∞ technique was applied to the design of GTEs control system. H_∞ control first needed the linear model of GTEs, and then used H_∞ loop shaping [76], mixed sensitivity synthesis [8,77], or other methods to design the controller according to the control requirements. Although the robust H_∞ controller guarantees the robustness of the system, the theory considers suboptimal controllers and system uncertainty, which inevitably increases the conservativeness of the controller.

In summary, the linear control method has achieved considerable success in the last century, but the limitations of its theory have restricted its development. The linear model used in the linear control method is easy to analyse and design, but the dynamic characteristics of the actual systems and the linear systems are quite different. For objects with strong nonlinearity such as GTEs, the performance of the controller at off-design points cannot be guaranteed. Although the robust linear control theory introduces uncertainty for model mismatch, it also leads to the conservatism of the controller, and the control performance may decrease. In addition, linear control methods cannot guarantee the stability and high performance of the control system in a large range of operating conditions, particularly in the GTEs with strong nonlinearity.

3.3. *Nonlinear control for aircraft GTE*

Nonlinear control is an important part of GTE control system design. In contrast to the linear control method, the nonlinear control method considers the mathematical model in a wider operating range, or the controller parameters change with the time-varying characteristics of the model, or the control output may be corrected by the predicted data measured in real time to solve the nonlinear influence of the system. There are several nonlinear control methods in GTEs, such as LPV control, sliding mode control (SMC), adaptive control, and model predictive control (MPC). This section will detail the four control methods mentioned and introduce their applications in GTEs.

3.3.1. *Linear parameter varying control*

LPV control is significant in the gain scheduling technique, which is widely applied in nonlinear systems [78]. In the 1990s, Shamma pioneered the introduction of the LPV model and used it for system analysis and gain scheduling controller design [79]. With the development of control theory, robust gain scheduling control based on the LPV model has attracted widespread attention [80], as it can solve the problems of traditional gain scheduling that cannot guarantee the stability and robustness at off-design points of a nonlinear plant [81].

For several years, researchers have attempted to use LPV technology to manage the control problem of GTEs. This section will provide the main research on LPV control on GTEs. First, the problem definition and basic theory for LPV control are introduced. Second, the LPV model of the GTEs is detailed. Then, we show the application of different LPV control methods on GTEs. Finally, the status and problems of LPV control in GTE applications are summarised and discussed.

3.3.1.1. Problem definition and basic theory for LPV control. Two survey studies on the field of gain scheduling have focused on modelling and control of LPV and quasi-LPV (q-LPV) systems (see Refs. [82,83]). LPV systems, whose state-space coefficient matrix continuously relies on time-varying parameter vectors $\alpha(t)$, are composed of finite-dimensional linear systems. The scheduling variables $\alpha(t)$ are assumed to be unknown but measurable, and are pre-constrained in a specified bounded set. In contrast, q-LPV models have scheduling variables that belong to the system state. In this study, the models described in Ref. [84] are adopted. The definitions of the LPV and q-LPV systems are provided below.

Definition 3.1. (LPV Systems): Given a compact subset $\boldsymbol{P}\subset\boldsymbol{R}^s$, the parameter variation set $\boldsymbol{F}_P$ denotes the set of all piecewise continuous functions mapping $\boldsymbol{R}^+$ (time) into $\boldsymbol{P}$ with a finite number of discontinuities in any interval. Given continuous functions, $A:\boldsymbol{R}^s\rightarrow\boldsymbol{R}^{n\times n}$, $B:\boldsymbol{R}^s\rightarrow\boldsymbol{R}^{n\times n_u}$, $C:\boldsymbol{R}^s\rightarrow\boldsymbol{R}^{n_y\times n}$, and $D:\boldsymbol{R}^s\rightarrow\boldsymbol{R}^{n_y\times n_u}$.

A nth-order linear parameter-varying system is defined as:

$$\begin{bmatrix}\dot{x}(t)\\ y(t)\end{bmatrix}=\begin{bmatrix}A(\alpha(t)) & B(\alpha(t))\\ C(\alpha(t)) & D(\rho(t))\end{bmatrix}\begin{bmatrix}x(t)\\ u(t)\end{bmatrix}\tag{1}$$

where $\alpha(t)\in\boldsymbol{F}_{\mathscr{P}}$.

Definition 3.2. (q-LPV Systems): Given an LPV system (1), a q-LPV system is obtained if the state vector $x(t)$ can be decomposed into scheduling states $\rho(t)\in\boldsymbol{F}_{\mathscr{P}}$ and non-scheduling states $\mu(t)$:

$$x(t)=[\rho(t)\quad\mu(t)]^{\mathrm{T}}\tag{2}$$

Therefore, the quasi-LPV model can be described as:

$$\begin{bmatrix}\dot{\rho}(t)\\ \dot{\mu}(t)\\ y(t)\end{bmatrix}=\begin{bmatrix}A_{11}(\alpha(t)) & A_{12}(\alpha(t)) & B_1(\alpha(t))\\ A_{21}(\alpha(t)) & A_{22}(\alpha(t)) & B_2(\alpha(t))\\ C_1(\alpha(t)) & C_2(\alpha(t)) & D(\alpha(t))\end{bmatrix}\begin{bmatrix}\rho(t)\\ \mu(t)\\ u(t)\end{bmatrix}\tag{3}$$

where the scheduling variable vector is $\alpha(t)=[\rho(t)\quad\omega(t)]$ and $\omega(t)\in\boldsymbol{R}^{n_p}$ are exogenous parameters.

For the LPV system given in Eqs. (1) and (3), Apkarian et al. [80] proposed a novel controller structure that contains the same scheduling variables as the plant. That is:

$$\begin{bmatrix}\dot{x}\\ u\end{bmatrix}=\begin{bmatrix}A_K(\alpha(t)) & B_K(\alpha(t))\\ C_K(\alpha(t)) & D_K(\alpha(t))\end{bmatrix}\begin{bmatrix}x\\ y\end{bmatrix}\tag{4}$$

where y is the vector of outputs and u is the vector of control inputs. Based on measurable scheduling variables $\alpha(t)$, this controller can "self-schedule" to adapt to the plant dynamics and maintain stability and high performance along all trajectories $\alpha(t)$.

The H_∞ method is often used to design LPV controllers. A useful tool in H_∞ control theory is the bounded real lemma (BRL).

Theorem 3.1. (BRL): given a continuous transfer function $G(s)$ of (not necessarily minimal) realisation $G(s)=D+C(sI-A)^{-1}B$, the following statements are equivalent:

(1) A is stable, and $\|G(s)=D+C(sI-A)^{-1}B\|_\infty<\gamma$

(2) there exists a positive definite solution to the matrix inequality:

$$\begin{bmatrix}A^{\mathrm{T}}X+XA & XB & C^{\mathrm{T}}\\ B^{\mathrm{T}}X & -\gamma I & D^{\mathrm{T}}\\ C & D & -\gamma I\end{bmatrix}<0\tag{5}$$

Based on BRL theory, the researcher uses the Lyapunov function method to design the LPV controller.

Lemma 3.1 (Quadratic H_∞ performance) [80]: The LPV system (1) has quadratic H_∞ performance γ if and only if there exists a positive definite symmetric matrix X such that:

$$\begin{bmatrix}A(\alpha)^{\mathrm{T}}X+XA(\alpha) & XB(\alpha) & C(\alpha)^{\mathrm{T}}\\ B(\alpha)^{\mathrm{T}}X & -\gamma I & D(\alpha)^{\mathrm{T}}\\ C(\alpha) & D(\alpha) & -\gamma I\end{bmatrix}<0\tag{6}$$

for all $\alpha(t)\in\boldsymbol{F}_{\mathscr{P}}$. Then, for every $\alpha(t)$, the system is exponentially stable, and the $\boldsymbol{L}_2$ gain between the output and input is bounded as $\|y\|_2<\gamma\|u\|_2$.

Lemma 3.2 (Parameter-dependent Performance) [85]: Given a compact set $\mathscr{P}\subset\boldsymbol{R}^s$, and $\{v_i\}_{i=1}^s>0$. If there exists a continuously differentiable function $X(\alpha)>0$ such that:

$$\begin{bmatrix}A(\alpha,\dot{\alpha})^{\mathrm{T}}X(\alpha)+\sum_{i=1}^{s}\left(\dot{\alpha}_i\frac{\partial X}{\partial\alpha_i}\right)+X(\alpha)A(\alpha,\dot{\alpha}) & X(\alpha)B(\alpha,\dot{\alpha}) & C(\alpha,\dot{\alpha})^{\mathrm{T}}\\ B(\alpha,\dot{\alpha})^{\mathrm{T}}X(\alpha) & -\gamma I & D(\alpha,\dot{\alpha})^{\mathrm{T}}\\ C(\alpha,\dot{\alpha}) & D(\alpha,\dot{\alpha}) & -\gamma I\end{bmatrix}<0\tag{7}$$

for all $\alpha(t)\in\boldsymbol{F}_{\mathscr{P}}$ meeting $\dot{\alpha}_i\le v_i$, then, the system is exponentially stable, and the $\boldsymbol{L}_2$ gain between the output and input is bounded as $\|y\|_2<\gamma\|u\|_2$.

In the corresponding citations, the attracted researchers can obtain the proof of the above lemma. In recent research, several novel LPV technologies have been adopted for GTEs. The details are as follows:

3.3.1.2. LPV model for aircraft GTE. It is important to establish a high-accuracy model for LPV control [82]. There are three main modelling methods for LPV models [84]: Jacobian linearisation, state transformation, and function substitution. First, the Jacobian linearisation method establishes different linear time-invariant objects at different equilibrium points of the entire operating envelope and parameterizes the state matrix coefficients of the LPV model with scheduling variables [86,87]. Second, the state transformation method is suitable for q-LPV systems. It uses differentiable state and input variables that do not belong to scheduling variables to transform the state of the system. Thus, the nonlinear terms that do not depend on the scheduling variables are eliminated [88]. Third, the decomposition function is replaced by a linear combination of a scheduling parameter-dependent function and a scheduling vector in the function substitution method [89]. The Jacobian linearisation approach is the most widespread methodology used to obtain LPV models.

The aircraft GTE has an extremely complex aero-thermodynamic process, and its own state dramatically changes under different operating conditions. Thus, it is important to establish an LPV model that includes the inflow conditions and internal states. With the development of research, the scheduling variables of GTE's LPV model have been considered single flight condition [90−93], internal state of engine [81,94−99], and both of them [100]. Researchers usually use a single scheduling variable to identify the GTE's LPV model, which is often a single-in single-out (SISO) system. In Ref. [101], the authors compared three different scheduling parameters for the LPV modelling of turbofan engines and built the full-envelope LPV modelling of the concerned turbofan engine; however, the q-LPV model at both ground and air conditions is not provided. Tang et al. [100] proposed a double-layer LPV model. It considers flight conditions and engine state as the scheduling variables. Figure 7 shows the double-layer LPV model. However, most LPV models are still SISO and are difficult to operate within a wide range of envelopes.

Yu et al. [102] proposed the equilibrium manifold expansion (EME) model to solve the GTE nonlinear control problem. The EME model was developed from the linearized model and has the same structure as the q-LPV model. Ideally, this model has high accuracy near the steady-state equilibrium points of the system. In addition, the model has a simple structure to meet the needs of real-time simulation [103,104]. Within the assumptions of the EME model, it can be regarded as an approximate model of a GTE. Thus, the nonlinear control method can be used on the EME

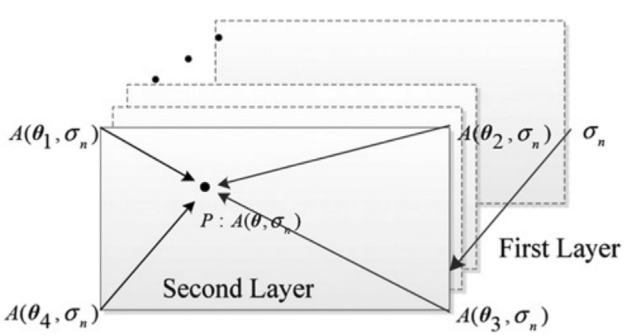


Figure 7 Double-layer LPV model whose scheduling variables are both flight conditions and engine's state [100].

model to manage the GTE control problem. Zhao et al. [105] proved that the EME model has the same linearisation results as the original nonlinear system. Liu et al. [106] combined the EME model with an adaptive method to obtain a more accurate engine model. Zhu et al. [107] proposed a novel corrected EME model, which uses the dynamic similarity criterion of similarity theory to improve the accuracy. However, considerable work should be performed on the EME model, such as the identification of MIMO models and the consideration of flight condition variations.

In short, LPV modelling is challenging. On the one hand, increasing the number of scheduling variables can improve the ability of the LPV model to express the dynamics of nonlinear systems; however, it also causes difficulties in the control system design. On the other hand, different scheduling parameters have different changing rules, and even contradict each other. If these scheduling parameters are fitted at the same time, the calculation is complicated and conservative, and the final LPV model hardly meets the accuracy requirements. In addition, with the increasing demand for GTE performance, multivariable control has become a research tendency. Currently, it is difficult to obtain a satisfactory MIMO LPV model of GTE in wide flight envelope. Thus, establishing an accurate and wide-ranging MIMO LPV model is also an innovative task.

3.3.1.3. LPV control for aircraft GTE. The approach based on the Lyapunov function provides enough vitality to the LPV control and theoretically guarantees the performance and stability of the control system. In 1995, Apkarian published Ref. [80], in which a robust gain-scheduling controller was designed for a class of affine parameter-dependent LPV systems using BRL and quadratic Lyapunov function. This study transformed the affine parameter-dependent LPV system into a polytope system, combined the convex optimisation theory to design the vertex controller, and then realised gain scheduling control according to the convex decomposition of the scheduling variables, which can theoretically ensure global stability and robustness within the entire range of scheduling variables. Gary et al. [81] applied the LPV controller to the turbofan and compared it with the H_∞ controller. The simulation results showed that the performance of the LPV controller was better than that of the H_∞ controller over a wide range of operating envelopes. Ali et al. [108] applied the mixed sensitivity method to the LPV model based on the quadratic Lyapunov performance. Pakmehr et al. [95] studied gain scheduling control, which uses a single quadratic Lyapunov function to maintain stability, and experimental verification was performed on the turboshaft engine. However, the method adopted by Apkarian was based on a quadratic Lyapunov function; that is, the system was limited at each vertex such that it had the same constant Lyapunov function matrix at each vertex. Therefore, the time-varying characteristics of the parameters were neglected in the system design process, which leads to the conservatism of the designed control system. To solve this problem, many parameter-dependent Lyapunov function methods have been discussed [85,109,110]. Turso et al. [111] used a scheduled linear parameter varying the quadratic Lyapunov function to design the GTE controller, which solved the control problem after engine degradation, and maintained system stability. Jia et al. [98] studied the closed-loop system regional pole assignment, which uses a linear matrix inequalities approach to maintain the pole placement of the control system in a pre-design range and meets the robust H_∞ performance. Yang et al. [112] applied the parameter-dependent Lyapunov function method to reduce the influence caused by frequent switching of Markov switched LPV systems, and proposed the H_∞ bumpless transfer reliable control for the SISO turbofan engine, which could work in the case of actuator failure.

GTEs are affected by external environmental variables and internal aerodynamic and thermodynamic processes during operation; thus, it is difficult to characterise GTEs using a single LPV model. The control method considering switched LPV systems has proven to be effective for GTEs. Switched LPV systems inherit the characteristics of both LPV and switched systems and approximate the real nonlinear system [113]. The Lyapunov function method has been widely used in the design and analysis of switched LPV systems [114,115]. The main idea of the method is to ensure that the Lyapunov function between switched subsystems keeps decreasing before and after switching. Liu et al. [97] designed a switched LPV robust tracking control of aero-engine rotor speed based on a common Lyapunov function and proposed a hysteresis switching logic that can avoid switching caused by disturbances. Zhu et al. [91] combined the multiple parameter-dependent Lyapunov functions method with the hysteresis switching law and proposed an aero-engine-switched LPV control algorithm that considers actuator saturation. Figure 8 shows the switching signal of the hysteresis switching law. Yang and Zhao [92] built a resilient observer and designed an H_∞ resilient control for the switched LPV system by using the multiple parameter-dependent Lyapunov functions. Tang et al. [100] studied a double-layer LPV model that contained flight conditions and rotor speed as the scheduling variables. An arbitrary switching logic and dependent-parameter Lyapunov function method were applied to design the switched LPV control of aero-engines. Yang and Zhao [116] studied the H_∞ output tracking control of an aero-engine with switched LPV models and designed a set of parameter- and mode-dependent switching signals.

In 1996, Morse [117] proposed the method of dwell time based on multi-Lyapunov functions. This method guaranteed the decay of two Lyapunov functions between the subsystems by limiting the interval of switching, thereby offsetting the instability caused by the increase in the Lyapunov functions. The resident time method is a stability analysis method based on multiple Lyapunov functions, which is considerably significant in engineering applications. In 1999, Hespanha et al. [118] extended the dwell time method to the average dwell time method to meet the requirements of multiple switching in a short time in engineering applications. Since then, a less conservative switched control method that limits the constraint of average dwell time to the common subsystem was proposed [119]. Zhu and Zhao [93] designed a mode-dependent average dwell time switching method for aero-engine LPV systems. Zhu et al. [120] introduced mixed event triggered control based on the average dwell time switching mechanism for aircraft engines. The system structure under the mixed-event triggered control scheme is shown in Figure 9. The two schemes depend on the state and parameter triggers. Yang et al. [121] applied the parameter-dependent multiple discontinuous Lyapunov function method to a switched LPV model of an aero-engine and designed a parameter-driven and dwell time-dependent switching law. Then, a parameter-dependent disturbance observer that meets H_∞ refined antidisturbance performance was established for an aero-engine control system.

The method based on the Lyapunov function is important in LPV control. However, the LPV control of GTE is difficult to solve. Several researchers have focused on this

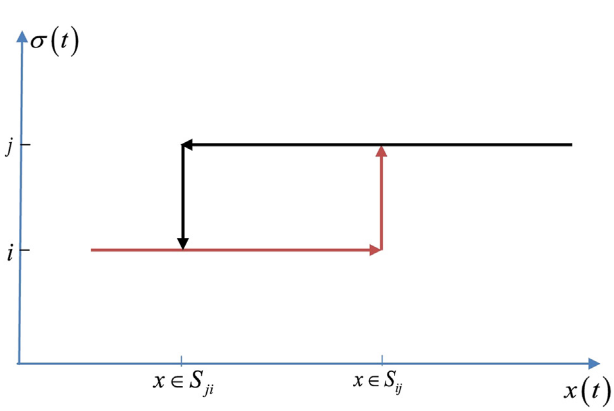


Figure 8 Hysteresis switching law [97].

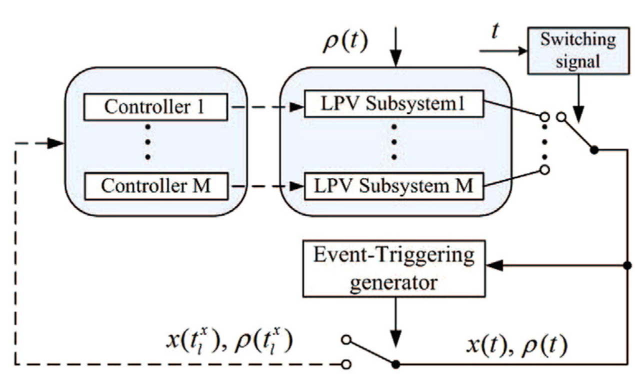


Figure 9 System structure under the mixed event triggered control scheme [120].

issue. First, the sum of squares (SOS) programming has been applied to solve the LPV controller of GTE. In recent years, SOS programming has rapidly developed owing to its convenience and superiority in managing polynomial nonlinearities, and it has also become an effective tool for nonlinear control system analysis and synthesis [122]. Wu et al. [94] converted the polynomial fixed-order controller [90] solving problem of turbofan engines into SOS programming. Based on BRL theory, the researcher used the Lyapunov function method to design the LPV controller. In Ref. [96], Lemma 3.1 was transformed into SOS programming and a MIMO LPV controller was designed for GTE. Sun et al. [123] discussed the application of SOS programming in the switched LPV control of GTE based on the parameter-dependent Lyapunov function. Tang et al. [124] established an off-equilibrium LPV model for SISO GTE and solved the LPV controller based on quadratic H_∞ performance by SOS programming. Second, to address the nonlinear control of GTE, Yu et al. studied a type of q-LPV model, also known as EME model. In Ref. [105], Zhao proposed feedback linearisation control based on the EME model for aero-engines. Shi et al. [125] established a switched EME model with different scheduling variables and designed a switching control system based on a feedback linearisation controller. The EME model was used to manage the switching control of acceleration and safety protection for GTE [126]. Furthermore, sliding mode [127] and adaptive control [128] are applied to GTEs based on LPV models.

3.3.1.4. Discussion on LPV control for aircraft GTE. Recent research on LPV control of GTEs is summarised in Table 1. The LPV methods often use the BRL and Lyapunov function method to design a stable controller. The advantage of this method is the application of mature robust control theory to a nonlinear plant with an LPV model structure. Compared with linear control, LPV control provides parametric characteristics to controller parameters and improves the control performance and stability of GTEs. However, there are some shortcomings in LPV control:

- Lack of accurate and comprehensive LPV models for GTEs. Considering the complicated nonlinearity of flight conditions and engine state, the LPV model of GTEs in the full envelope range is difficult to obtain. Even if the above situation is solved, GTE is still a MIMO system. Many LPV models that consider SISO cannot meet the control requirements, and the complex MIMO LPV system increases the difficulty of identification.
- Complex nonlinearity of LPV models with multiple scheduling variables for GTEs. With the modern development of GTEs, engine control has more and more degrees of freedom to meet engine performance and safety requirements. The LPV model need describe more comprehensive engine operating conditions, and its scheduling parameters need to include one or more states. The above reasons will cause the LPV model to be non-linear, which makes the control design hard.
- Difficulties in solving LPV controllers. It is difficult for researchers to solve controllers with variable parameters, especially LPV model with multiple scheduling variables. The multi-cell vertex technology brings convenience to the solution of the LPV controller, but the conservativeness of the controller still exists. Although SOS programming provides an effective tool for solving the polynomial LPV control system, the control solution needs to frequently adjust the set value of the index in the inequality to manage the unsolvable situation. In addition, the requirements of MIMO LPV control for GTEs increase the complexity of the controller solution.
- There is no effective LPV control research of GTEs in the entire envelope. Owing to the difficulty of LPV model identification and controller solution, the LPV control for MIMO GTEs is less discussed, which is the focus of future research.

3.3.2. Sliding mode control

SMC is a type of special nonlinear control characterized by discontinuous control quantity. The difference between this method and other control methods is that the system structure is not invariable, but discontinuously moves according to the designed state trajectory in the dynamic process. The basic idea of SMC is to make the system arrive from any initial state and stay on the set sliding surface through a specific control law. On this sliding mode surface, the system can spontaneously move towards the equilibrium point. The research on SMC can be divided into three stages. At the earliest, in the 1950s, the research was mainly aimed at SISO linear systems, and the theory of SMC was proposed and preliminarily developed. In the second stage, the sliding surface design is discussed for the high-order linear MIMO system. Since the 1970s, interest on SMC has increased and it has become an important part of control theory [129,130].

With the development of control technology, SMC has also been applied to the control design of aero-engines. This section introduces the relevant theories of SMC and shows its application in aero-engine control. Finally, the advantages of SMC and the problems that need to be urgently solved are presented. The theoretical introduction of sliding mode control may not be detailed enough and interested readers may find their favourites in Ref. [131].

3.3.2.1. Problem definition and basic theory for SMC. Compared with the conventional control strategy, the SMC is discontinuous, that is, it switches: the system structure is not fixed and can change with time. Thus, it is completely invariant to parameter changes and disturbances.

SMC has two stages: (1) arrival stage: the system state trajectory can reach the designed sliding mode surface from

Table 1 Summary of recent research on LPV control for GTEs.

Reference	Goal	Technique	Modelling
Balas 2002 [81]	Summary of the application.	Single or parameter-dependent Lyapunov function.	SISO.
Turso and Litt 2004 [111]	Control deteriorated Turbofan.	Quadratic Lyapunov function, Mixed sensitivity.	SISO.
Gilbert et al., 2010 [90]	Design polynomial fixed-order controller.	Parameter-dependent Lyapunov functions.	SISO, transfer function.
Li and Zhang 2010 [99]	PI gain scheduling controller.	PID controller.	SISO.
Yu et al., 2011 [102]	Establish EME models for GTEs.	Two-step “dynamic and static” identification.	SISO, EME modelling.
Zhao et al., 2011 [105]	Study nonlinear control based on EME model for GTEs.	Feedback Linearisation.	SISO, EME model.
Liu and Zhao 2012 [103]	Establish the surge margin for GTEs.	Two-step “dynamic and static” identification.	EME modelling.
Pakmehr et al., 2013 [95]	Design gain scheduling control.	Quadratic Lyapunov function.	MIMO, Only 5 fixed points.
Liu and Yuan 2014 [104]	Establish EME models for GTEs.	Two-step “dynamic and static” identification.	SISO, EME modelling.
Liu et al., 2014 [106]	Establish EME models for GTEs performance degradation.	Adaptive technique.	SISO, EME modelling.
Zhu et al., 2015 [91]	Design state feedback control.	Multiple parameter-dependent Lyapunov functions, Hysteresis switching.	SISO, switched LPV.
Yang and Zhao 2016 [92]	Design observer-based H_∞ resilient control.	Multiple parameter-dependent Lyapunov functions, Resilient observer.	SISO, switched LPV.
Wu et al., 2016 [94]	Apply SOS approach to solve LPV controller.	LPV/PI control, SOS programming.	SISO, transfer function.
Wu and Huang 2016 [96]	Apply SOS approach to solve LPV controller.	Quadratic Lyapunov function, SOS programming.	MIMO, 13 fixed points without flight condition.
Tang et al., 2016 [100]	Design switching LPV controller meet both H_∞ and H_2 performances.	Common Lyapunov function, Arbitrary switching logic.	SISO, double-layer LPV model, Whole flight envelope.
Zhu and Zhao 2017 [93]	Design switched LPV systems with inexact parameters.	Multiple parameter-dependent Lyapunov functions.	SISO.
Jia et al., 2017 [98]	Control both rotor speed and temperature.	Closed-loop system regional pole assignment.	MIMO without flight envelope.
Yang and Zhao 2017 [116]	H_∞ output tracking control.	Multiple parameter-dependent Lyapunov functions, Parameter and mode-dependent switching signals.	SISO.
Shi and Zhao 2017 [125]	Improve control effect in Ref. [105].	Feedback linearisation, Event-triggered switching law.	SISO, switched EME model.
Sun et al., 2018 [123]	Apply SOS approach to solve LPV controller.	Parameter-dependent Lyapunov function, SOS programming.	SISO, whole flight envelope.
Zhu et al., 2018 [120]	Mixed event triggered control.	Average dwell time.	SISO.
Chen and Zhao 2018 [126]	Acceleration and safety protection switching control.	Lyapunov functions.	SISO, EME model.
Liu et al., 2019 [97]	Robust tracking control.	Common Lyapunov function, Hysteresis switching logic.	SISO, switched LPV.
Yang et al., 2019 [128]	Adaptive control based on LPV model.	Radial basis function neural networks.	SISO.
Zhu et al., 2020 [107]	Consider the dynamic similarity criterion of similarity theory.	Two-step “dynamic and static” identification.	SISO, corrected EME.
Yang et al., 2020 [112]	H_∞ bumpless transfer reliable control to actuator failures.	Parameter-dependent Lyapunov function, Markovian switching.	SISO, Markovian switching LPV model.
Yang et al., 2020 [121]	H_∞ refined antidisturbance control.	Parameter-dependent multiple discontinuous Lyapunov function, parameter-driven and dwell time-dependent switching law.	SISO, switched LPV.
Tang et al., 2020 [124]	Off-equilibrium linearisation-based nonlinear control.	Quadratic Lyapunov function, SOS programming.	SISO, Off-equilibrium linearisation models.
Yang et al., 2020 [127]	Limit protection.	Sliding mode regulator.	SISO.

any initial state in finite time; (2) sliding mode stage: the system is forced to make sliding motion on the pre-designed sliding mode surface. The corresponding two design steps are as follows. First, the sliding mode surface is selected and describes the ideal dynamic characteristics of the system. The sliding mode should be asymptotically stable and have a good dynamic quality in the design. Second, the SMC law is designed. The sliding mode controller is designed such that the approaching motion can reach the sliding mode surface in a limited time.

For general systems:

$$\dot{x} = f(t, x, u), t \in R, x \in R^n, u \in R^m \tag{8}$$

To select the sliding surface:

$$s(x) = 0, s \in R^m \tag{9}$$

As shown in Figure 10, the sliding surface divides the state space into $s(x) > 0$ and $s(x) < 0$. The system state trajectory approaches the sliding mode surface from both sides at point C, which is the termination point. If all points on the sliding mode switching surface are termination points, then the motion of the system in this area is called "sliding mode motion" [132].

To obtain the variable structure control:

$$u_i(x) = \begin{cases} u_i^+(x), s_i(x) > 0 \\ u_i^-(x), s_i(x) < 0 \end{cases} \tag{10}$$

where, $u_i^+(x) \neq u_i^-(x)$, then.

(1) The sliding mode exists;
(2) To satisfy the accessibility condition, the motion points outside the switching surface will reach the switching surface in a limited time;
(3) The stable performance of the sliding mode motion is guaranteed.

The above three points are the basic requirements and preconditions of the SMC; that is, the control with these three conditions simultaneously can be called SMC.

There are several common design methods for sliding mode variable structure control:

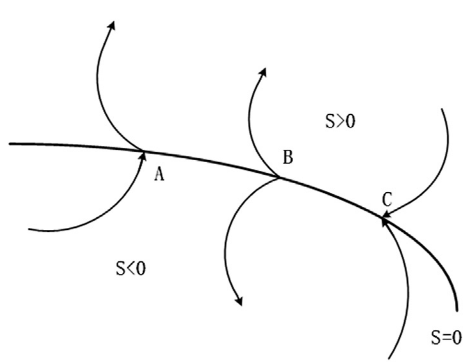


Figure 10 Sliding surface [132].

(1) Constant switching control:

$$u = u_0\, sgn(s(x)) \tag{11}$$

(2) Function-switching control:

$$u = u_{eq} + u_0\, sgn(s(x)) \tag{12}$$

(3) Proportional switching control:

$$u = \sum_{i=1}^{k} \varphi_i x_i, k < n \tag{13}$$

$$\varphi = \begin{cases} \alpha_i, x_i s < 0 \\ \beta_i, x_i s > 0 \end{cases} \tag{14}$$

where α_i and β_i are constants.

The major advantage of SMC is that when the system enters the sliding mode, the dynamic characteristics of the system are completely unaffected by the interference of matching, and the system is extremely robust. In contrast, the traditional design-based robust controller can only suppress the influence of interference. Second, SMC also has order reduction properties. The sliding mode surface can be designed in a space lower than the original system dimension, which can simplify the design.

However, SMC has an evident disadvantage, which is the sliding mode chattering. Theoretically, when the sliding mode moves, the switching speed is infinite, which is impossible to achieve. In fact, owing to the limited switching speed, the system does not move smoothly when entering the sliding mode surface, resulting in track interweaving around the sliding mode surface and generating chattering. This is an unfavourable factor for the control system. In practical applications, the characteristics of inertia, dead zone, and hysteresis of control system components also aggravate this chattering, which accelerates the wear of system components, and, in severe cases, stimulate the unmodeled characteristics of the system and lead to system instability. Currently, there are several methods to solve chattering, such as terminal sliding mode, high-order sliding mode, and integrated sliding mode surfaces, which are used when designing sliding mode surface. In terms of improving the discontinuity of control switching, the boundary layer and saturation function methods are proposed.

3.3.2.2. SMC for aircraft GTE. In the field of aero-engine SMC, Richter [133−135] studied the design of a sliding mode controller, including the design point tracker design. The sliding mode limit control method was validated on the aero-propulsion system simulation package at NASA Green Research Center. This method maintains the key variables within the limit value, optimises the control effect, and validates the feasibility of applying the sliding mode limit control method to aero-engines, which has extensive engineering significance. At present, the SMC regulator has been

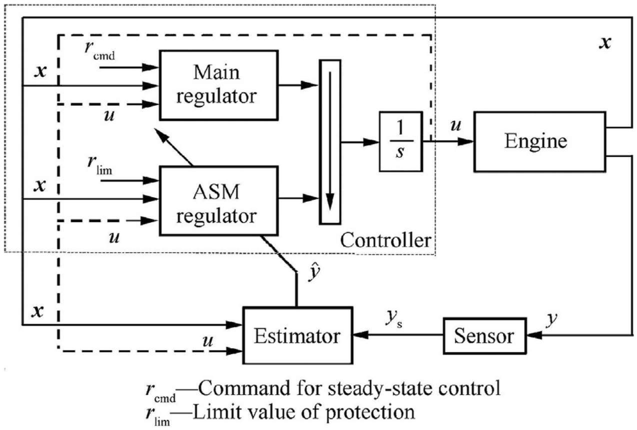


Figure 11 Overview of control system structure in Ref. [141].

developed to replace the traditional linear regulator in aircraft engine control, in which the SMC can strictly maintain the relevant output within its limits and improve the control performance.

Theoretically, as long as the system is stable in the sliding mode and various properties of the sliding mode variable structure control system are retained, the sliding mode surface can have different structures. Therefore, several researchers have proposed a variety of sliding surfaces.

First, a linear sliding surface is the simplest and most widely used. In recent years, design methods based on standard sliding surfaces have been further popularised. Du et al. [136] proposed a single-variable sliding mode controller to replace all linear controllers and solve the problem of insufficient traditional single-variable linear controller Min−Max switching method. Second, the terminal sliding mode method is a multi-sliding mode and multi-hierarchical control with good stability and disturbance immunity. The stability analysis of the system is convenient, and the controller design is simple. In a work with rigid robotic manipulators, Man et al. [137] introduced the terminal attraction in a NN terminal, and proposed a robust MIMO terminal SMC technique, which can quickly make the state error convergence. However, traditional terminal sliding mode control has the problem of singularity. In addition, the nonlinear part affects the convergence speed of the equilibrium state, which lead to a fast convergence speed near the equilibrium state and a slow convergence speed far from the equilibrium state. To solve this problem, Miao et al. [138] studied an aeroengine terminal sliding mode control method based on a radical basis function (RBF) network. In this method, a terminal sliding mode plane and an RBF NN are used to compensate for the uncertainty of interference and parameters. Third, global SMC is a novel method for GTEs. In the traditional SMC, the state of the system from the initial to the equilibrium point is composed of the arrival and sliding mode stages. The sliding mode stage has the advantage of invariability, but the arrival stage does not have such robustness and is easily disturbed. Lu et al. [139] first proposed the idea of a global sliding-mode controller. By constructing a dynamic sliding mode hyperplane function, the system falls into the hyperplane of the sliding mode at the beginning. The system only has a sliding mode stage, which achieves entire-course robustness, and also reduces the arrival time and accelerates the response of the system. Liu et al. [140] investigated an improved multi-power reaching law of the sliding mode to reduce the high-frequency oscillation phenomenon that appeared in the multi-power tracking control process of an aero-engine.

In addition, Yang et al. [141] proposed an adaptive SMC structure for the limit protection of aircraft engines under unreliable measurement. According to an online estimator, the uncertainty of output is analysed, and the adverse impact on the measured output is calculated. Based on this, a sliding controller is designed. The structure of the system is shown in Figure 11.

3.3.2.3 Discussion on SMC for aircraft GTE. Table 2 summarises the application of SMC in aero-engines in recent years. When the system is in sliding mode motion, it becomes insensitive to parameter changes and disturbances, thus the SMC has strong robustness. In addition, the design of the controller is simple and easy to implement because the SMC has a reduced-order characteristic and does not require online identification. It is suitable for both linear and nonlinear systems as well as continuous and discrete systems.

However, owing to discontinuous switching, the system will have a chattering problem under the influence of time

Table 2 Summary of recent research on SMC for GTEs.

Reference	Goal	Technique	Modelling
Miao et al., 2010 [138]	Weaken the chattering.	RBF neutral network, terminal sliding surface.	MIMO, RBF NN for uncertainty.
Richter and Litt 2011 [133], 2012 [134,135]	Sliding mode controller for aggressive limit management.	H_2/H_∞ sliding surface.	SISO, linear model.
Du et al., 2016 [136]	Multi-input constraint management.	Min−max switching logic, multivariable sliding mode.	MIMO, linear model.
Yang et al., 2018 [141]	Limit protection.	Lyapunov theorem, low-pass filter, online estimator.	SISO, linear model.
Liu et al., 2019 [140]	Tracking controller, Test in DGEN380 aero-engine.	Multi-power reaching law.	MIMO, linear model.

delay and inertia. Most of the traditional sliding-mode variable structure control design methods consider the bounded uncertainty as a prerequisite to ensure the robust stability of the closed-loop system. This approach avoids chattering, but the control system is more conservative, which limits the control performance.

3.3.3. Adaptive control

Owing to the strong nonlinearity and complex working mechanism of an aero-engine, it is difficult to obtain an accurate mathematical model. Therefore, several researchers have focused on the research and application of adaptive control on aero-engines. Based on the system of all input and output of information, a certain performance indicator is measured and compared with the desired one. Then, the adaptive mechanism can modify the parameters of the controller or generate an auxiliary signal for the system to apply performance requirements and remain consistent with them [142]. The method has a good control effect on the uncertainty and nonlinearity of the system. There are several types of adaptive control. This section provides some basic theories of adaptive control, and introduces the application in aero-engines in recent years. Finally, the advantages, disadvantages and development of the adaptive method are discussed.

3.3.3.1. Problem definition and basic theory for adaptive control. The research object of adaptive control is a system with uncertainty. The so-called uncertainty is mainly reflected in the following aspects: 1) the structure and parameters of the system are unknown, or the mathematical model established is different from the system; 2) the external environment has various disturbances to the system; 3) the system changes with time and working environment during operation. These uncertainties are common in aircraft GTEs. Adaptive control involves modifying the GTE through continuous measurement during the operation of the controlled system, such that the engine can achieve the expected goal. The adaptive control system has rapidly developed since it was proposed. Model reference adaptive control (MRAC) and self-tuning regulator are classified according to the structural characteristics of the adaptive system. Among them, MRAC has been widely studied in aircraft GTEs.

The MRAC is characterised by simple principles and rich design methods. Moreover, the dynamic and static performance of the desired control object can be designed using the reference model. The idea of this method is to add a model reference auxiliary system to express the expected output, and then compare the actual system output with the reference one to obtain an error value. The system is adjusted with this error value until the error reaches a minimum or is equal to zero. Figure 12 shows the structure of the MRAC, which is composed of two loops. The inner loop constitutes the adjustable system by the controller and the plant, and the outer loop has the reference model and adaptive mechanism.

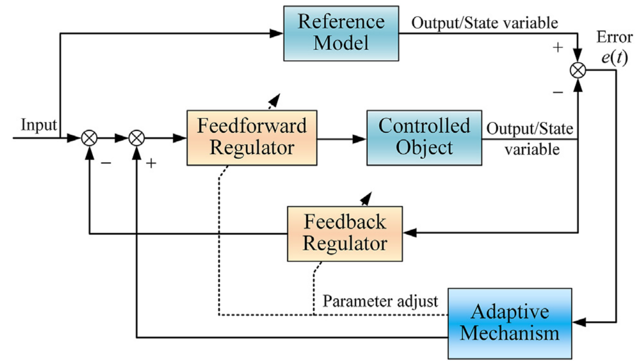


Figure 12 MRAC system composition diagram.

The early development of model reference adaptation can be divided into four stages. In the first stage, the model reference adaptive system was first proposed by Whitaker et al. [143] in 1958, and the algorithm of adaptive law (MIT law) was described by parameter optimisation theory. The idea was to construct a performance index $J = \int_{t_0}^{t} e^2(t)\mathrm{d}t$ according to the error $e(t)$ between the controlled object and the output value of the reference model, and adjust the controller parameters to minimise this index. However, the main aspect of this method is local parameter optimisation, thus the stability of the system cannot be guaranteed. In the second stage, to solve this stability problem, Parks [144] proposed the second Lyapunov method to construct the control law related to the reference model and the state error of the control object. An appropriate Lyapunov function is constructed to achieve consistency between the characteristics of the controlled object and the reference model. To avoid the process of selecting complex Lyapunov functions, Landau [145] used the Popov hyperstability theory to implement adaptive control of the system. The basic idea was to transform plants into an equivalent feedback system, which consisted of a positive real linear part located in the positive channel and a nonlinear feedback part satisfying the Popov integral inequality. However, it is not easy to obtain the all-state signal and output differential signal of some systems, thus the corresponding regulation law cannot be obtained. In the third stage, based on the limitations of the second stage, Monopoli [146] used the generalised error to design adaptive control systems. Narendra [147] proposed an adaptive control method that only used the measured values of the input and output of the system. At this stage, the control method based on the hyperstability theory was further developed. However, there were still some deficiencies in the robustness of the developed methods. In the fourth stage, based on the existing MRAC method, the robustness of the system was considered, and a robust MRAC was further developed [148].

Several other MRAC methods combined with NNs are also effective.

3.3.3.2 Adaptive control for aircraft GTE. MRAC has been widely studied in aircraft GTEs. Thus, we introduce the recent progress on the MRAC of GTEs in this section. In addition, some other adaptive methods are also mentioned. In the early stage, the MRAC applied to an aero-engine was a traditional control method based on the Lyapunov stability theory and Popov hyperstability theory. These methods were feasible and had good control effects at that time. However, with the improvement of engine performance, the internal structure and parameters of GTEs become increasingly complicated, and the adaptive control method also needs to be improved.

The MRAC method has been maturely developed in the SISO aero-engine. In the mid-1980s, the United States adopted the model-based control method to study the integrated flight/propulsion control system of the PW1128 and F15 fighter jet engines, which achieved good control results [149,150]. In 2011, Wiederhold et al. [151] adopted an adaptive control method on an axial flow turbofan engine to improve flight performance. In the experiment, they adopted the slope-seeking algorithm and used a Kalman filter to accelerate gradient estimation.

The development of MRAC in MIMO systems is not as mature as that of SISO systems, but there are some research achievements. Li et al. [152] proposed an adaptive law design method based on a projective operator and applied it to the design of a model reference adaptive controller in view of the complex external disturbance phenomenon under a large range of work packages of variable-cycle aero-engines. This method improved the robustness of the adaptive control system. Jin et al. [153] investigated an improved reference model to solve the problem of poor dynamic performance of a common reference model. In this study, state feedback was adopted to realise state tracking, and the tracking error was introduced into the reference model, which effectively restrained the overshooting of the tracking response. The multi-variable MRAC method is independent of the precise mathematical model and has a strong adaptive type, which can meet the tracking and control requirements of the engine in steady and transition states.

With the improvement of technical requirements, an increasing number of adaptive methods are used in combination with other methods, such as a combination of adaptive and SMC methods. Zhang et al. [46] studied a combined fault-tolerance algorithm based on an adaptive sliding-mode observer in aero-engine DCS fault-tolerant control when sensors and actuators fail simultaneously. Xiao et al. [154] designed an adaptive sliding mode controller (ASMC) for an MRAC structure. The adaptive law is derived based on the Lyapunov function to estimate the unknown upper bound of uncertainties and external disturbances. A block diagram is shown in Figure 13.

3.3.3.3. Discussion on adaptive control for aircraft GTE. Table 3 shows the application of adaptive control in aero-engines in recent years. The main objectives of the research are to remove the augmented error signal, reduce adjustable parameters, improve the

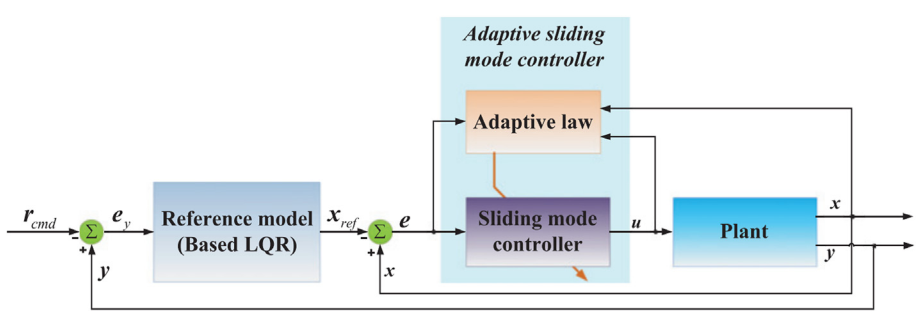


Figure 13 Model reference ASMC block diagram in Ref. [154].

Table 3 Summary of recent research on adaptive control for GTEs.

Reference	Goal	Technique	Modelling
Wiederhold et al., 2011 [151]	Accelerate the closed-loop control performance.	A slope-seeking control, Kalman filter.	SISO, linear model.
Li et al., 2018 [152]	Improve robustness, suppress external disturbances.	Robust Adaptive Control, MRAC.	MIMO, linear model.
Xiao et al., 2019 [154]	Suppress uncertainty and external disturbances.	Model reference, adaptive sliding mode control.	MIMO, variable cycle engine.
Zhang et al., 2020 [46]	Fault-tolerant control with Markov time delay.	Robust adaptive SMC.	MIMO, distributed control system.
Jin et al., 2020 [153]	Reduce overshoot of the tracking process.	Improved reference model.	MIMO, linear model.

robustness of the system, and overcome system interference. Because the adaptive control method does not require a precise mathematical model of the control object, the adaptive control theory solves the problem of an inaccurate model of an aero-engine. Due to various objective uncertainties during flight, the structure and parameters of the controller are adjusted and updated by constantly measuring the input, state, output, or performance parameters of the system. Under a certain performance index, the control effect is optimised or approximately optimal, which solves some control problems of the engine with changing flight conditions.

However, adaptive control has difficulties for its application. First, the estimated parameters in the adaptive tracking controller generally do not converge to their true values. This is because the "continuous excitation" condition of the input signal cannot be satisfied in the actual tracking control problem. Second, the current adaptive control algorithm has no outstanding performance in the application of aircraft GTEs. Owing to the complex nonlinearity of aero engines, the adaptive control of GTEs needs more research to obtain a satisfactory control effect.

3.3.4. Model predictive control

3.3.4.1. Problem definition for MPC. MPC is an online rolling optimisation control algorithm based on a finite-time-domain objective function, which is a special precise open-loop control law. Based on the predictive model, MPC adopts the quadratic online rolling optimisation index and feedback correction to overcome the modelling error and the influence of uncertain factors such as structure, parameters, and environment. It effectively compensates the shortcomings of modern control theory for complex controlled objects. The technical advantage of MPC is that the targets and constraints can be modified online to achieve control under different operating conditions [155]. The key to realising MPC is the accuracy and efficiency of the calculation model.

The three elements of MPC are: predictive model, rolling optimisation, and feedback correction. The predictive model predicts the output of the system in several future steps based on the current and historical state information of the system. Rolling optimisation solves the optimal performance index in the finite time domain based on the prediction model and determines the optimal input of the system in the future. Although each step of the optimisation calculation is static, it achieves global dynamic optimisation. According to the output error between the actual system and the predictive model, MPC corrects the output of the prediction model or the control command of the controller to improve the control accuracy and robustness of the control system, and achieve feedback correction. Figure 14 shows the MPC strategy. By minimising the objective function, the predictive control signal makes the predictive output as close as possible to the reference trajectory [156].

MPC was first proposed to solve problems in the industrial field, obtaining good control effect and being quickly applied in many fields, including aviation. The aero-engine system is a complicated aero-thermodynamic system with a wide operating range and complex operating conditions. There are several uncertainties, such as disturbance and unmodeled dynamics in the actual system. In fact, air-breathing aero-engine control is a difficult problem with multiple constraints. In response to such problems, MPC is widely used in aero-engine control system design because of its performance optimisation property and its convenience in managing various constrained problems [157−160]. According to the difference between predictive models, MPC can be divided into linear (LMPC) and nonlinear MPC (NMPC). From the results of the literature review, NMPC has been widely used in aircraft GTEs. This is also consistent with the strong nonlinearity of the engine, and the control system requires a complex nonlinear model to approximate the dynamic characteristics of the engine as much as possible.

3.3.4.2. MPC for aircraft GTE. On the one hand, the engine model based on linearisation is often used as a prediction model in MPC research because of its real-time calculation. In terms of the LMPC optimisation algorithm, Mu et al. [161,162] used the continuous linearized model at each sampling time as the predictive model, and introduced the generalised predictive control algorithm to form the approximate MPC (AMPC) to the GTE. The analysis showed that approximate MPC was superior to traditional NMPC in terms of calculation amount, which provided a theoretical idea for real-time applications. Based on linear predictive control, Qiao et al. [163] performed a constrained predictive control of aero-engines using a constrained quadratic performance index. The difficulty of LMPC is that the linear predictive model does not adequately fit the nonlinear engine. Therefore, some researchers have adopted the multi-model method to

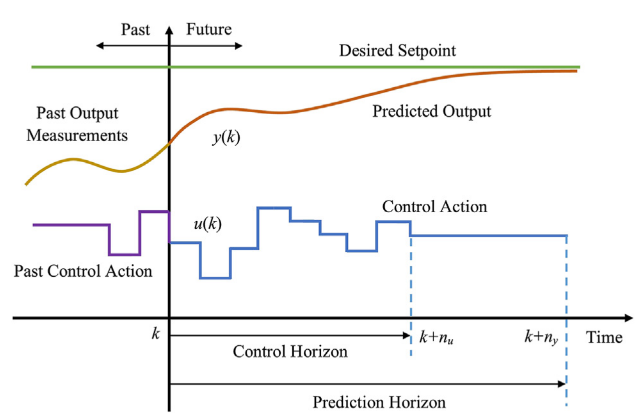


Figure 14 MPC strategy [156].

design the predictive controller by choosing different predictive models under different working conditions. Richter [160] proposed a multiplexed predictive control strategy, which reduced the calculation time of traditional online optimisation of LMPC under small performance degradation. Miao et al. [164] established 29 sets of engine linear models within the full envelope to provide a more accurate prediction model. Du et al. [165] proposed an LMPC scheduling strategy using fuzzy membership logic to schedule various linear model predictive controllers within the flight envelope to improve the constrained predictive control.

On the other hand, the complex nonlinear characteristics like multiple constraints and large time delays restrict the application of LMPC in aircraft GTEs. Aiming at this problem, many researchers have proposed using a nonlinear model with higher precision to adapt the dynamic characteristics of an engine in an MPC. Brunell et al. [157,158] established a simplified real-time model of an aircraft engine and used it as a predictive model for NMPC. They considered the model mismatch and various disturbances, and reconstructed the state and related parameters using an extended Kalman filter (EKF). The simulation results show that Brunell's study can improve the performance of the controller under constrained conditions. DeCastro [166] used a rate-based LPV model to investigate the NMPC, which guarantees stability within transient regimes. Xiao and Huang [167] combined MPC with an adaptive algorithm, in which an on-line adaptive model of the engine was built to quickly estimate engine output parameters. Wiese et al. [168] directly performed MPC studies based on the reduced-order results of a nonlinear physics high-order model of gas turbine systems, and completed experimental verification of the control system. The singular perturbation method was applied to reduce the order of the MIMO physical model.

In addition, the NMPC method is often combined with NN technology, using the nonlinear approximation ability of NN to construct predictive models. Diwanji et al. [169] used an artificial NN (ANN) to NMPC research on gas turbines, and solved the engine thrust tracking control problem. Wang et al. [170] established an NN nonlinear auto regressive moving average model to predict the aero-engine output, and designed the estimation mechanism of prediction error by relevance vector machine. To improve the response performance of the control, Zheng et al. [171,172] proposed the online-sliding window deep NN as a predictive model, which was used for direct thrust control of aero-engines. The control structure of NMPC and the simulation results in the literature [171] are provided in Figures 15 and 16, respectively. The results show that the NMPC based on DNN has a better control effect than the NMPC based on EKF.

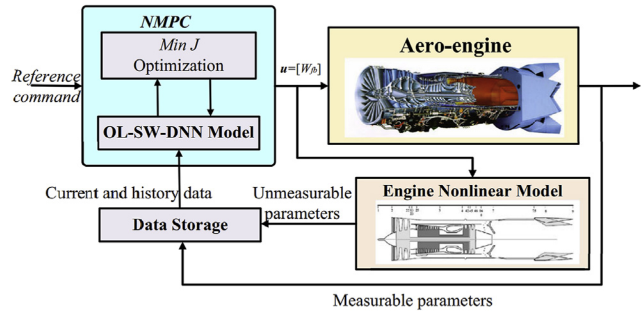


Figure 15 Control structure of NMPC [171].

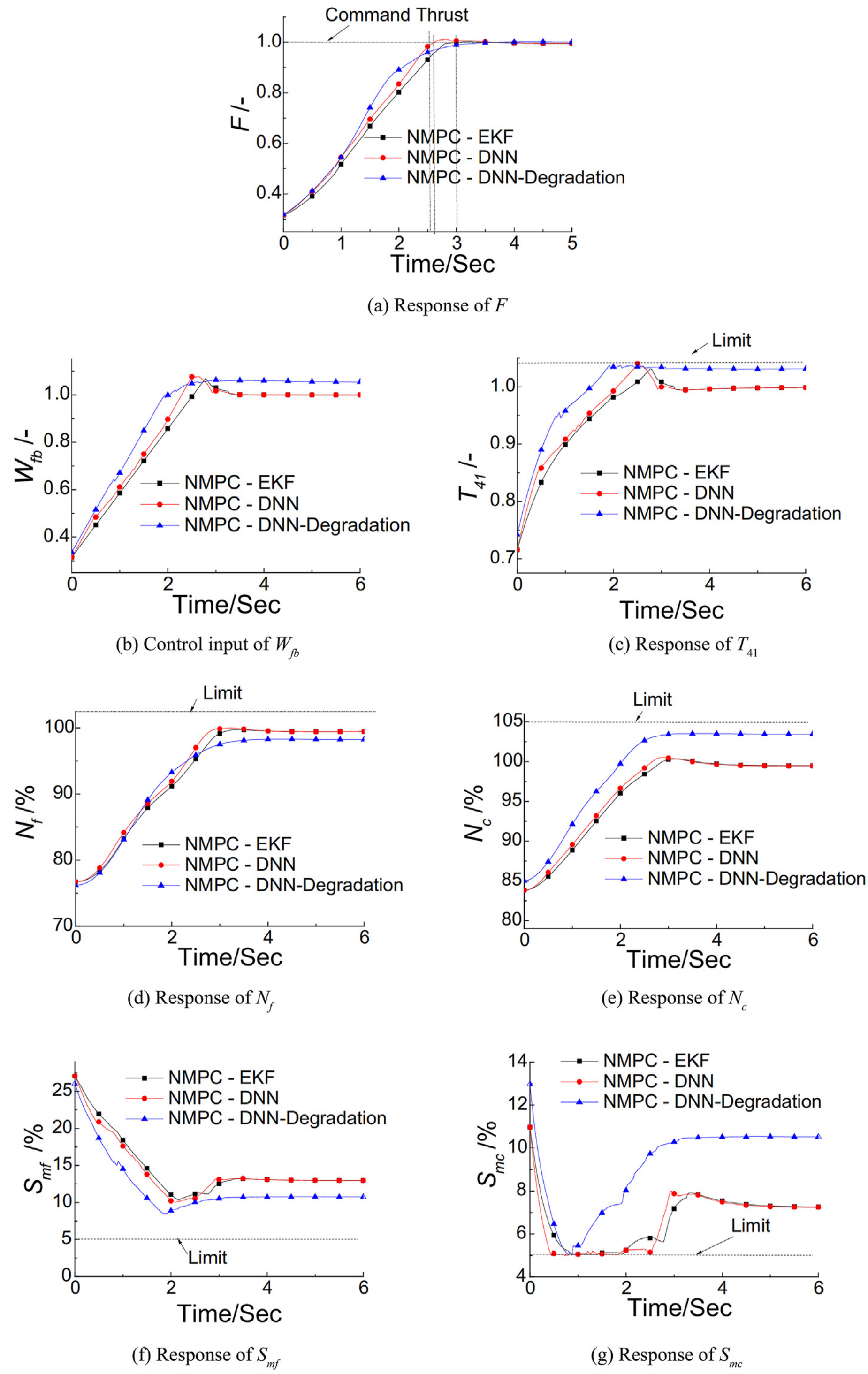
3.3.4.3 Discussion on MPC for aircraft GTE. Table 4 shows the application of MPC for aircraft GTEs. There are two advantages to MPC. First, it can simultaneously realise performance management and limit management, thus omitting the complicated structure of limiter and selection logic. Second, it can also conveniently control the system with multiple variables and achieve a better control effect. From the basic idea, the MPC algorithm using the future dynamic characteristics of the system is better than the deviation feedback control method using historical information. However, MPC is not perfect for control. Its shortcomings include the large amount of calculation, particularly the NMPC, in aircraft GTEs. To prevent the engine state from excessively deviating from the value at the beginning of the prediction, the MPC must complete the prediction and optimal control solution within the specified time to achieve the purpose of real-time control. The general sampling period of the control system is 15−20 ms. This means that the control system must complete various operations within the sampling period, including sensor data transmission, control law calculation, and control command input. Among them, the calculation time of the control law only occupies a small part of the sampling period, which hinders the application of most of the current MPC algorithms to the actual control of aero-engines. Therefore, the development of airborne computers with higher computing speed and storage capacity and MPC algorithms with more real-time computing are important research directions in the future.

3.4. Intelligent control for aircraft GTE

Intelligent control is a novel research direction for aircraft GTEs advanced control. This section starts with fuzzy and NN control, and then introduces the application of intelligent control in aircraft GTEs.

3.4.1. Fuzzy control

Aiming at the strong nonlinearity of aircraft GTEs, the fuzzy theory, proposed by Zadeh in 1965 [173], is used to study the control system design. In the fuzzy theory, the nonlinear plant is divided into multiple individual rules through the core language of "If-Then". Each rule can be used to accurately describe the local features of the system;



(a) Response of F

(b) Control input of W_{fb}

(c) Response of T_{41}

(d) Response of N_f

(e) Response of N_c

(f) Response of S_{mf}

(g) Response of S_{mc}

Figure 16 Acceleration simulation of NMPC based on EKF and NMPC based on DNN [171].

thus, the difficulty to identify the nonlinear system mathematical model is reduced. From the literature search, T−S [174] and NN-based fuzzy models are commonly used. The former is usually a combination of constant or linear functions, whereas the latter is nonlinear. The T−S fuzzy model has certain advantages in describing the aircraft GTE with continuous segmentation characteristics, but the NN is important in the construction of T−S models because of the strong nonlinear approximation ability. In addition, the fuzzy-set theoretic control is a new and feasible approach to the GTEs [175].

3.4.1.1. Problem definition and fuzzy model for fuzzy control. The core of fuzzy control is a knowledge base composed of "If-Then" rules. Here, we use the mature T−S fuzzy control as an example to introduce fuzzy control.

Table 4 Summary of recent research on MPC for GTEs.

Reference	Goal	Technique	Modelling
Brunell et al., 2002 [157], 2004 [158]	Constrained multivariable control with state estimation.	NMPC, EKF.	MIMO, simplified real time model.
Mu et al., 2004 [162], 2005 [161]	Improve the real-time calculation of MPC.	AMPC, nonlinear autoregressive moving average with eXgenous input.	NN model.
Qiao et al., 2005 [163]	Constrained multivariable control.	LMPC.	MIMO, state space model.
Diwanji et al., 2006 [169]	Thrust tracking control.	NMPC, ANN.	MIMO, NN model.
DeCastro 2007 [166]	Regulate blade tip clearances and avoid harmful blade-shroud rub.	Gain-Scheduled technology.	Rate-based LPV model.
Richter et al., 2008 [160]	Reduce the computational burden of MPC.	Multiplexed predictive control.	MIMO, linear model.
Xiao and Huang 2012 [167]	Introduce adaptive model to improve control effect.	Adaptive nonlinear model predictive control.	Numerical-ARX (auto regressive with external input) parallel prediction model.
Miao et al., 2012 [164]	Deal with the control in wide flight envelope.	Multi-model predictive control, sliding model control.	MIMO, multi linear model.
Saluru and Yedavalli 2013 [155]	Fault tolerant, constrained multivariable control.	MPC.	MIMO, linear model.
Wang et al., 2013 [170]	Distributed control system for time delay.	Multi-step predictive based on relevance vector machine.	SISO, neural network nonlinear auto regressive moving average model.
Wiese et al., 2015 [168]	Constrained multivariable control, tracking and regulation experiments.	NMPC, model reduction.	Reduced-order, internal model for any gas turbine system.
Du et al., 2017 [165]	Adaptive MPC with a scheduling scheme in flight envelope.	LMPC, Fuzzy membership degree logic, linear interpolation method.	SISO, linear models.
Montazeri-Gh et al., 2019 [156]	Hardware implementation of MPC and HIL testing.	MPC.	MIMO, linear model.
Zheng et al., 2019 [171], 2020 [172]	Aero-engine direct thrust control.	NMPC, EKF.	MIMO, online-sliding window deep neural network model.

The basic idea of T−S fuzzy control is as follows: the aircraft GTE is approximated into a series of weighted linear subsystems by the designed fuzzy rules, and the corresponding weights are described by the membership functions to form the T−S fuzzy model of the nonlinear system. Then, the parallel distributed compensation principle is used to design and obtain the final control law. The parallel distributed compensation principal designs corresponding sub-controllers for multiple linear models, and finally forms a global fuzzy controller by connecting the sub-controllers with a membership function shared with the T−S model. Figure 17 describes the normal design process of the T−S fuzzy control. Fuzzy controllers are often converted into linear matrix inequalities for solving [176].

The T−S model for nonlinear systems has the following form [177]:

$$\begin{cases} \text{Rule}^{\,i}: \text{if } \omega_1 \text{ is } \Phi^i_{1j}, \omega_2 \text{ is } \Phi^i_{2j}, \cdots, \omega_k \text{ is } \Phi^i_{kj} \text{ then} \\ \begin{cases} \dot{x}(t) = A_i x(t) + B_i u(t) \\ y(t) = C_i x(t) + D_i u(t) \end{cases} \end{cases} \tag{15}$$

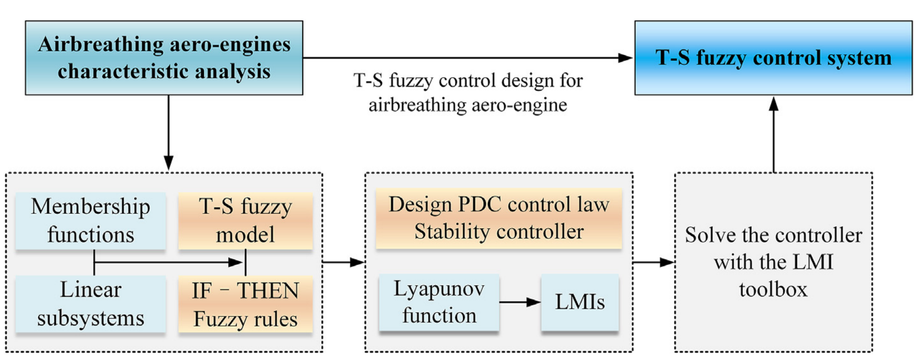


Figure 17 Block diagram of the design steps of T−S fuzzy control.

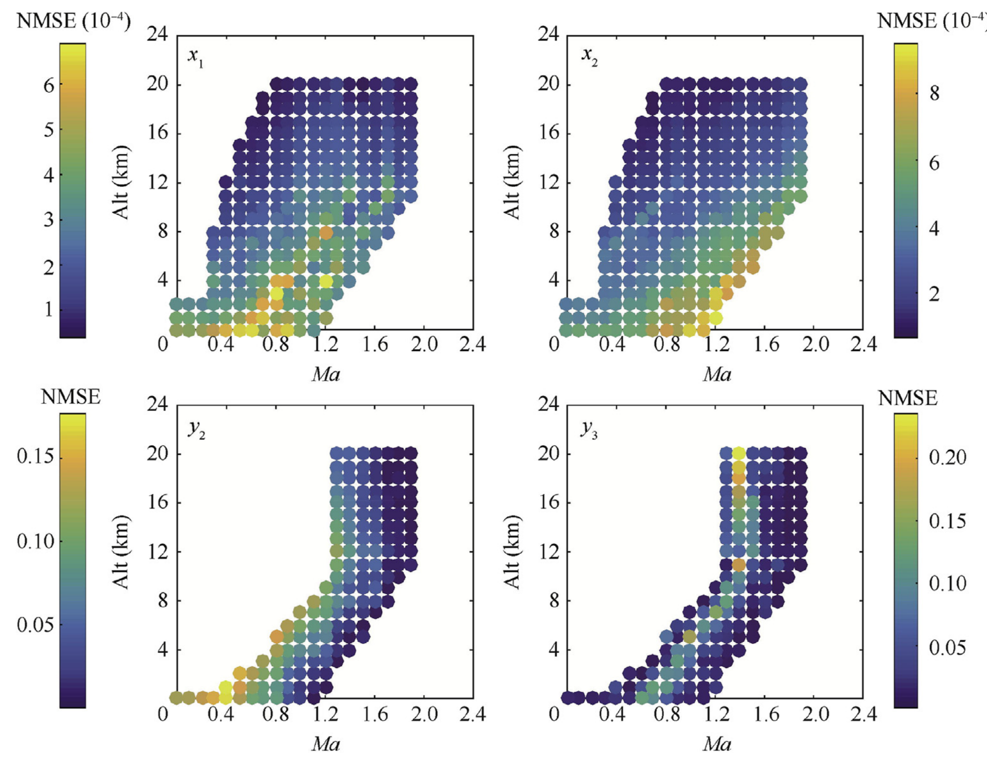
where Rule i is the i-th fuzzy rule, ω_k is the premise variable, which can be flight height, Mach number, and state of GTEs, and Φ^i_{kj} is the corresponding membership function. The T−S model weighs multiple linear aero-engine models through fuzzy rules and membership functions.

The application of the T−S model to aircraft GTEs has been developed for many years. Cai et al. [178] proposed a T−S fuzzy model identification method for aero-engines, which used the least squares method to identify the subsequent parts of the fuzzy model, applied the back propagation (BP) method to identify the remaining parameters, and established the T−S fuzzy model of the aero-engine based on airborne data. Wang et al. [179] determined the antecedent parameters by defining the generalised flight distance and used a separate identification method for multiple output conclusion parameters, that is, established multiple membership functions to determine the T−S model of aircraft GTEs. Li et al. [180] focused on the stability of the subsystem design of the T−S model. They added stability constraints when identifying the submodels, turned the aero-engine model identification problem into a secondary optimisation problem, and used the YALMIP toolbox to solve it. The central model with stability constraints ensures that the identified T−S model is stable within the full envelope. Figure 18 shows NMSE over the entire flight envelope, which indicates that the states achieve high fitting accuracies. Zhou et al. [181] established a T−S nonlinear model, which is adaptively optimised by an artificial NN. Figure 19 shows the adaptive result of the membership functions. The clustering and identification method was used to build a T−S model of the aircraft GTE in the range of the full envelope, which was studied by Pan et al. [177]. In addition, to better reflect the physical meaning of the aircraft GTE, Pan et al. [182] transformed the method of dividing the fuzzy subsystem according to the flight conditions into the expression of the total temperature and pressure of the incoming flow. Figure 20 shows the corresponding relationship between the flight and operation envelopes.

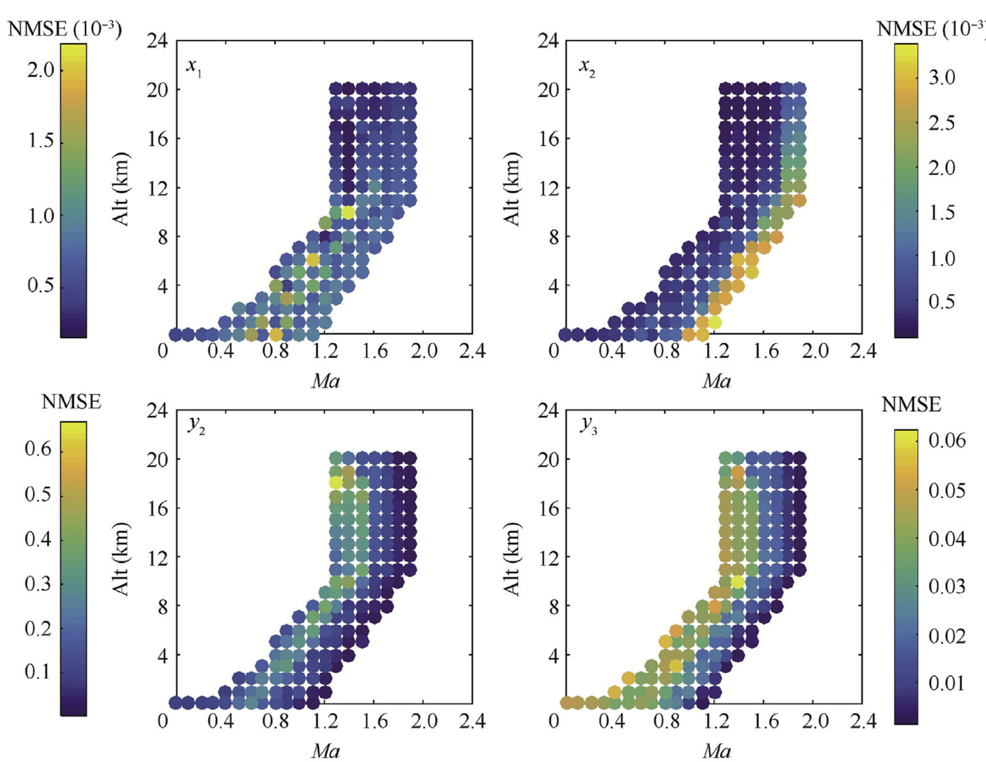
3.4.1.2. Fuzzy control for aircraft GTE. The application of fuzzy control on aero-engines is mainly reflected in two aspects. One is to design many control laws in advance based on the aerothermodynamic characteristics of the aircraft GTE. According to different knowledges, different fuzzy rules are formulated and corresponding membership functions are designed to complete the entire fuzzy logic control. The other is to set up a T−S model, which is represented by a weighted membership function with a linear structure, and design the controller based on the parallel distributed compensation principle. To enhance the adaptability and accuracy of the membership function, some researchers have used NN technology to establish a T−S neural model. Fuzzy control usually uses the same membership function with a fuzzy model. The implementation of the controller is represented by the weighted result of sub-controllers based on membership functions.

For the first method, a fuzzy logic controller is usually designed. Bica et al. [183,184] applied fuzzy control to aircraft GTEs and designed a fuzzy controller based on a multi-objective genetic algorithm. In addition, the fuzzy rules and membership functions were optimised directly for the nonlinear model. Chang and Li [185] proposed an optimisation method for a fuzzy neural controller. The parameters of the membership function were global and were optimised using a genetic algorithm. The weight of the NN represented the control rules of the fuzzy system, and it was adjusted by the error back propagation algorithm of the NN. Bazazzadeh et al. [186] used a NN to define the optimum fuzzy fuel functions and designed a fuzzy logic controller containing error and delta error. Montazeri-Gh and Safari [187] solved the thrust regulation and safety considerations of aero-engines using a fuzzy fuel controller. Based on the steady-state controller, the control system designed a fuzzy logic controller that guarantees thrust and safety under different fuzzy rules. Liu et al. [188] established an aero-engine model using the frequency domain model matching method. Different PID controller parameters were designed in the flight envelope, and the switching control system was completed under fuzzy rules. Mohammadi et al. [189] applied a hybrid invasive weed optimisation/particle swarm optimisation method to the fuzzy-based fuel flow controller of aircraft GTEs.

Research based on the T−S fuzzy control of aircraft GTEs includes the following. Zhai et al. [190] proposed an aero-engine nonlinear T−S model based on the division of flight envelopes, and established a nonlinear DCS with network derivational time delay. Then, the model was regarded as a discrete switched system, and a fault observer based on time delay compensation was established. Ren et al. [191] adopted the common Lyapunov function and designed an adaptive sliding mode controller based on an aero-engine T−S distributed system. Hanachi et al. [192] applied the fuzzy method to multi-mode diagnosis, established an adaptive neuro-fuzzy model of GTE, and proposed a data-driven fault detection method. Zhou et al. [181] studied the rotor speed control of aircraft GTEs based on the T−S fuzzy method and established a discrete T−S model of GTE, which was adaptively optimised by artificial NN and was valid within the flight envelope, and the robust H_∞ control method was used to design the controller based on the maximum error first-try once discard scheduling strategy. Combining the idea of Leitmann with robust stability, Pan et al. [182] developed a multi-variable uncertain T−S fuzzy model of aircraft GTE and performed research on robust control that includes uncertainty. This method avoids the difficulty to solve the controller parameters of the uncertain complex system, guarantees the uniformly bounded performance of the system based on the non-quadratic Lyapunov function, and proposes a control method of GTE that combines robust multivariable control with Leitamnn structural uncertainty in all flight envelopes. Although Pan's study solved the

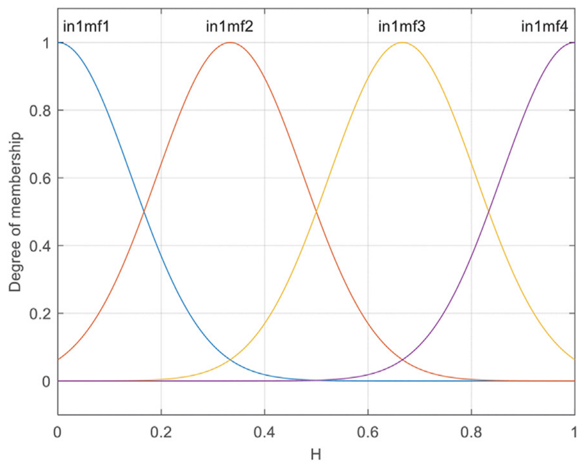


(a) NMSE of the first sample (l=1)

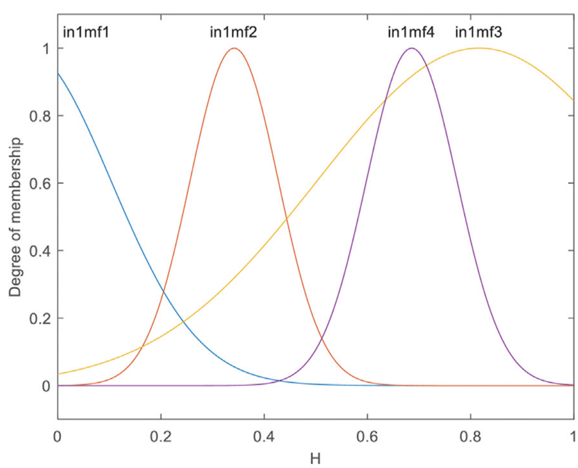


(b) NMSE of the first sample (l=2)

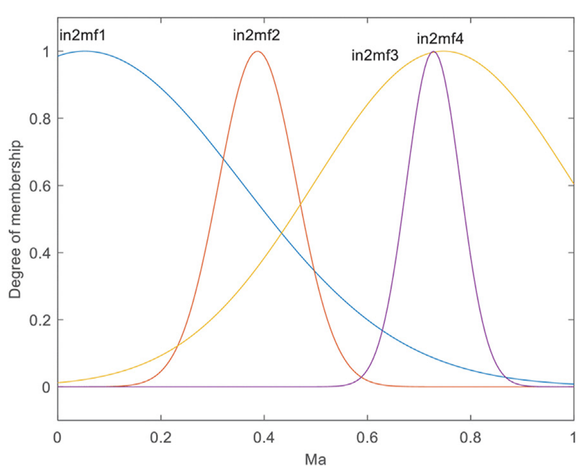
Figure 18 NMSE over the entire flight envelope [180].



(a) Initial membership function



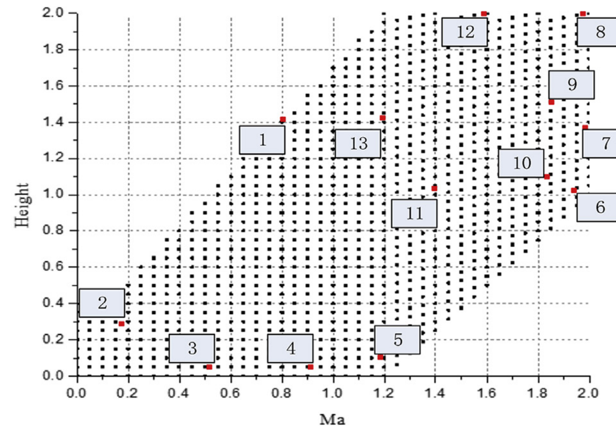
(b) Final membership function of H



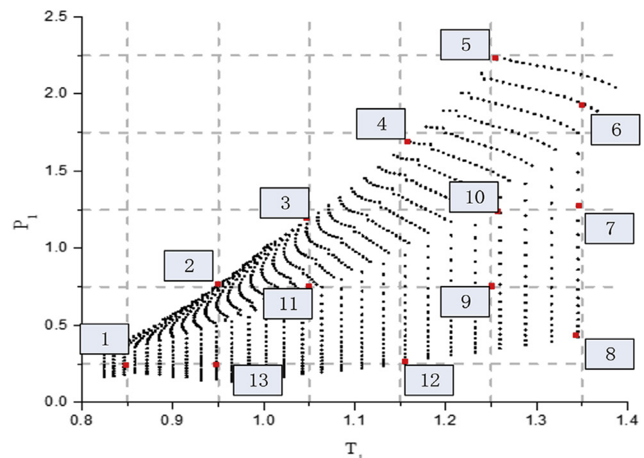
(c) Final membership function of Mach

Figure 19 Membership function of the T−S system [181].

problem of multivariable control of the aircraft GTE in the flight envelope, the result provided in Figure 21 also shows that the control effect of the controller can be improved. Pan et al. [175] proposed a novel robust control design for GTEs, which contained an uncertain dynamic system, fuzzy sets with



(a) Turbofan flight envelope



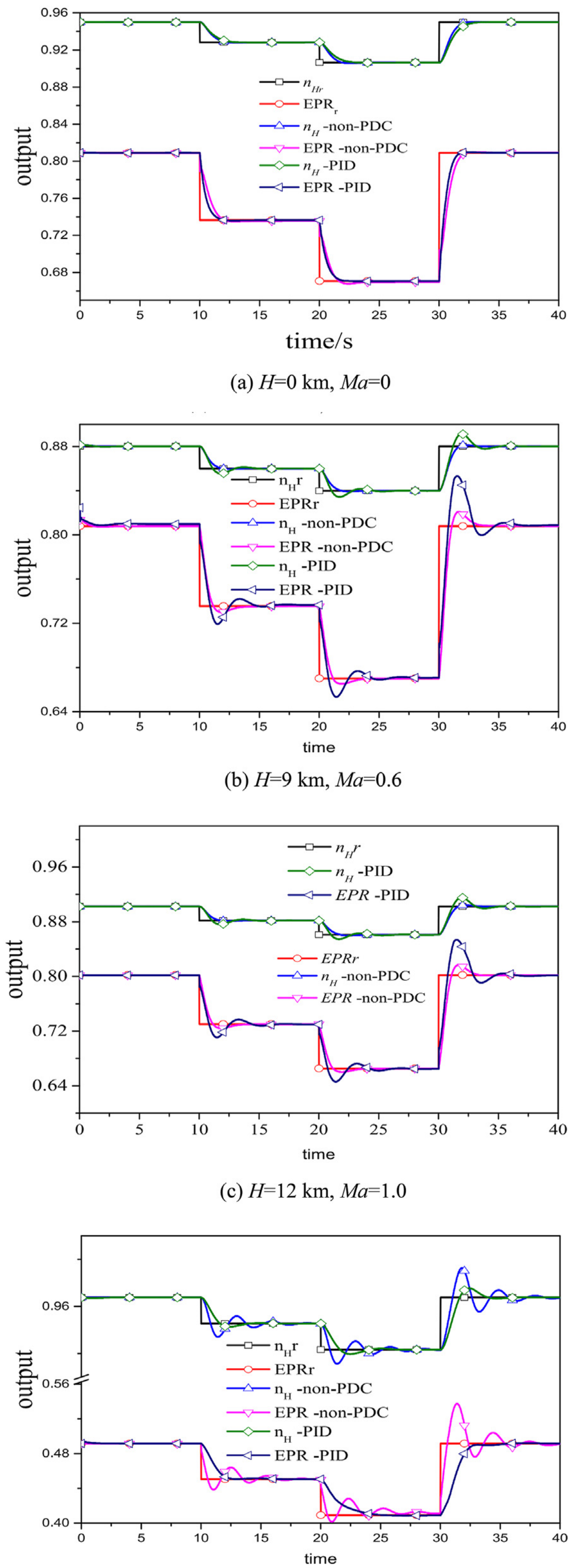
(b) Turbofan operating envelop

Figure 20 Schematic diagram of converting flight envelope to operating envelope for T−S model identification [182].

engine's uncertainty, and a deterministic robust controller. This control design combined optimality with mismatched uncertainty and was applied to the turbofan engine hardware-in-the-loop test in the flight envelope.

3.4.1.3. Discussion on fuzzy method for aircraft GTE. Recent research on fuzzy control of GTEs is summarised in Table 5. The fuzzy control can describe the complex dynamic process of aviation GTE through fuzzy rules, and the final controller is weighted by a membership function as in the gain scheduling. The controller design based on the T−S fuzzy model has some mature theories to prove the stability of the closed-loop system. However, fuzzy control also has some shortcomings:

- The complexity of fuzzy models for aircraft GTEs. With the expansion of the flight envelope for modern aircraft GTEs, the nonlinearity of the inflow condition faced by the engine is complicated, and the complexity of the fuzzy model is also significantly increased. Moreover, the MIMO aero-engine modelling requirements also bring challenges to the fuzzy model;



(a) H=0 km, Ma=0

(b) H=9 km, Ma=0.6

(c) H=12 km, Ma=1.0

(d) H=20 km, Ma=2.0

Figure 21 Control results in the flight envelope [182].

- The design process of the control system becomes more complicated. As the complexity of the fuzzy model increases, the number of fuzzy rules also increases;
- The design of the membership function relies on certain prior knowledge of the aircraft GTE;
- Stability problem of the fuzzy control system. It is a challenge for conventional fuzzy logic controllers to prove the stability of the control system throughout the flight envelope, such as gain scheduling. Although the fuzzy theory based on the T—S model can use the Lyapunov function to guarantee the stability of the control system, it is still a problem for stability proof because of the introduction of an NN;
- Control performance issues. The control effect of the multivariable fuzzy control method on aircraft GTEs needs to be improved. The application of T—S fuzzy control on aircraft GTEs can only provide stable and robust results, but research on high-performance control methods needs to be conducted.

3.4.2. *Neural network control*

Another widely discussed intelligent control method for aircraft GTEs is NN control. The traditional model-based control method designs the controller according to the mathematical model of GTEs and describes the control law analytically. Although this method is suitable when there is an accurate mathematical model of the GTE, some strong nonlinear problems are still difficult to solve. Thus, NN technology with strong nonlinear approximation ability has become a new research topic.

3.4.2.1 Neural network control for aircraft GTE. The application of NNs in aircraft GTEs is divided into the following categories: 1) establish a high-precision and real-time NN model of aircraft GTEs to serve the control method, which requires accurate models; 2) provide a trained NN controller of aero-engine; 3) approximate the optimisation function of the control system and find the controller with the optimal target value of GTEs.

First, direct thrust control is difficult for aircraft GTEs. This is mainly caused by the unpredictability of thrust. Relying on its strong nonlinear approximation ability, NNs have become important to solve the direct thrust control of the GTE. The method based on NN inverse control was applied by Yao et al. [193,194]. By training the NN, a NN inverse controller that approximates the inverse dynamics characteristics of the aero-engine was obtained, and a dynamic NN composed of a static NN and several integrators was used to construct the inverse system of the engine. Figure 22 shows the diagram of the NN for the thrust estimator and the inverse model of the aeroengine. Zheng et al. [195] proposed the online sliding window DNN to build an inverse mapping model for direct thrust inverse control of aero-engine. On this basis, the direct control of the model predictive thrust was performed in Ref. [171].

Second, NN technology is widely used in aircraft GTE fault diagnosis. Kobayashi and Simon [196] used an NN genetic algorithm technique to solve the diagnostics of the

Table 5 Summary of recent research on fuzzy control for GTEs.

Reference	Goal	Technique	Modelling
Bica et al., 1998, 2002 [183]	Fuzzy logic control for higher performance.	Multi-objective genetic algorithm, PI control.	Nonlinear model.
Chipperfield et al., 2002 [184]	Fuzzy logic control for gain scheduling.	Multi-objective genetic algorithm, PI control.	Nonlinear model.
Cai et al., 2007 [178]	Modelling.	Least square method, back-propagation method.	SISO, T−S model.
Chang and Li 2009 [185]	Fuzzy logic control for higher performance.	Genetic algorithm, fuzzy neural network.	SISO, linear model.
Bazazzadeh et al., 2011 [186]	Fuzzy logic control.	Fuzzy neural networks.	SISO, nonlinear model.
Montazeri-Gh et al., 2011 [187]	Fuzzy logic control for thrust performance and safety protection.	Multi-objective genetic algorithm.	SISO, nonlinear model.
Wang et al., 2013 [179]	Modelling.	Based on flight envelop division.	MIMO, T−S model.
Zhai et al., 2013 [190]	Distributed control for network derivational time-delay.	Fault detection observer with time-delay compensation.	MIMO, T−S model.
Liu et al., 2014 [188]	PID-fuzzy control, Establish frequency-domain model.	Fuzzy switching.	SISO, frequency-domain model matching.
Mohammadi et al., 2014 [189]	Fuzzy logic control for performance and protection.	Hybrid invasive weed optimisation/particle swarm optimisation.	SISO, nonlinear model.
Ren et al., 2016 [191]	Control parameter perturbation, external disturbance, and random time-delay.	Adaptive sliding mode controller.	MIMO, T−S model.
Li et al., 2018 [180]	Modelling.	Constrained quadratic optimisation, LMI.	MIMO, T−S model with guaranteed stability.
Hanachi et al., 2018 [192]	Multi-mode diagnosis.	Adaptive neuro-fuzzy.	SISO, neuro-fuzzy model.
Zhou et al., 2019 [181]	Combine with H_∞ control for gain scheduling.	Lyapunov function, switched system theory, parallel distributed compensation.	SISO, T−S nonlinear model.
Pan et al., 2019 [177]	Modelling.	Clustering and identification.	MIMO, T−S model for whole flight envelop.
Pan et al., 2019 [182]	Hierarchical robust control consisting of two level compensators.	Non-parallel distributed compensator.	MIMO, uncertain T−S model.
Pan et al., 2021 [175]	Mismatched uncertainty and optimality in the flight envelope	Fuzzy-set theoretic control design	MIMO, fuzzy set with system uncertainty

aero-engine. Figure 23 indicates that the trained NN was used to estimate the health parameters of the engine, and a genetic algorithm was applied to correct the measurement value of the sensor. Vanini et al. [197] established engine health and fault estimation systems with multiple dynamic NNs. By measuring the difference between each network and engine output, various standards can be built to complete the fault diagnosis task, thereby solving the problem of fault detection and isolation. Amozegar and Khorasani [198] also discussed the fault detection and isolation of GTEs. Research has shown that the use of independent models based on dynamic RBF networks and heterogeneous forms of the ensemble learning model can more effectively perform fault diagnosis.

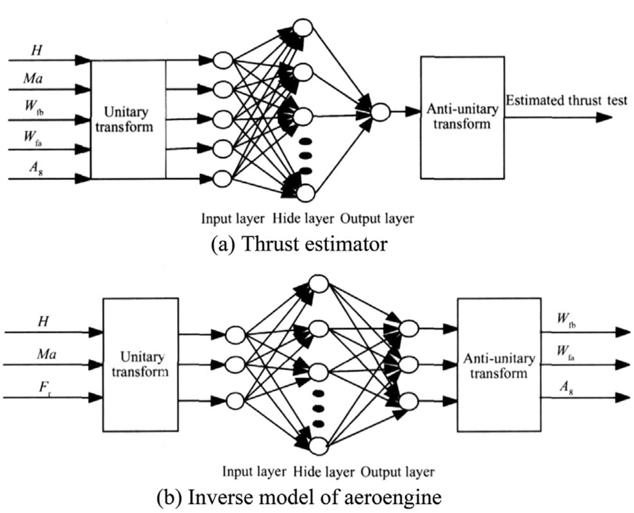


Figure 22 Diagram of NN for thrust estimator and inverse model of aero-engine [194].

In addition, the NN technique is often combined with other control methods to solve the control issue of aircraft engines. Pan et al. [199] used an RBF NN to estimate the unknown dynamic of an aero-engine and designed a SISO backstepping controller based on the NN model. To solve the multivariable control of aircraft GTEs, many decoupling controls based on NNs have been studied. Zhu et al. [200] established a decoupling controller based on a diagonal recurrent NN, which has the same structure as a PID controller. The corresponding parameters of the controller are updated by the gradient learning method. However, this

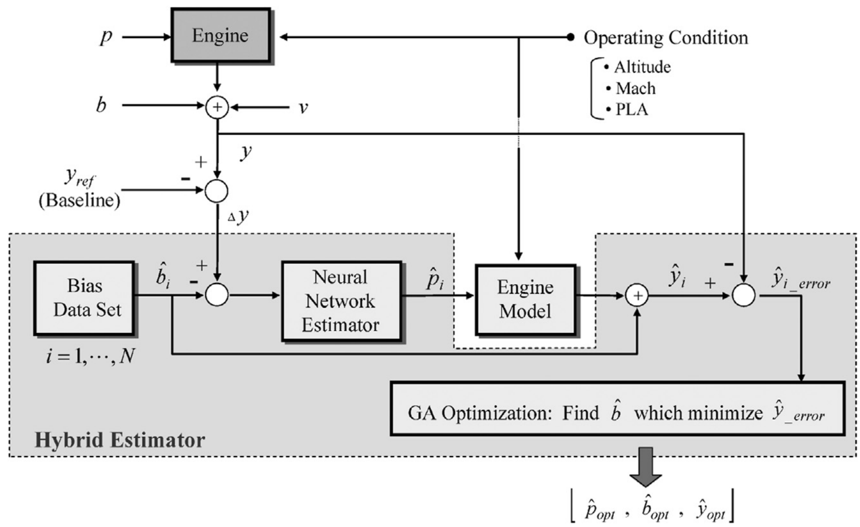


Figure 23 Hybrid engine health estimation architecture [196].

method needs to train the NN parameters offline. Qian et al. [201] also solved the decoupling control of GTEs with a dynamic NN identifier. Mu et al. [161] improved the nonlinear MPC for aircraft GTEs using a modelling method based on an NN autoregressive with exogenous inputs. Figure 24 shows the scheme of nonlinear MPC of GTEs. Based on the NN model, this method predicts the future behaviour of GTE to guide the controller to find the control output u that minimises cost J, thereby completing predictive control. Xiao et al. [202] used a back propagation NN to train the prediction model and designed the MPC to solve the control constraints and the performance need of aircraft engines. Combining the advantages of SMC and NN, Miao et al. [138] proposed a terminal SMC method based on an RBF network. In addition, as mentioned in Section 3.4.1, the NN can be incorporated into the fuzzy control [186].

3.4.2.2. Discussion on neural network method for aircraft GTE. Recent research on NN control of GTEs is summarised in Table 6. The advantages of the NN include the following points. First, the strong nonlinear approximation ability of NN is the characteristic that attracted attention in aero-engine control. Second, as a dynamic system, the NN can learn and adapt to the dynamic performance of severely uncertain systems. Third, the NN can decouple complicated nonlinear engine models to form multi-channel parallel models. Combined with the fast computing advantages, this model meets the demand of real-time simulation. However, the disadvantages of NNs in engine control applications also exist:

- NN has the problem of over-fitting, which leads to the versatility of the engine NN model used, whose accuracy and stability can only be guaranteed near the training data set;
- At present, NN control for aircraft GTEs is mainly focused on offline training of high-precision models or controllers. For online training, there are few studies on intelligent control of GTEs that are updated in real time. For NN control updated in real time, it is necessary to avoid the NN to fall into the local extremum during training, reduce the time spent in real-time calculations, and other issues;
- As a control system for aircraft GTEs, guaranteeing the stability of the closed-loop system is still a key issue for NN control.

4. Ramjet and scramjet control

The ramjet has abandoned the complex rotor components of traditional aviation gas turbines. Although it does not have the ability to start working from a standing state, it makes hypersonic flight possible [3]. Scramjets have become an important propulsion factor for hypersonic vehicles with the improvement of supersonic combustion techniques, as their performance and stability impact the hypersonic vehicle. Dual-mode scramjets have become an important research topic because they include both ramjet and scramjet operating conditions. The scramjet is mainly composed of an inlet, combustor, and nozzle, as shown in Figure 25. Ramming is the process of decelerating and increasing the static pressure of the incoming flow through the engine precursor and inlet. This process does not require high-speed rotating parts, which is the best advantage of the jet engine. After decelerating and pressurising, the high-speed incoming flow enters the combustor and burns with the fuel mixture. After burning, the temperature reaches 2000−2200 °C or even higher. After the expansion acceleration, the mixed gas is discharged from the nozzle to generate thrust.

Table 6 Summary of recent research on NN control for GTEs.

Reference	Goal	Technique	Modelling
Kobayashi and Simon 2005 [196]	Performance diagnostics.	Hybrid neural-network genetic-algorithm technique.	NN health parameter estimator.
Mu et al., 2005 [161]	Nonlinear model predictive control for disturbance and model uncertainties.	Neural network autoregressive with eXogenous inputs.	NN model, MIMO.
Zhu et al., 2006 [200]	Multivariable decoupling NN control, PID.	Diagonal recurrent neural network, gradient decent method.	Linear engine model, MIMO.
Qian et al., 2007 [201]	Multivariable decoupling NN control, PID.	Dynamic NN identifier.	Linear engine model, MIMO.
Yao and Sun 2007 [193]	Thrust estimator, Modelling.	Adaptive genetic NN algorithm.	Off-line, thrust model.
Yao and Sun 2008 [194]	Direct thrust control.	NN inverse control.	Off-line, inverse model, thrust output.
Pan et al., 2009 [199]	Backstepping control strategy for compressor speed.	RBF NN.	Off- line, SISO.
Miao et al., 2010 [138]	Terminal sliding mode control.	RBF NN.	NN model estimate uncertainty.
Bazazzadeh et al., 2011 [186]	Fuzzy logic control for high performance.	NN, Fuzzy control.	NN for optimum fuzzy fuel function.
Vanini et al., 2014 [197]	Fault detection and isolation.	Dynamic NNs.	Multiple NN health and fault model.
Amozegar and Khorasani 2016 [198]	Fault detection and isolation.	Dynamic NNs.	Ensemble NN output model.
Xiao et al., 2019 [202]	Nonlinear model predictive control.	BP NN, hybrid grey wolf optimisation.	NN model, MIMO.
Zheng et al., 2019 [195]	Direct thrust control.	On Line sliding window deep neural network.	Inverse model, Thrust model.
Zheng et al., 2019 [171]	Direct thrust control, nonlinear model predictive control.	DNN.	Inverse model, Thrust model.

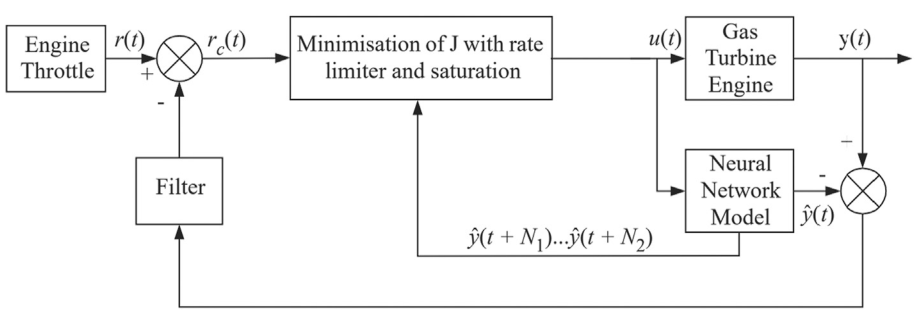


Figure 24 Scheme of NMPC with NN [161].

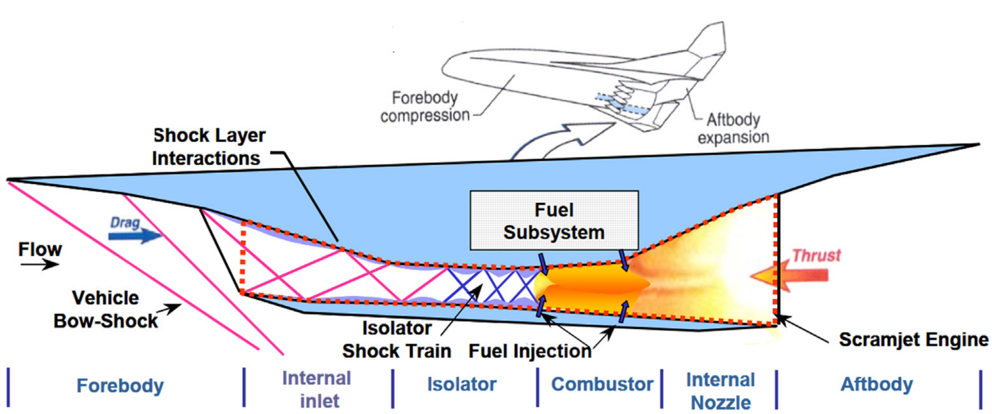


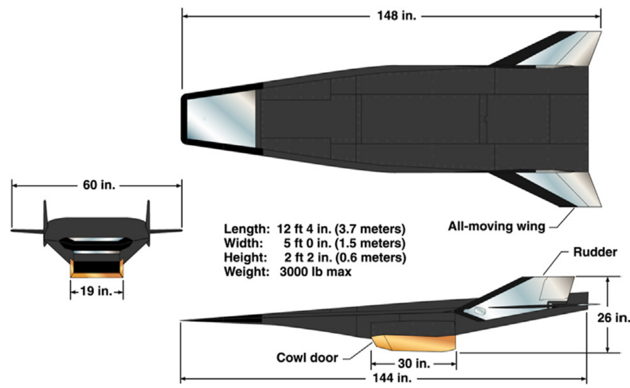
Figure 25 Sketch of scramjet [203].

In this section, we introduce recent progress in ramjet and scramjet control. First, the performance of the ramjet-based hypersonic flight tests is analysed. Hypersonic airbreathing aero-engines have always been an important direction for military powers in the world to seek for advances. In fact, this type of expensive design and development project can only be effectively performed under the operation of the state machinery. By analysing these representative experiments, we can identify the actual problems faced by hypersonic engines and future research directions. Then, we present the recent modelling and control progress of ramjets and scramjets. Finally, some special control issues that were observed in the flight tests are discussed in detail.

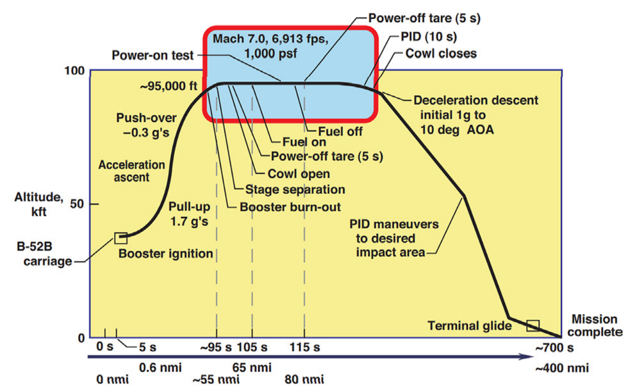
4.1. Results of hypersonic flight tests

The rapid development of airbreathing supersonic/hypersonic propulsion technology can be seen from the confirmatory flight tests performed several times over the past 20 years. Analysing the rise and fall of basic research in the field over the past 20 years, it is observed that every successful confirmatory flight test is always accompanied by an increase in the number of studies, and every unexpected flight test accident always leads to a new round of technical reflection.

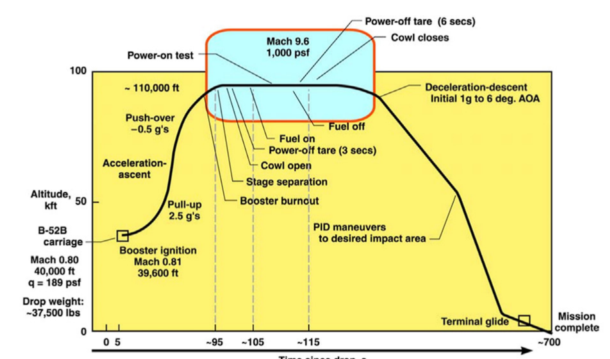
In 1980, the NASP was established by the United States. This plan can still be regarded as the landmark beginning of the international research on wave airbreathing supersonic/hypersonic propulsion technology [204]. Although NASP considerably promoted the improvement of airframe/propulsion integration, supersonic combustion, dual-mode scramjet, and other key technologies, it was terminated in 1995. In addition to expensive costs, one of the most severe critics was that it failed to conduct technical verification flight tests on the hydrogen-fuelled airframe-integrated dual-mode scramjet. To this end, the Langley Research Center and Dryden Flight Research Center of NASA launched the Hyper-X plan, which entered the design and manufacturing stage in 1997 [205]. The Hyper-X program actually implemented only three flight tests, and the corresponding technical verification aircraft was X-43A. The dates were June 2, 2001, March 27, 2004 and November 16, 2004. The first and second tests were cruise tests in Mach 7, and the last one was a cruise test in Mach 10. The vehicle configuration and flight mission profile of X-43A are shown in Figure 26. The first test in 2001 failed because of the booster, and the team conducted a nine-months investigation into the cause of the accident. Three years later, in 2004, the last two flight tests conducted were both successful. In the two tests, the demonstrator was separated from the booster and flew for 11 s and 10 s, respectively, relying on the hydrogen fuel scramjet, and the flying Mach numbers reached 6.83 and 9.68, respectively [22,206]. The last two tests of X-43A are representative. They set new speed records for hypersonic vehicles with airbreathing aero-engines and also rekindled academic interest in ramjets, particularly



(a) X-43A



(b) First and second mission profiles



(c) Third mission profile

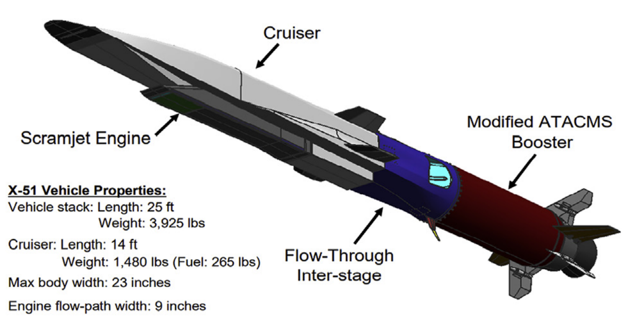
Figure 26 X-43A vehicle configuration and mission profiles in the Hyper-X program [22,206].

scramjet or dual-mode scramjet, and the airframe/propulsion integrated design of waverider vehicles.

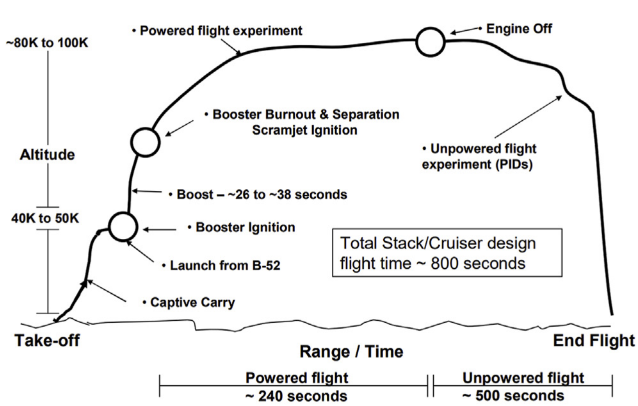
In the late 1900s and early 2000s, another flight test as compelling as the Hyper-X program was the Air Force Research Laboratory (AFRL) HyTech program, which was paired with X-51A. It also had a waverider aerodynamic configuration. Unlike the Hyper-X program, HyTech focused on a scramjet that used endothermic hydrocarbon fuel rather than hydrogen fuel. Therefore, the flight Mach number range selected for the X-51A flight test was lower than that of the X-43A flight test. In addition, X-51A was not a short cruise flight test of approximately 10 s, but a longer accelerated climb flight test (210 s), which aimed at achieving the goal of accelerating from Mach 4.5 to faster than Mach 6 for scramjet. Figure 27 shows the X-51A vehicle configuration and mission profiles in the HyTech program. Historically, X-51A conducted four flight tests on May 26, 2010, June 13, 2011, August 14, 2012, and May 1, 2013. However, compared with the two successful flight tests of X-43A, the completeness of each flight test of X-51A can only be described as unsatisfactory. Among them, only the first and fourth tests achieved powered flight of the vehicle, but they failed to accelerate to Mach 6. In the first test, the flying Mach when the ramjet started working was 4.74, and the aircraft only accelerated to Mach 4.87 after the engine worked for 143 s, during which the system reached a maximum acceleration of 0.18 g. In addition, the inlet unstart happened at 159.98 s and then the scramjet restarted by active controlling; however, the heat seal between the engine and the fuselage leaked, and the high temperature gas directly damaged the internal equipment of the aircraft, which led to the early termination of the flight test. In the second test, the inlet unstart occurred again during the ignition process, which directly led to the termination of the test. In the third test, the vehicle crashed due to tail failure. In the last flight test, after the booster accelerated the X-51A to Mach 4.8, the vehicle achieved a powered flight of 210 s and accelerated to Mach 5.1 [26,207,208].

In fact, the inlet unstart problem of the scramjet did not only appear in the X-51A flight test. In the 1990s, Russia performed many ground and flight tests to verify its axisymmetric dual-mode scramjet technology. Among them, the last flight test of joint CIAM-NASA was conducted in 1998. Figure 28 shows a dual-mode scramjet and its flight trajectory information in the CIAM/NASA flight test. Interestingly, the main purpose of this test was to verify whether the dual-mode ramjet could be converted from a subsonic combustion mode to a pure supersonic combustion mode during acceleration from Mach 3.5 to Mach 6.5. The problem of inlets not starting is an emergent problem. The test results were discouraging, as a combustion mode transition was not achieved, and the inlet unstart occurred. In addition, the control system had misjudgement and misoperation in monitoring the start/unstart state of the inlet [209,210].

The eight representative flight tests in the past 20 years are summarised in Figure 29. The reasons leading to flight test failure or unsatisfactory results are mainly concentrated in the following aspects: 1) start/unstart/restart problem of inlet; 2) combustion mode transition and control; 3) aircraft attitude control, particularly loss of control caused by rudder failure, and 4) limited acceleration of the airframe/propulsion integrated system.

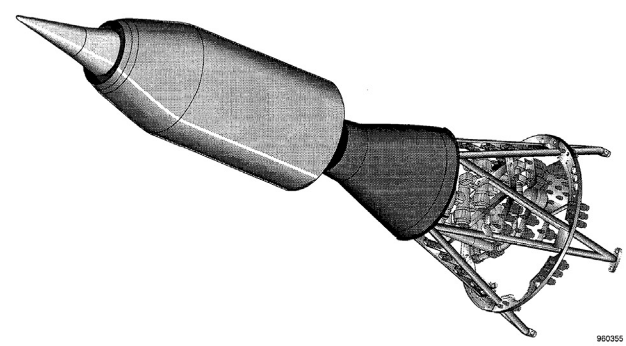


(a) X-51A SED vehicle

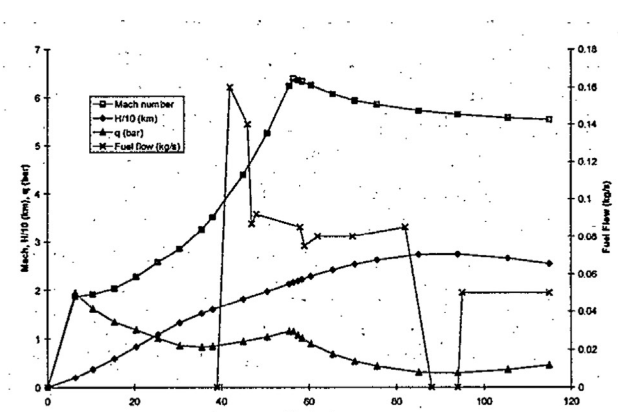


(b) Notional flight profile

Figure 27 X-51A vehicle configuration and mission profiles in the HyTech program [26].



(a) Axisymmetric dual-mode scramjet [209]



(b) Flight trajectory information [210]

Figure 28 Dual-mode scramjet and its flight trajectory information in the CIAM/NASA flight test.

4.2. Modelling of dual-mode scramjet

Although the flight test can obtain valuable ramjet and scramjet data, it is not widely performed due to the high cost and safety restrictions required. The best solution is to establish a mathematical model of the engine that meets the accuracy requirements and perform a series of preliminary studies involving performance analysis, structural design, and control system verification. Ramjet is an air jet engine that relies on high-speed oncoming flow to decelerate and pressurise. Ramjets can be divided into ramjets for supersonic flight and scramjets for hypersonic flight. At present, dual-mode scramjets are mostly focused, as they can span both sub- and super-combustion modes to meet a wide range of flight requirements. We will also focus on the development of dual-mode scramjet modelling.

4.2.1. Scramjet model without regeneratively-cooled technique

The detailed combustion flow field structure of a scramjet can be obtained using complex chemical reaction dynamics in multidimensional calculations. Several meaningful studies have been conducted on the shock wave development and combustion mode transition mechanism of scramjets [211–215]. However, they are limited by the development level of control theory, and thus difficult to apply to control models to design control laws. The multidimensional model has a large computational burden and cannot run in real time to better meet the requirements of control design and evaluation. The control-oriented scramjet calculation model requires relatively less calculation time to obtain a relatively accurate flow field, which is used to quickly predict engine performance and response characteristics under variable operating conditions. The following mainly focuses on the status of the reduced-order model.

The thermal analysis method of the Brayton cycle is widely used in the fields of internal combustion engines and aero-engines. This method is also suitable for analysing the performance of scramjet engines. It is useful for evaluating the overall performance of the engine and comparing the advantages and disadvantages of different types of engines under different task requirements. Roux et al. [216,217]

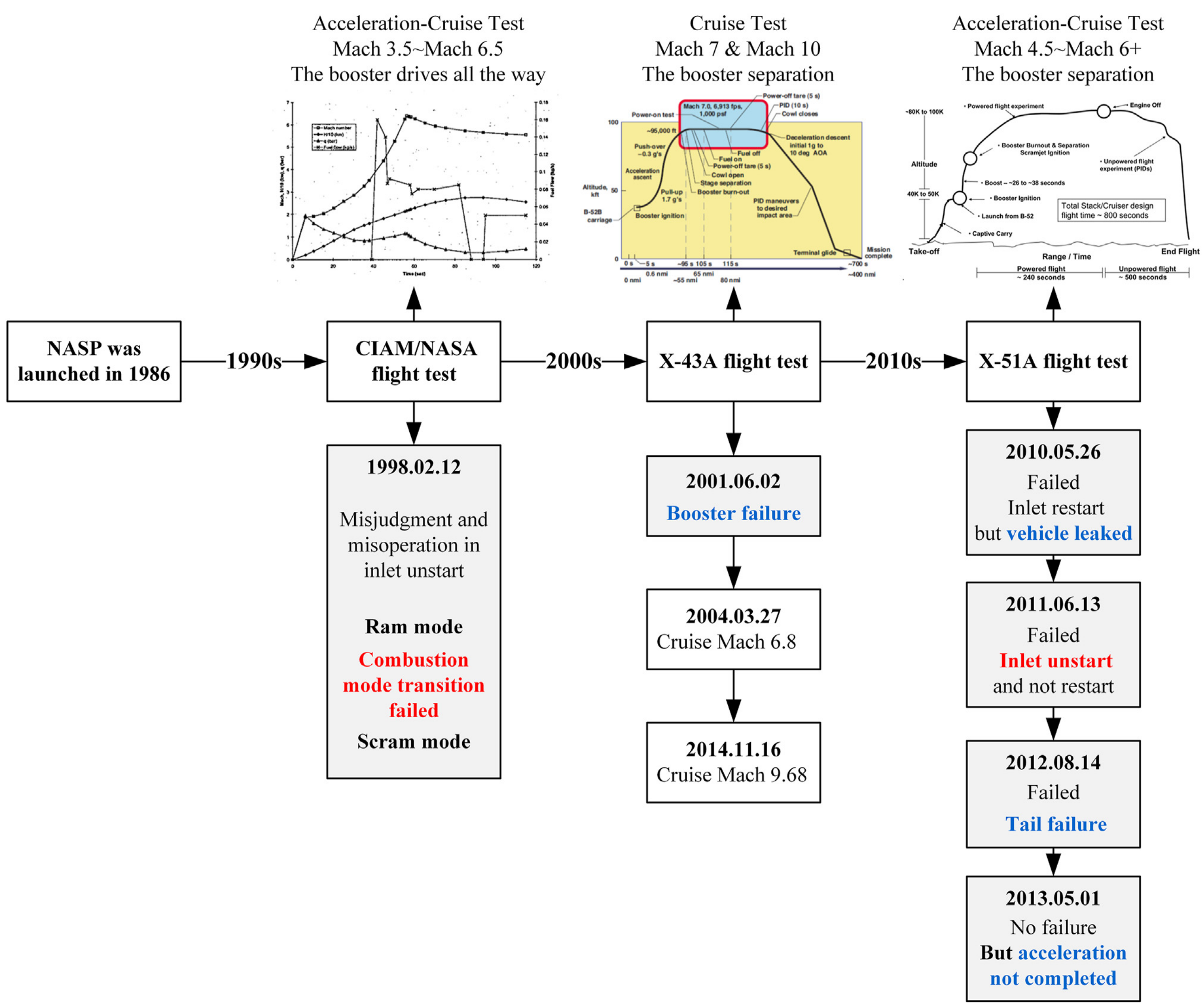


Figure 29 Eight representative flight tests in the last two decades.

used the Brayton cycle to construct the temperature-entropy diagram of ramjet and scramjet engines, as shown in Figure 30. The free-flow air temperature was T_0. For an ideal ramjet engine, the air is isentropic compressed to the stagnation condition T_{t2}, and the total gas temperature in the combustor is raised to T_{max} with an isostatic state of Mach $\approx$ 0. Then, the vertical dotted line is followed to perform isentropic expansion in the nozzle, and finally the gas is discharged into the atmosphere. In an ideal scramjet, air is isentropic compressed to the supersonic state of T_2, and then maintained at supersonic speed (Mach $>$ 1) for iso-total pressure combustion. The gas at the outlet of the combustor is heated to the static temperature T_{max}, and then discharged into the atmosphere after isentropic expansion in the nozzle. This method can be used to evaluate and analyse the properties of ramjets and scramjets under ideal conditions [218−220]. On this basis, the following researchers considered the non-isentropic compression of the inlet [221], and further improved the optimal performance analysis [222] and trajectory optimisation [223]. The parametric description method of thermal analysis based on the Brayton cycle provides a simple and convenient method for evaluating the performance of ramjets and scramjets.

The lumped parameter method decomposes the engine into different parts, and treats the flow parameters in each part as a uniform whole to analyse the engine performance. This method can also be called a zero-dimensional analysis method. Liu and Zhang [224] adopted a component-level modelling method, in which the shock/expansion wave theory was used in the forebody/inlet modelling, the conservation equation of variable cross-section heating pipe flow was used in the combustor modelling, and the combustor volume effect was simplified to represent engine dynamics. The thermal analysis method based on the Brayton cycle and lumped parameter method cannot accurately describe the extremely strong distributed parameter characteristics of the scramjet in the operating process, which directly affects the control effect of the engine. Therefore, the distributed parameter control concept of a scramjet was proposed [225,226].

The one-dimensional (1-D) distribution of the scramjet flow field can reflect the average characteristics of the flow

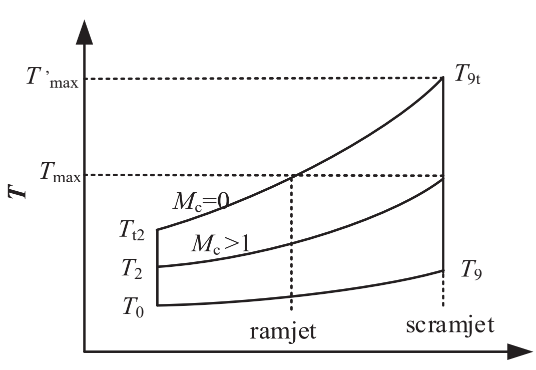
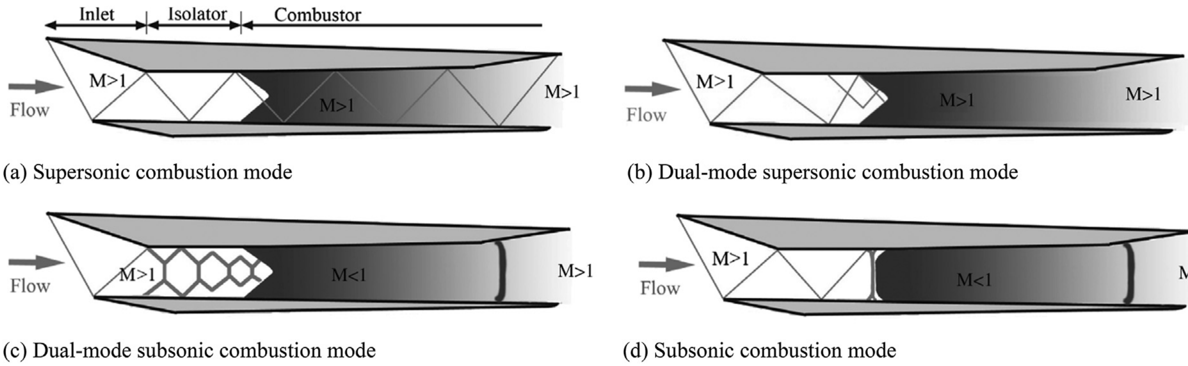


Figure 30 T−S diagram comparison for ideal ramjet and scramjet [216].

parameters of each section along the axial direction. The parameters are measured during the experiment. From the perspective of dimensionality, it is also 1-D. The distribution of 1-D parameters can directly or indirectly reflect the combustion position, thrust, combustion efficiency, etc. In addition, the 1-D method is more in line with the controllability and observability of the control system, and the performance error and uncertainty caused by 1-D simplification can be solved by the robust analysis and design techniques in the control theory. Therefore, the development of a 1-D ramjet model with excellent accuracy and real-time performance is significant for control studies. At present, the methods used in 1-D modelling of scramjets can be summarised into two categories: based on ordinary differential equations or partial differential equations.

First, the 1-D model of a scramjet based on ordinary differential equations needs to assume a steady flow in the flow field. The entire equation does not include the time term. All flow parameters are related only to the cross-sectional area of the flow channel in the engine. The steady-state distribution of 1-D flow field parameters is obtained by simultaneously solving the mixed gas, mass conservation, momentum conservation, energy conservation, and gas state equations [227−229]. Owing to the relatively small difficulty in numerical solutions, ordinary differential equations have been widely used in performance analysis, initial combustor design, control research, and hypersonic aircraft integrated research [230−233]. In addition, Tian et al. [234] divided the working modes of the dual-mode scramjet engine in detail and established a pre-combustion shock train (PCST) model with adjustable intensity in the isolation section. The model can accurately describe the flow properties under multiple operating modes. Figure 31 shows a sketch of the entire process of the dual-mode scramjet engine. However, when the flow velocity in the main flow area of the engine is close to the speed of sound, there is a mathematical singularity problem in solving ordinary differential equations. When considering the transition between supersonic and subsonic combustion modes, the singularity problem is complicated and cannot be avoided [235,236].

Second, Bussing [237] established a 1-D model of a scramjet based on partial differential equations. This method has been developed for several years to obtain the evolution of the engine's 1-D flow field. However, partial differential equations require a complicated finite difference method to solve, which limits the application of this method. For this problem, Ma et al. [238] established a 1-D unsteady dual-mode scramjet combustor model with partial differential equations, and used a quadratic function to modify the normal shock wave. The 1-D unsteady model coupled with the isolator shock train model and oblique shock wave modification can treat variable area, fuel addition, combustion heat release, variable specific heat, inflow air vitiation component, wall friction, and mixing efficiency. In addition, the model can simulate the transition between the ram-mode and scram-mode operations.



(a) Supersonic combustion mode (b) Dual-mode supersonic combustion mode

(c) Dual-mode subsonic combustion mode (d) Subsonic combustion mode

Figure 31 Sketch of the entire process of the dual-mode scramjet engine [234].

Figure 32 indicates the modification of the normal shock wave. In addition, Ma et al. compared the wall pressure distribution of the combustor experimental and the 1-D model under different fuel injection conditions. The results of the experimental and numerical calculations, provided in Figure 33, showed that the 1-D model exhibited good accuracy.

4.2.2. *Regeneratively-cooled scramjet model*

When a scramjet is flying at a high Mach, the combined effect of the incoming aerodynamic heat and combustion causes the engine wall to bear a high thermal load and strong oxidation of gas. Current advanced materials cannot meet the long-term, high-temperature, and high-strength work requirements in case of adopting the passive cooling method. Thus, active thermal protection technology is required. Regenerative cooling techniques are an active cooling technology method considered to be an effective and feasible solution to ensure safe and long-term operation of scramjets [239].

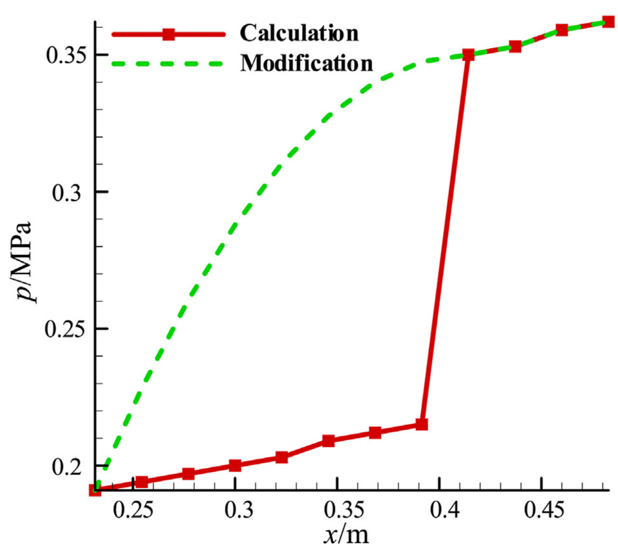


Figure 32 Pressure modification schematic at normal shock wave [238].

Researchers have conducted extensive research on regenerative cooling scramjet engines, mainly including fuel cracking and cooling performance [240−242]. In general, the calculation cost of the flow in the cooling channel considering the chemical reaction of the fuel is relatively high. If the regeneratively cooled scramjet is combined with a newly designed control system, a large number of simulations need to be performed under design or off-design conditions to evaluate the applicability and performance of the control system. However, the design and evaluation of the control system requires multiple iterations. As the calculation is time-consuming, the time invested and the benefit are disproportional, which seriously delays the work schedule of the control engineer. Therefore, 1-D analysis is an important method for studying regeneratively cooled scramjets.

The 1-D model has a good physical characterisation ability for the engine working process, can reflect the characteristics of distributed parameters, and also has the ability to quickly simulate the flow and heat transfer characteristics of the regeneratively cooled scramjet. Over the years, considering the urgency of applying regeneratively-cooled technique to scramjets, several models have been studied. These studies established a 1-D flow and heat transfer model of the cooling channel [243−245], provided a steady-state model based on ordinary differential

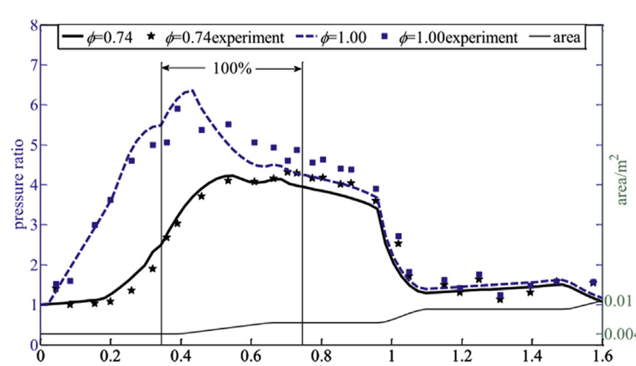


Figure 33 Experimental and numerical normalized wall pressure distributions with fuel equivalent ratios of 0.74 and 1.0 [238].

equations [246], and discussed the simulation calculation of a full-scale regeneratively-cooled scramjet combustor. In addition, Ma et al. [247] established a control-oriented unsteady 1-D model for a hydrocarbon regeneratively cooled scramjet based on partial differential equations. Figure 34 indicates a schematic of the regeneratively-cooled scramjet engine, in which the dotted line is the fuel flow path. The hydrocarbon fuel was used as a coolant. Before entering the combustor, the fuel first flows in the cooling channel outside the engine wall and absorbs heat to reduce the wall temperature below the acceptable temperature. Then, the heat loss from the wall returns to the combustor through the fuel, which forms a regenerative cycle of energy regeneration.

This section focuses on the model mentioned in the literature [247]. The modelling process was considered as a coupling between the flow-combustion and regenerative cooling modules, which are connected by boundary conditions. First, the regenerative cooling module has heat convection from the burned gas to the gas-side wall of the engine, wall heat conduction from the gas-side to coolant-side, and heat convection from the coolant-side wall of the engine to the coolant. These three heat transfer processes are shown in Figure 35. More details can be found in Ref. [247]. Then, based on unsteady 1-D Euler equations, the flow-combustion module can consider the variable area, fuel addition, combustion efficiency, variable specific heat, inflow air vitiation component, and wall friction. The mixture gas parameters can be obtained by the mass-weighted average. The unsteady 1-D Euler equations are given below:

$$\frac{\partial(\boldsymbol{U})}{\partial t}+\frac{\partial(\boldsymbol{F}(\boldsymbol{U}))}{\partial x}=\boldsymbol{S}(\boldsymbol{U}) \tag{16}$$

where,
$\boldsymbol{U} = (\rho A, \rho A u, \rho A E t)^{\mathrm{T}}$,
$\boldsymbol{F}(\boldsymbol{U}) = (\rho A u, pA + \rho A u^2, (p + \rho E_t) A u)^{\mathrm{T}}$,

$$\boldsymbol{S}(\boldsymbol{U})=\left(\frac{\mathrm{d}\dot{m}_{\mathrm{comb}}}{\mathrm{d}x},\ p\frac{\mathrm{d}A}{\mathrm{d}x}-\frac{\rho u^2}{2}f(x)\cdot C_w+u_{x,\mathrm{oil}}\frac{\mathrm{d}\dot{m}_{\mathrm{comb}}}{\mathrm{d}x},\ (H_{\mathrm{comb}}+H_{\mathrm{add}})\cdot\eta_{\mathrm{comb}}\cdot\frac{\mathrm{d}\dot{m}_{\mathrm{comb}}}{\mathrm{d}x}-H_{\mathrm{loss}}\right)^{\mathrm{T}}$$

This module can be referred in detail from Ref. [238].

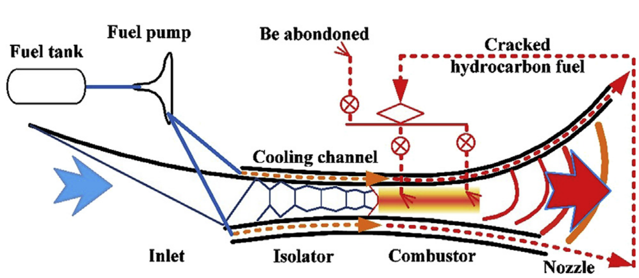


Figure 34 Schematic of regeneratively-cooled scramjet engine [247].

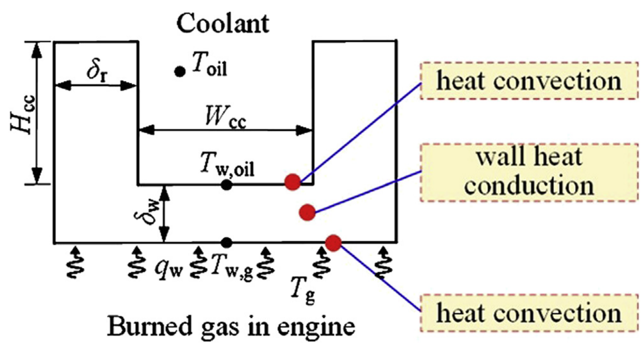


Figure 35 Schematic of heat transfer process among burned gas, wall, and coolant in rib [247].

4.3. Control issues on ramjet and scramjet

For the study of ramjet and scramjet, there has always been an experimental orientation. Scientists are affected by the results of important flight tests and conduct research on exposure issues. Through the above analysis of important flight tests, the control problems faced by the ramjet and scramjet are still mainly concentrated in the inlet unstart, combustion mode transition, multi-object coordination protection, and airframe/propulsion integration.

4.3.1. Inlet unstart control

The fact that the inlet unstarts frequently during flight tests, particularly in the X-51A flight test accident, has inspired the academic community to study the interaction between supersonic or hypersonic inlet, isolations, and combustors in the 21st century. In recent years, there has been considerable work on the mechanism and control system design based on numerical simulations or ground tests for unstarting problems [248]. The main feature of the inlet unstart is that there is a strong shock-wave system near the inlet. At this time, the flow capture of the inlet sharply decreases and the flow field quality deteriorates, thus the engine becomes unable to generate thrust, and even causes surge, structural damage, over temperature, or flameout [249]. Scramjets operate in a wide range of flight Mach. In the operating process, the inlet may experience the following work states: low Mach unstart, start state, and high Mach unstart. It is difficult to solve the inlet unstart through the design process. The stability of the inlet and safety work of the engine must be solved by monitoring the inlet states and applying feedback control.

From the perspective of engine performance requirements, the closer the engine is to the critical state, the better the performance and the higher the thrust. However, for the control system of the engine, the closer the engine is to the critical state, the harder it is to ensure safety. Achieving an effective balance between engine performance and stability is a problem that the control system needs to consider. In short, for the engine control system, it is necessary to introduce the inlet protection control loop such that the engine can run close to the stable boundary without inlet unstart. It is also necessary to study the unstart boundary and the stability margin control of the hypersonic inlet. First, many numerical simulations need to be performed for the inlet to find the influencing factors of the inlet unstart boundary and determine its expression form. Second, active control is used to expand the inlet unstart boundary, and feedback control may provide a safer and more effective method.

For the control study of inlet/isolation, Chang et al. [250] analysed the starting boundary and margin of the scramjet inlet, and studied the hysteresis between inlet start and unstart. A closed-loop CFD/MATLAB simulation platform for hypersonic inlet margin control was built, and the performance of the control system under different inlet flow conditions was guaranteed by the gain scheduling method [251]. Ashley et al. [252] successfully controlled the unstart phenomenon of the hypersonic inlet through front edge monitoring of the shock train and feedback control. Vanstone et al. [253] used a proportional-derivative controller to perform real-time feedback control of the shock train position under the condition of Mach number 2.2 sub-combustion mode, and verified three shock train leading-edge monitoring methods. Furthermore, the closed-loop control of unstart in a Mach 1.8 isolator was verified in the literature [254]. Kojima et al. [255] conducted an experimental study on the control problem of the inlet, focussing on the analysis of the control strategy of the engine inlet during normal operation. In addition, because the position of the shock train is closely related to the inlet unstart, it is also a feasible method to control the position of the shock train. Considering the impact of the incident shock wave, Li et al. [256] conducted an experimental study on shock train control in isolation, and used a PI controller to control the front edge position of the shock train in a closed loop. Li considered the effects of incident shocks and designed a closed-loop control loop with a PI controller. Figure 36 shows the control loop with incident shocks. The shock wave model was modified by analysing the flow field. The control experimental results of the shock train leading edge location at Mach 2.72 are shown in Figures 37 and 38. Compared with the descriptions in Figure 37, the control system modifies the original order to avoid the effects of the shock wave-boundary layer interaction. The trajectory shown in Figure 38(a) indicates that the shock train leading edge adequately follows the modified instruction. The shock train leading edge is controlled and dominated by back-pressure. By means of feedback control and changing control instructions, the uncontrolled oscillation process of shock train can be effectively avoided. Furthermore, Li et al. [257] analysed the complex motion behaviour and the unstable characteristics of shock trains from the perspective of controllability, and conducted in-depth research to understand the control characteristics of shock trains.

4.3.2. Combustion mode transition control

In low flight Mach, the isolation of dual-mode scramjet compresses the supersonic airflow and achieves subsonic combustion. In high Mach, the entire flow passage of the engine is supersonic, and supersonic combustion is realised [258]. The combustion mode reflects the combustion state in the combustor when the engine is working and represents the working state of the engine under the combined action of the current flow conditions and fuel injection combustion. In recent years, with the deepening of research work, different researchers have provided different definitions and classification methods for the concept of combustion modes from different angles.

In the first category, the engine combustion mode is directly defined from the working Mach number of the combustor and the development of the PCST in the isolator [259]. This classification method is the most intuitive and basic. Thus, the combustion mode of a scramjet can be divided into three types: sub-combustion mode, initial super-combustion mode (oblique shock wave super-combustion mode), and late super-combustion mode (pure

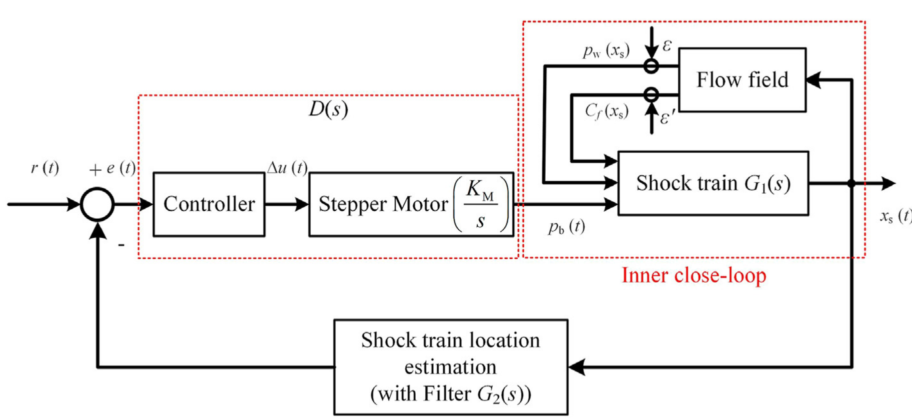


Figure 36 Control loop with incident shocks [256].

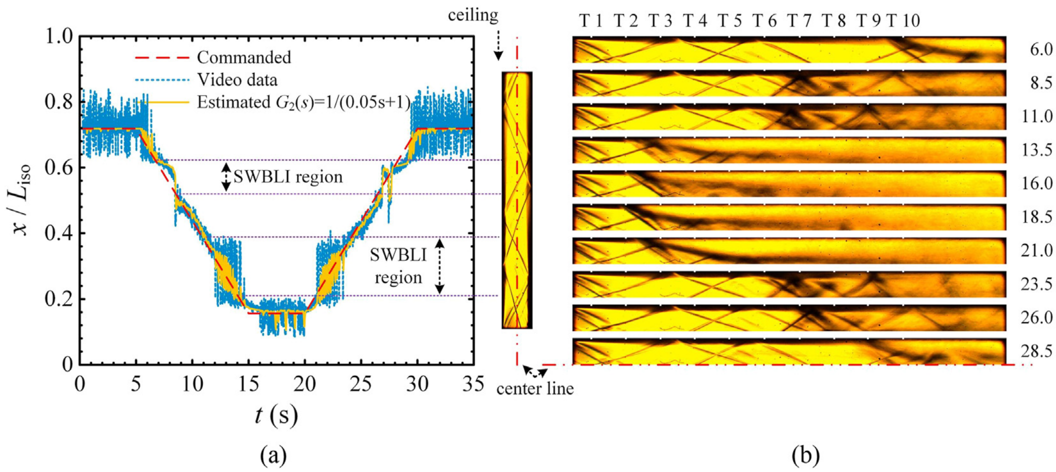


Figure 37 Shock train location control at 2.72 Ma with incident shocks and ramp instruction: (a) trajectory of the shock train leading edge compared with the command, (b) schlieren images of the shock train leading edge from t = 6.0 s to 28.5 s [256].

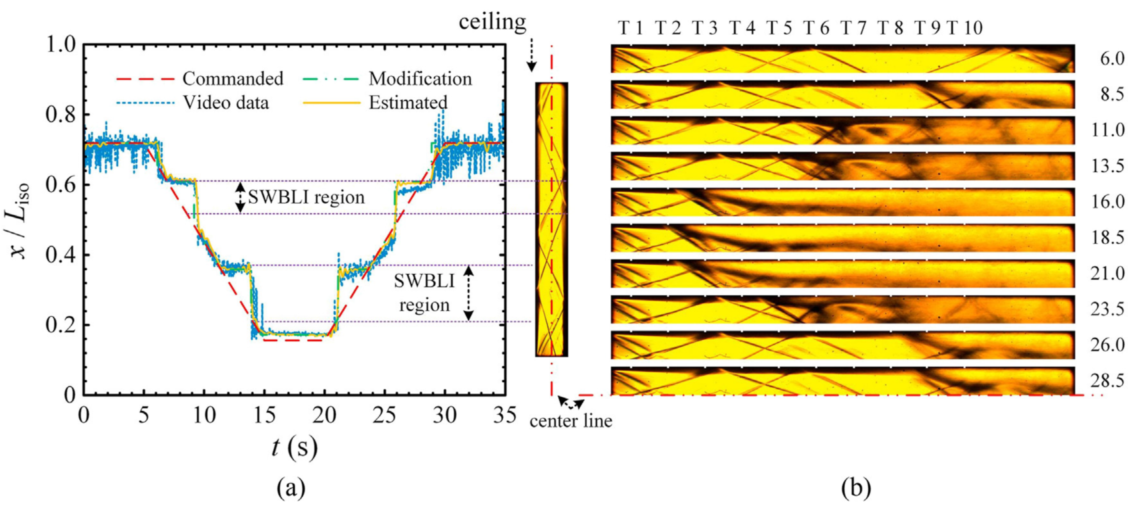


Figure 38 Shock train location control at 2.72 Ma with modification instruction: (a) trajectory of the shock train leading edge compared with the command, (b) schlieren images of the shock train leading edge from t = 6.0 s to 28.5 s [256].

super-combustion mode). Figure 39 shows a schematic diagram of the engine flow field under the three combustion modes, considering an acceleration process from Mach 3 to Mach 12. The engine fuel equivalent ratio remained unchanged during the entire process. In addition to the Mach number distribution given in Figure 39, another important feature of this combustion mode definition and classification method is the pressure change upstream of the combustor. In the ram mode, the pressure upstream of the combustor shows a downward tendency. In the early scram mode, there is an isobaric combustion zone upstream of the combustor. In the late scram mode, the pressure in the combustor first rises and then decreases. The second type of combustion mode is from the perspective of flame propagation [260]. The third type is based on the experimental measurement results [261]. These three types have their own characteristics and are inherently compatible. The first focuses on concepts, reflecting the working state of the engine, and has better universality. The second focuses on the physical mechanism and grasps the physical nature of combustion. The third focuses on experimental observation results, reflecting the evident flame characteristics of the engine under different combustion modes. At present, in research such as engine performance analysis and 1-D model construction, the first one is more widely used.

Combustion mode transition is proposed with the objective demand of a scramjet for high performance in a wide Mach number range [203]. Scramjets operating in a wide Mach range need to optimise the selection of the combustion mode and mode transition control to improve the thrust and economic performance. Figure 40 shows a schematic diagram of combustion mode selection. In the flight stage of a low Mach number (the part of the red curve in Figure 40), the dual-mode scramjet engine has a higher performance under the thermal cycle condition of the ram mode. Currently, there is a strong pre-combustion shock wave series in the isolation, which causes the combustor airflow to change into a subsonic velocity. In the mid-Mach

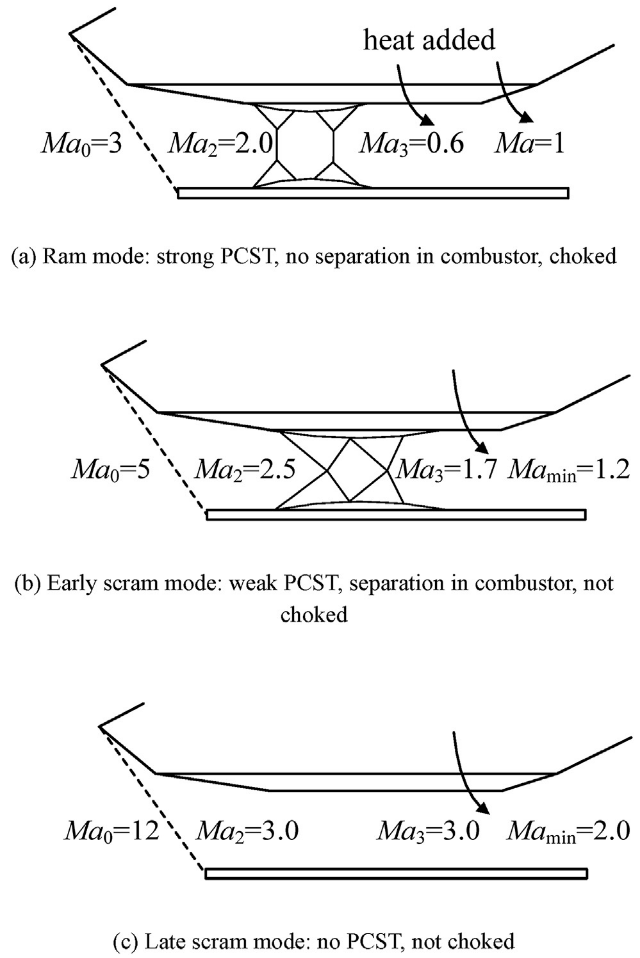


Figure 39 Schematic of isolator PCST for ram, early scram, and late scram modes [259].

number flight phase (green curve in Figure 40), the scram mode thermal cycle with the PCST has a higher performance. There is a weak PCST in the isolation section because the isolation exit is still supersonic. In the high Mach number flight phase (blue curve in Figure 40), the thermal cycle of the scram mode exhibits a higher performance. At this time, the boundary layer does not separate, and there is no PCST in the isolation section. The entire flow channel is supersonic. Therefore, it is important to choose the most reasonable operating mode of engines for higher performance. In addition, the combustion mode transition introduces special problems such as changes in heat transfer characteristics, sudden changes in thrust and existence hysteresis [262–269], and combustion mode oscillations [270]. The catastrophe phenomenon of thrust in the transition between different modes is shown in Figure 41. When the scramjet changes from the weak to the strong combustion mode, the engine thrust suddenly increases considerably in Figure 41, reaching twice the original value.

Therefore, the study of combustion mode transition characteristics and control methods is very important for dual-mode scramjets. The essence of combustion mode transition control is to change the working mode of the dual-mode scramjet by actively adjusting the fuel distribution and flow rate to achieve thrust optimisation or economy requirements. Although the physical mechanism of the influence of combustion mode transition on thrust changes is not in-depth enough, the sudden change and hysteresis characteristics in the combustion mode transition must be considered for scramjet control, as they have a significant impact on the stability and effectiveness of the engine control system. Otherwise, the control system can lose stability and cause the flight mission to fail.

4.3.3. Multi-objective coordinated control

The performance potential of the scramjet should be maximised to achieve high efficiency, which can cause the engine to work at the maximum performance boundary. The slightest disturbance leads the engine to a dangerous working mode. Therefore, the control system must ensure the maximum performance and safe operation of the engine. The control of a scramjet is a multi-objective coordination problem. Specifically, the control of scramjet mainly achieves two goals: first, to quickly track the thrust command to provide the required thrust for various flight tasks of the hypersonic vehicle; second, to ensure that the engine does not have destructive hazardous conditions such as inlet unstart and combustor overtemperature, that is, control of the safety boundary. The dual-mode scramjet, which has experienced both the ram and the scram modes, faces a wide range of flight environments and different safety problems. In ram mode, the safety problem is mainly concentrated in the inlet unstart, whereas it turns to combustor overtemperature in the scram mode. Thus, various regulations aim for different conditions of the scramjet to achieve higher performance potential.

Qi et al. [271] designed a switched multi-objective safety protection control for the inlet buzz of a scramjet. Related verification was performed on the 1-D scramjet model. The controller system considered the uncertainty of the scramjet model and contained a switching logic of command. When the inlet buzz occurs, the safety sub-controller generates an appropriate correction signal to replace the original thrust command to ensure the safety of the scramjet. Cao et al. [272,273] proposed two switching control methods to manage the multi-objective control for scramjet, which ensured the best thrust performance and avoided inlet unstart. Figure 42 shows the block diagram of the switching control system for the thrust adjustment and inlet protection of the scramjet in the two studies. The basic idea of the min strategy was to compare the output of the thrust regulation controller and the inlet unstart protection controller, and the min one was selected as the control output. Integral initial values resetting can set the switching rules according to the user's needs, select the necessary controller to cut into the online state, and compose the control system with the controlled plant. The continuity of the output of the controller before and after the switch is ensured by this method.

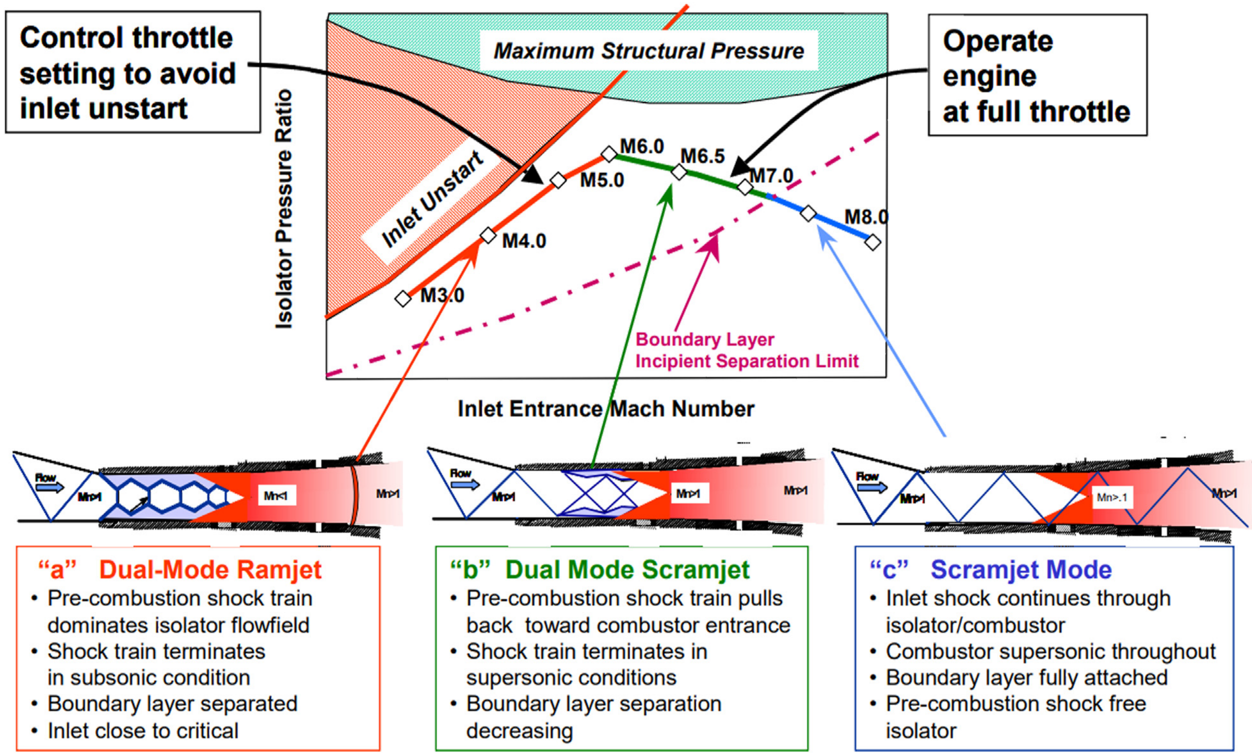


Figure 40 The isolator provides dual-mode scramjet seamless transition to scramjet [203].

The switching control method was able to manage the multi-objective control problem of the scramjet. In addition to the inlet unstart, the problem of overheating also needs to be considered in scramjet control. If regenerative cooling technology is applied, the over-temperature problem also becomes an important safety protection goal. To this end, Ma et al. established a 1-D mathematical model of a regeneratively-cooled scramjet with two-stage kerosene injection [247], and designed a multi-objective coordinated control system [38]. A schematic diagram of the multi-loop coordinated control system in the literature [38], is shown in Figure 43. Compared with the control system shown in Figure 42, the control target of the regeneratively-cooled

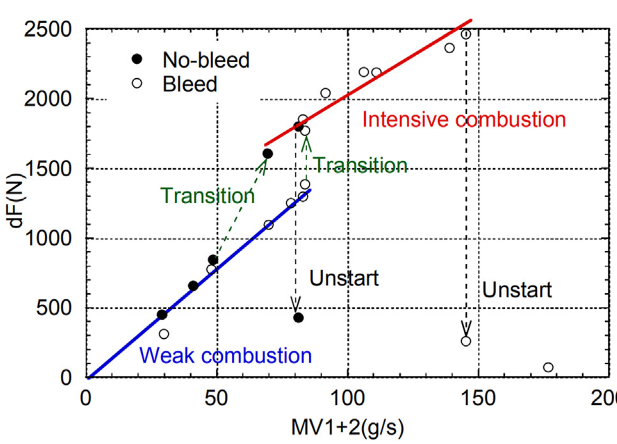
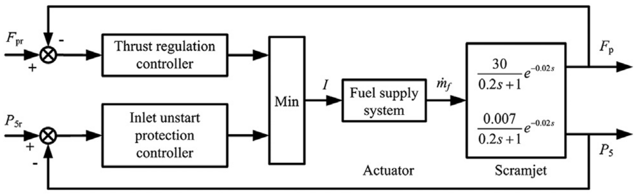


Figure 41 Catastrophe phenomenon in the transition between different modes [268].

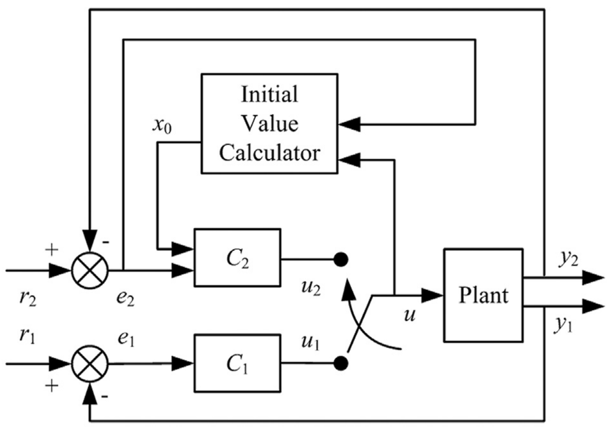
scramjet increased the kerosene temperature at the cooling channels outlet. The switching controller includes restart recovery, margin protection, overtemperature recovery, temperature protection, and thrust sub-controllers. The switching between subsystems adopts a bumpless switching method introduced in the literature [273]. Figure 44 indicates the dynamic response of the control system. The results show that the integrated control system can guarantee thrust performance and safety requirements. The control effect under the change of the switching command also shows that the entire system is stable during the switching process. At 30 s, it is considered that if the inlet unstart, the restart recovery controller can quickly adjust and ensure the normal operation of the switched control system. In addition, Lv et al. [32] used a multivariable control method to complete the acceleration of the regeneratively-cooled scramjet. The control system was divided into two multivariable sub-controllers. In the low-speed section, the sub-controller simultaneously controls the thrust and the inlet steady margin. In the high-speed section, another sub-controller is responsible for thrust and temperature protection control.

4.3.4. Airframe/propulsion integrated control

Airframe/propulsion integrated control is essential for ramjets, particularly scramjet control. On the one hand, ramjet-based engines often work in a complex environment between Mach 2 and Mach 8, where the internal and external flow aerodynamic thermal processes faced by the engine are extremely complicated. In addition, the engine



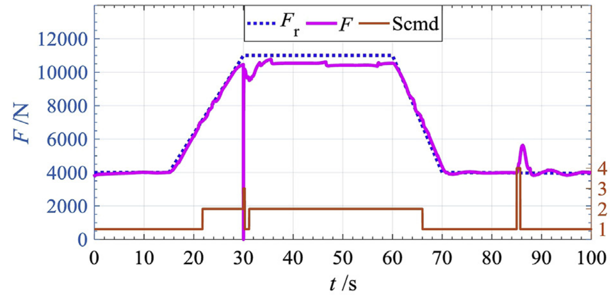
(a) Based on min's strategy [272]



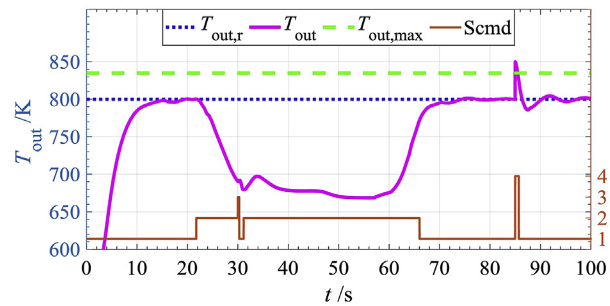
(b) Based on the integral initial values resetting [273]

Figure 42 Structure diagram of multi-loop switching control system.

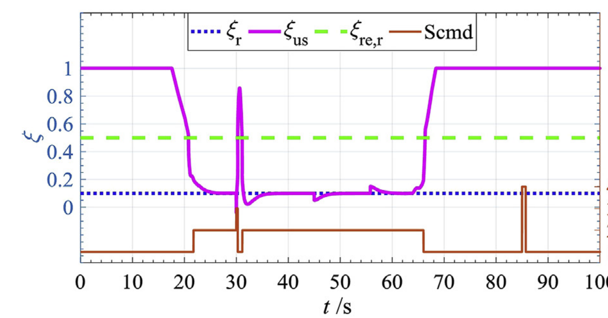
faces the control problems discussed above, such as the inlet unstart and combustion mode transition. On the other hand, the stability control of the supersonic vehicle itself is also a control problem that needs to be solved. As the flight Mach increases, the interaction between the engine and vehicle is intensified, and the integrated control becomes one of the keys to hypersonic vehicles.



(a) Thrust



(b) Kerosene temperature at cooling channels outlet



(c) Steady margin

Figure 44 Dynamic response of controlled engine output in multi-loop coordinated control system [38].

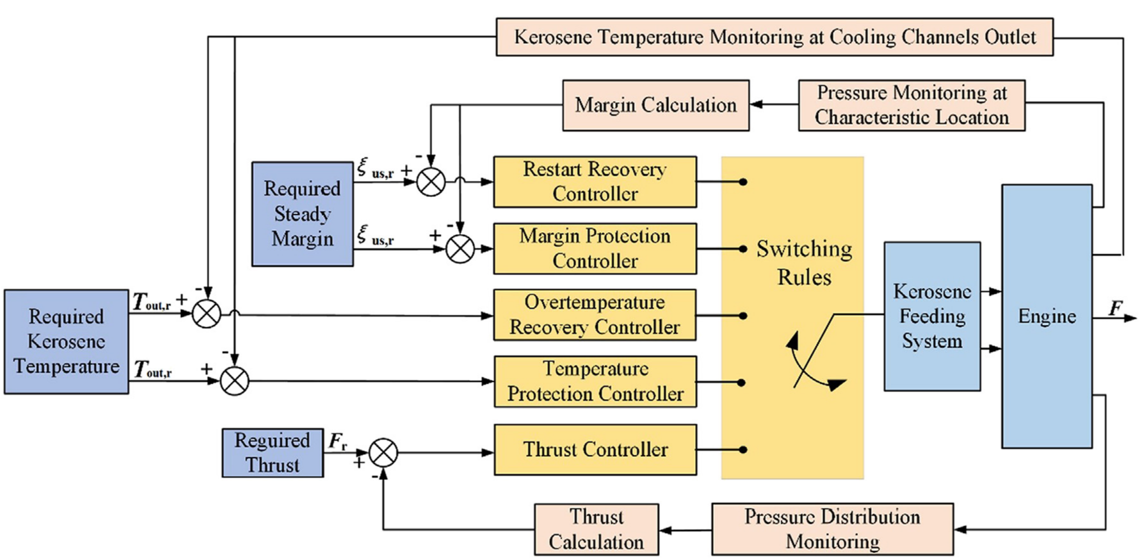


Figure 43 Scheme diagram of multi-loop coordinated control system [38].

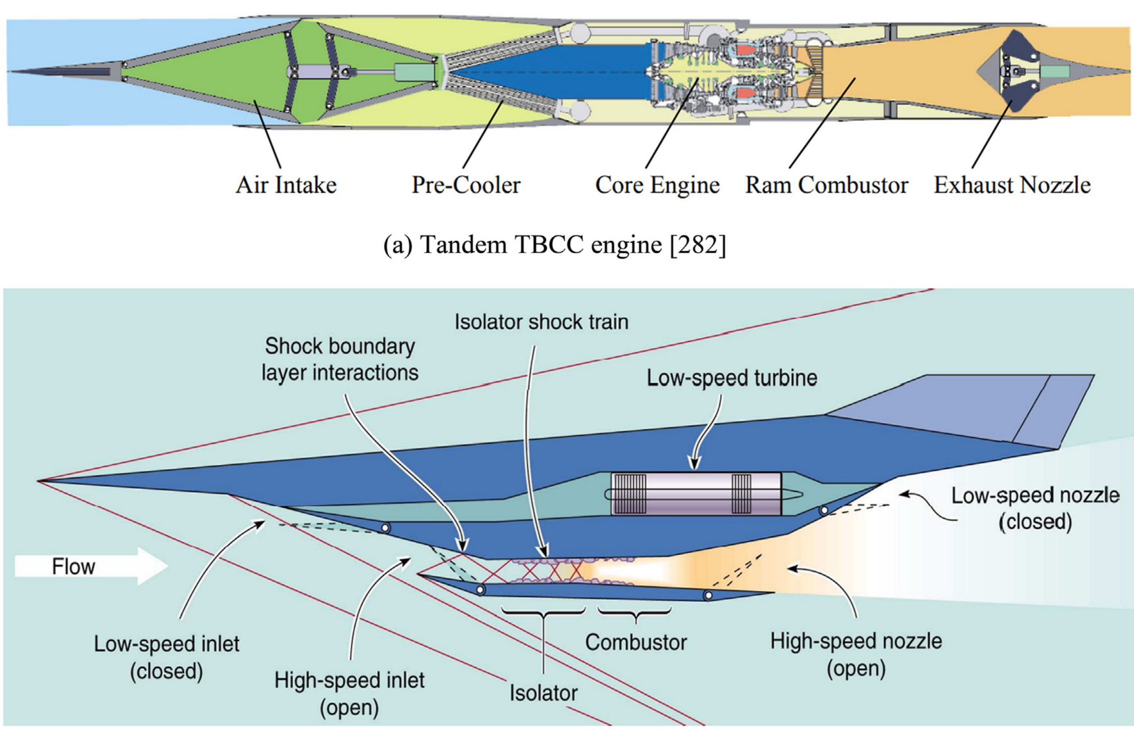
The research progress and details of airframe/propulsion integrated control for hypersonic vehicles with ramjet-based engines can be found in the sixth part of this paper.

5. Combined cycle engine control

Based on the long-distance and large-airspace flight requirements of hypersonic vehicles, the propulsion system needs to ensure the continuous output of thrust under a wide range of Mach numbers. However, the thrust advantage of a single engine cannot completely cover the flight conditions over a wide speed range. This can be seen from the air-breathing propulsion performance shown in Figure 1. Therefore, a reasonable combination of multiple engines is a practical solution for propulsion systems in a wide speed range. Combined power has received considerable attention since the concept was proposed. Currently, the major combined powers are TBCC and rock-based combined cycle (RBCC). In addition, there are studies that combine rockets, turbines, and ramjets to form combined power, such as the turbo-aided rock-augmented ramjet combined cycle engine (TRRE).

First, the TBCC engine is a combination of a turbine engine and ramjet. From the perspective of engine structure, TBCC engines can be divided into tandem and parallel types. This classification is based on the arrangement of the two sub-engines. Figure 45 shows the normal structure of the TBCC engine [282,283]. The first TBCC engine in the United States was the J58, which first flew in 1962 as the engine of the SR-71 aircraft, with a maximum flight speed of Mach 3.3 [242]. In 2001, the Revolutionary Turbine Accelerator program was started, and the engine of the program was expected to fly to Mach 5 [24]. However, due to financial and technical constraints, the program was forced to be suspended in 2005. Later, the research and development of the SR-72 aircraft was put on the schedule, in which a parallel TBCC engine was used. The turbine engine of SR-72 worked from the ground to Mach 4, and the scramjet worked to Mach 6 after the conversion. In 2016, the U.S. Defense Advanced Research Projects Agency proposed the advanced full range engine program. This program plans to study a TBCC engine combining a turbine engine and a dual-mode scramjet, and requires the Mach of the ram-scram mode transition to be 1.5−3.0 [274]. Russia conducted ground tests on full-scale turbo-ramjet engines in the 70s and 80s [275]. In 2004, Japan started the development work from the air-turboramjet expander cycle engine [276] to the precooled turbojet engine [277,278], and verified the windmill starting performance of the engine through wind tunnel tests. Germany restarted the Sanger aerospace aircraft program in 1985, and successfully completed the ground test of the TBCC engine in 1991 [279,280]. In 2015, Chinese researchers proposed the TRRE engine program with three power combinations of the turbo-rocket-ram engine [281].

Second, the RBCC engine is an advanced propulsion system that organically combines a rocket and a ramjet. It uses the high thrust-to-weight ratio of the rocket and the high specific impulse of the ramjet, such that the efficiency



(a) Tandem TBCC engine [282]

(b) Parallel TBCC engine [283]

Figure 45 Normal structure of TBCC engine [282,283].

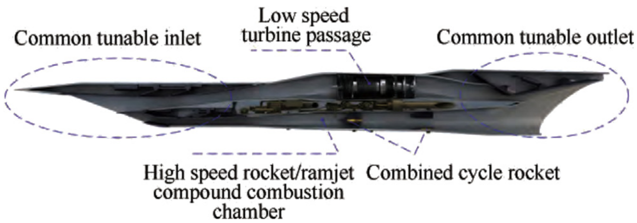


Figure 46 Structure of TRRE engine [281].

and economy of aerospace propulsion are possible. Third, the TRRE engine is a new type of combined power with complex technology and strong innovation, which provides a new solution for propulsion technology in an extremely wide range. Figure 46 shows the structure of the TRRE engine.

At present, a variety of power schemes were developed for the combined propulsion system, and some characteristics of these engines have been mastered through preliminary evaluation. Among them, the core speed technology of ramjets and the high Mach turbine technology have been extensively researched, and certain results have been obtained. Compared with RBCC engines requiring an expensive launch platform and TRRE engines that need to overcome the technical problems of coupling of three types of engines, TBCC engines have lower technical risks and can achieve takeoff and landing on ground airports. In addition, TBCC engines expand the range of the aircraft's operating Mach and enable the aircraft to start from the ground to hypersonic flight. Therefore, the following content will focus on the TBCC engine and introduce its modelling and control issues.

5.1. Modelling of TBCC

In 1993, NASA republished the structural design and analysis of a Mach zero-to-five turbo-ramjet system [284]. In 2009, the SJPIRITECH company performed a high Mach transient engine cycle code (HiTECC) simulation model [285,286]. The HiTECC model can simulate most events under the entire flight envelope and focuses on the mode transition from Mach 2.5 to Mach 4.0. The critical mode transition period was Mach 3.75. Figure 47 shows the HiTECC simulation platform. In 2010, NASA [287,288] proposed a reconfigurable simulation model of the propulsion system. The model of each engine component can be individually removed, modified, or replaced. In addition, each component model can run independently, thus the controller can be separately designed, and its structure is shown in Figure 48. Zhu et al. [289] established a steady-state model of the turbofan-ramjet, which can be used to quickly evaluate the performance of the TBCC engine. Zhang et al. [290] studied a TBCC engine performance simulation program for an airbreathing hypersonic propulsion system. In the ram-scram mode transition, Zhang formulated a strategy to maintain the thrust as continuous as possible. In addition, Zheng et al. [31,291] established over-under TBCC engines and analysed the coupling effect between a hypersonic vehicle and a TBCC engine. In addition, the performance uncertainty propagation of TBCC was discussed in the literature [292].

From the public literature, certain research results have been achieved for the overall modelling of TBCC engines. Although these simulation models meet the requirements of hypersonic propulsion system design to a certain extent,

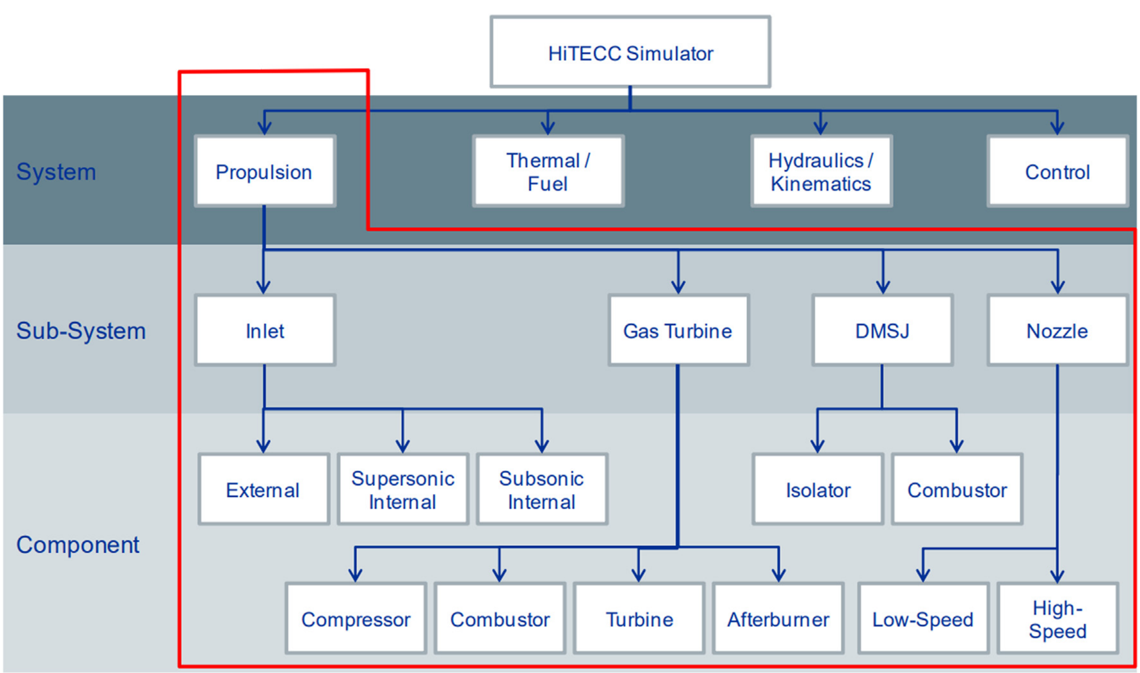


Figure 47 Composition of HiTECC simulation platform [285].

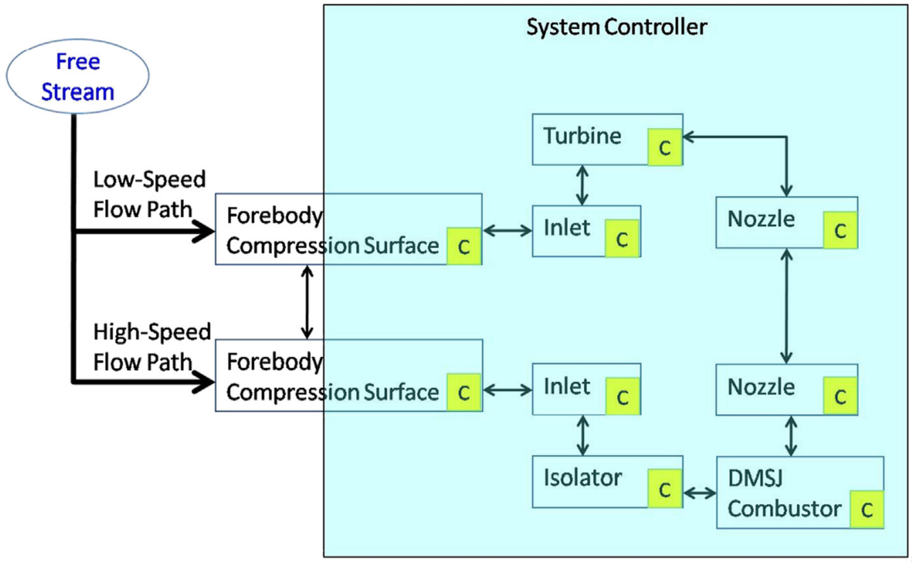


Figure 48 Simulation and control flow chart of hypersonic propulsion system [287].

because of the excessive simplification of the inlet model, it is difficult to accurately describe the coupling characteristics between the two inlet channels of the TBCC engine. Therefore, research on the ram-scram mode transition has certain limitations. From this perspective, the design of key components such as the TBCC dual-channel inlet is still the focus of current researchers, which also restricts the research of TBCC engine control systems.

5.2. *Mode transition and thrust pinch control issues on TBCC*

To date, there have been relatively few studies on the control of TBCC engines from the propulsion perspective. The main reason is that the current TBCC propulsion technology is not sufficiently mature for practical applications. In addition to the control problems of turbine engines and ramjets, especially the control problems mentioned above for ramjets. Key issues for TBCC still unsolved, such as full-speed range combined inlet, high Mach turbine, thrust pinch, and high and low inlet channel matching problems, limit the development of corresponding control strategies and methods. TBCC engine control has special problems that need to be solved. First, through analysis, the mode transition is the key issue of TBCC engines. Numerous studies have been performed on this topic. Compared with the ram and scram mode transitions of the dual-mode scramjet, one of the TBCC engines mainly lies in the working modes between the turbine engine and the scramjet. Second, the complex mode transition problem brings another focus of TBCC engine control: the thrust pinch, which is inevitable. The specific manifestation is that during the mode transition, the turbine channel gradually closes, and the turbine thrust gradually decreases, while the ram channel gradually opens, and the ram thrust gradually increases. During this process, the thrust connection between the turbine and ramjet is nonlinear, which results in a possible sudden decrease in thrust, that is, the thrust pinch. Therefore, most of the published studies on TBCC control are performed on the special mode transition and focus on thrust performance.

Daniel et al. [285] proposed a control strategy for the TBCC engine and simulated the performance of the control system during the entire operation but did not provide considerable details in the published literature. Chen et al. [293,294] developed a component-based series TBCC engine model that can simulate the mode transition between turbofan engines and ramjets. Based on this model, the team designed a multivariable controller of TBCC based on the Newton–Raphson multi-objective programming algorithm and realised a stable mode transition. The mode transition control of the TBCC engine was mainly based on adjusting the fuel flow of the two sub-engines, and the goal was to control the total thrust of the TBCC engine to be constant to achieve a safe, reliable, and smooth transition [295,296]. Furthermore, Nie et al. [297] performed control research on a TBCC engine based on the EKF online real-time engine model, which had several geometric adjustments. The structure of the model is shown in Figure 49. The adopted control algorithm was a mixed sensitivity method. The controlled variables mainly included engine thrust, air flow, and fan surge margin. In the simulation verification, a smooth transition of thrust and flow in the mode transition was realised. In addition to the control of the entire engine, research on TBCC control and optimisation was performed for key components such as the inlet [298,299] and exhaust systems [300]. In addition, Zheng et al. [5] overcame the transition thrust pinch from the perspective of energy analysis and completed the trajectory optimisation.

6. Hypersonic airframe/propulsion integrated system control

As the flight Mach increases, the coupling between the propulsion and airframe deepens, and the requirements of hypersonic integrated system control become increasingly important. The control of airbreathing aero-engines is difficult, and becomes more complicated if the effect of airframe is added. The supersonic or hypersonic airframe/propulsion coupling system with ramjets, scramjets, or combined cycle engines is a large-scale power system involving multiple disciplines. The so-called large-scale means that the entire system is composed of several subsystems. Thus, as the integrated system runs, complicated interactions between its subsystems occur, that is, the strong coupling problem of the airbreathing airframe/propulsion integrated system. Thus, it is necessary to study integrated system control for hypersonic vehicles.

In addition, a supersonic or hypersonic vehicle with a non-axisymmetric waverider aerodynamic shape and an airframe/propulsion integrated structure has a natural head-up moment, and its longitudinal attitude is statically unstable. The lower surface of the front and rear bodies has a dual role in the integrated system. They act as the aerodynamic part of the vehicle itself to form aerodynamic force and torque and as an external compression and expansion of the propulsion system. As a result, the coupling influence of the waverider is more variable and complicated than an axisymmetric one. Therefore, modelling and control research for hypersonic vehicles has always been focused.

6.1. Modelling of hypersonic vehicle

In response to the airframe/propulsion coupling problem, many research teams have focused on deepening the construction of the integrated hypersonic vehicle mathematical model, with the aim of developing a more complete basic simulation platform for the subsequent aircraft attitude/trajectory/propulsion integrated coordinated control. In 1994, Chavez and Schmidt [301] took the lead in explaining the construction method of a type of aeropropulsive/aeroelastic hypersonic vehicle coupling longitudinal mechanism model based on X-30. This early work used a large amount of time to show the linearisation results of the integrated model with small deviations at a specific cruise operating point.

In 2007, the most representative Bolender−Doman airframe/propulsion coupled longitudinal nonlinear mechanism model was proposed, which largely retained and inherited the mathematical description of scramjet in the Chavez−Schmidt model [302]. However, it should be highlighted that the engine model at this specific stage refers to the (pure) scramjet model with only supersonic combustion mode. This model does not address the modelling of thermal or geometric blockage caused by heat release or geometric factors. Compared with the Chavez−Schmidt model, the Bolender−Doman model is a more in-depth and detailed presentation of the mechanism construction method of the aircraft aerodynamic force. According to the oblique shock wave theory and Prandtl−Meyer flow formula, the Bolender−Doman model obtains the longitudinal aerodynamic forces and moments of the upper, lower, and control surfaces of the fuselage. By adding an active control mechanism, it is assumed that the engine intake system can still capture the ideal situation of the maximum air quality flow even under non-design conditions. In addition, the approximate formula for the pressure distribution in the Chavez−Schmidt model was used. The model can obtain the longitudinal aerodynamic force and moment of the high-temperature gas acting at the lower surface of the nozzle outlet. The two-dimensional (2-D) geometry of the Bolender−Doman model is shown in Figure 50.

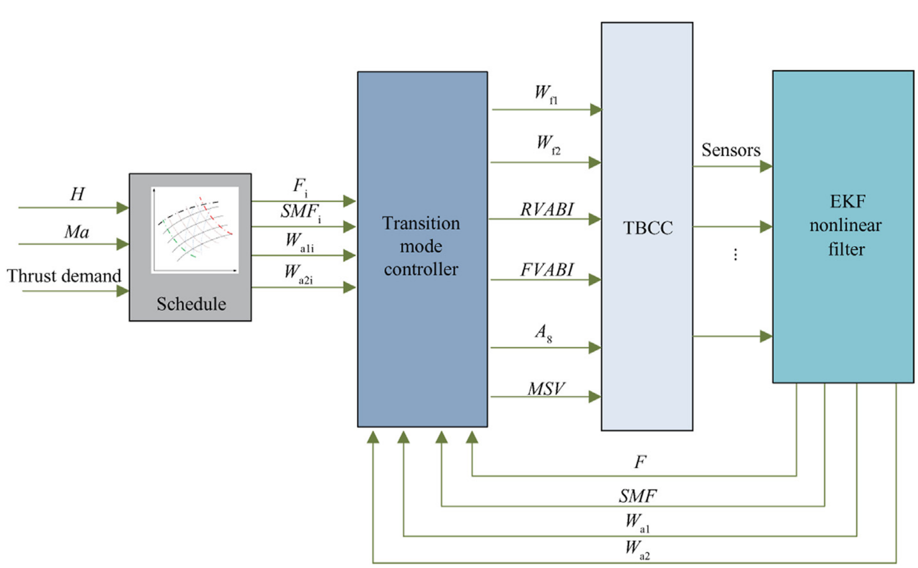
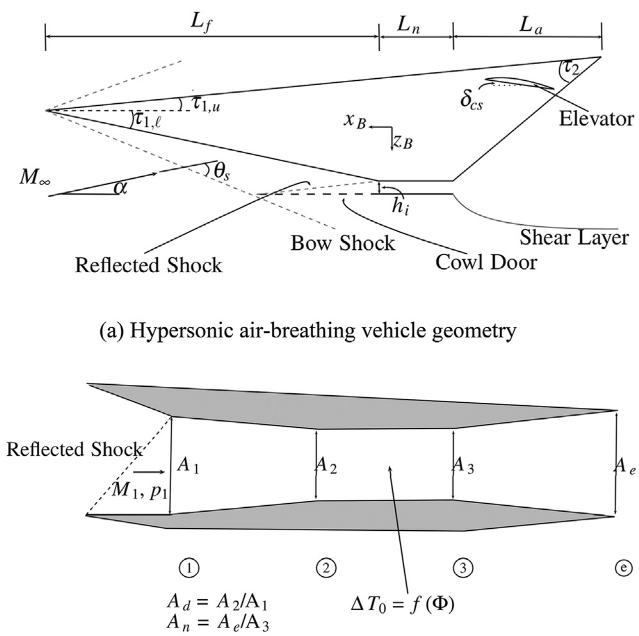


Figure 49 Multivariable controller of online engine real-time model based on EKF [297].

Parker et al. [303] applied certain simplifications and parameterisations based on the Bolender–Doman model, and developed a control-oriented airbreathing hypersonic vehicle longitudinal dynamic model. It uses the fitting method to parameterize the nonlinear equations of force and moment in the original mechanism model into a multivariate polynomial that is more convenient for control system design. This model is consolidated as a control-oriented simulation platform and is widely cited. The Parker control-oriented model is a dynamic model, whose dynamics are reflected in the 3-degree of freedom (DOF) dynamics equation of the aircraft. Thus, equation further simplifies the mathematical description of the scramjet based on the mechanism model. However, it can only describe the (pure) scramjet. The longitudinal dynamic model is shown in Eq. (17)

$$
\begin{aligned}
&\dot{h}=V\sin(\theta-\alpha)\ ,\ \dot{V}=\frac{1}{m}(T\cos\alpha-D)-g\sin(\theta-\alpha)\\
&\dot{\alpha}=\frac{1}{mV}(-T\sin\alpha-L)+Q+\frac{g}{V}\cos(\theta-\alpha)\ ,\ \dot{\theta}=Q\\
&I_{yy}\dot{Q}=M+\tilde{\psi}_1\ddot{\eta}_1+\tilde{\psi}_2\ddot{\eta}_2\\
&k_1\ddot{\eta}_1=-2\zeta_1\omega_1\dot{\eta}_1-\omega_1^2\eta_1+N_1-\tilde{\psi}_1\frac{M}{I_{yy}}-\frac{\tilde{\psi}_1\tilde{\psi}_2\ddot{\eta}_2}{I_{yy}}\\
&k_2\ddot{\eta}_2=-2\zeta_2\omega_2\dot{\eta}_2-\omega_2^2\eta_2+N_2-\tilde{\psi}_2\frac{M}{I_{yy}}-\frac{\tilde{\psi}_2\tilde{\psi}_1\ddot{\eta}_1}{I_{yy}}
\end{aligned}
\tag{17}
$$

where the system state $x_{TM}\in R^9$ is composed of the nine state variables h, V, α, θ, Q, η_1, η_2, $\dot{\eta}_1$, and $\dot{\eta}_2$. More details can be found in Ref. [303].



(a) Hypersonic air-breathing vehicle geometry

(b) Scramjet cross section

Figure 50 2-D geometry of the Bolender–Doman model [302].

In the same period, Mirmirani et al. [304,305] also considered the construction of an integrated mathematical model based on computational fluid dynamics (CFD) numerical simulation. However, the computational time and cost of CFD technology has been infinitely magnified when establishing an accurate mathematical model. As Bolender [306] indicated in 2009, efforts should be focused on constructing a first-principles-based model of hypersonic vehicle control. In summary, looking at the development process of the integrated mathematical model construction in the past 20 years, the importance of the Bolender–Doman mechanism and Parker control-oriented models is reflected in the two leading approaches. First, construct a parametric model that focuses on aircraft dynamics. Second, build a 1-D reduced-order steady-state model that focuses on the mechanism of the dual-mode scramjet.

In 2009, Sigthorsson and Serrani [307,308] used the Parker oriented-control model as a basis and provided an LPV model of the aircraft in the longitudinal attitude. The parametric method showed the remarkable parameter varying characteristics of the airbreathing hypersonic vehicle and provided a simulation platform for the application of the LPV control algorithm on the vehicle [309,310]. In 2011, Shakiba and Serrani [311] proposed a control-oriented 6-DOF dynamic model of a hypersonic vehicle. In addition, Zinnecker and Serrani [312] identified the isolation model of a scramjet based on CFD simulation results. Figure 51 shows the structure of the 6-DOF control-oriented model that was established in the literature [311]. Among these works, the work of the steady-state model (Michigan/AFRL scramjet in vehicle, MASIV model) of the airbreathing propulsion system was supported by the research of Driscoll et al.

Specifically, Driscoll et al. conducted an in-depth study of the modelling of a dual-mode scramjet under the background of airframe/propulsion integration. These works were based on the Bolender–Doman model. The research results were concentrated in the steady-state model MASIV of the dual-mode scramjet engine that considered various physical/chemical effects and the airframe/propulsion coupling model MASTrim (Michigan/AFRL scramjet trim) from the MASIV. Both MASIV and MASTrim provided a simulation platform that can achieve fast calculations for subsequent research work on control system design and system parameter optimisation. The construction of the MASIV model can be divided into reduced-order steady-state models of the inlet (internal/external compression) system [313,314] and the exhaust (internal/external expansion) system [315]. The above modelling work transformed the interaction relationship between the shock wave and the expansion wave or shock wave into a 2-D Riemann problem. Compared with the 2-D CFD numerical calculation, the accuracy of the obtained reduced-order model could be maintained within 10%, and the calculation time was in seconds. The rapidity of this reduced-order modelling method was the basis for control. Another important task was to build a combustor model.

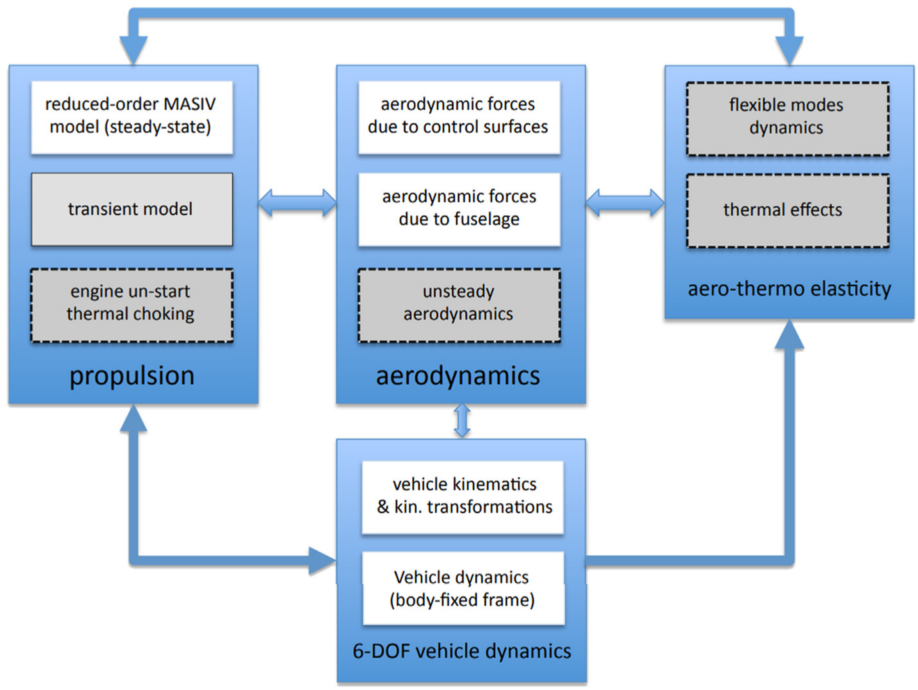


Figure 51 Structure of the 6-DOF control-oriented model (blocks in white denote available modules at the time of submission; solid blocks in grey refer to modules under development; dashed blocks in grey will be considered at a later stage of the research) [311].

The research was mainly focused on constructing a 1-D steady-state model that considered the limited chemical reaction rate, high-temperature gas physical properties [229,259], and combustion mode transition [235]. Furthermore, the integrated model MASTrim had the ability to trim longitudinally at any point within the selected flight envelope. Therefore, in the acceleration according to the isokinetic pressure line, the MASTrim model can define and calculate the distribution characteristics of the inlet unstart boundary and the mode transition boundary between the ramjet and scramjet modes [316]. The geometries of the vehicle and engine in the MASIV are shown in Figure 52. In recent years, Mbagwu and Marley further expanded the functions of the MASTrim model. Driscoll et al. [317,318] presented a mathematical method to calculate the engine combustion efficiency and flameout boundary. Driscoll et al. [319] discussed the influence of active and passive cooling on the performance boundary of the airframe/propulsion integrated system.

Summarising the development of the airframe/propulsion integrated mathematical modelling work in the past 20 years, we can find two aspects. On the one hand, control-oriented is always the basic starting point of modelling work. On the other hand, it increasingly considers the details and particularities of the integrated coupling problem. However, until now, there are still some problems that need to be discussed in depth in modelling. From the early Chavez–Schmidt model to the recent MASTrim model, the mathematical description of the ramjet or scramjet in the airframe/propulsion integrated mathematical model mostly

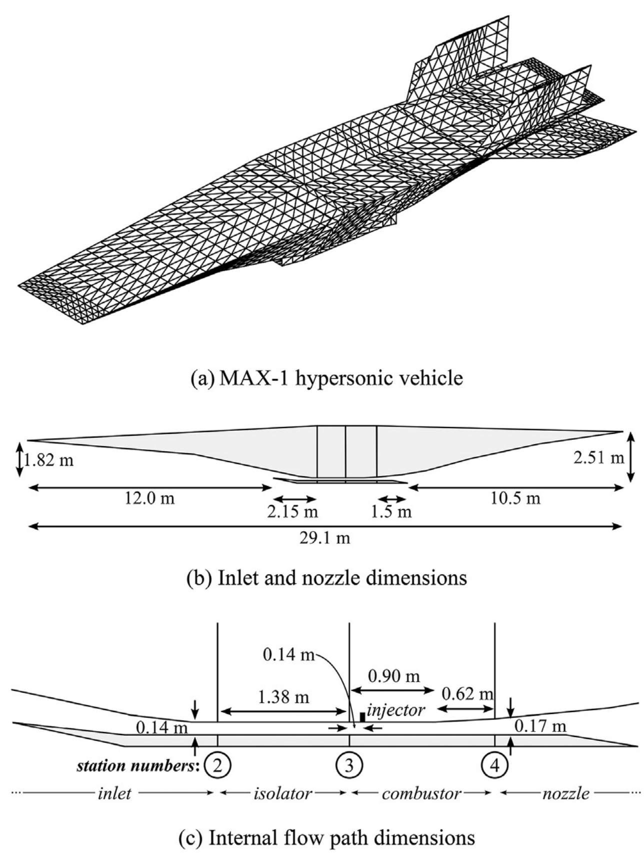


Figure 52 Geometries of vehicle and engine in MASIV. MAX-1 vehicle and flowpath dimensions. The engine width is 2.143 m [316].

adopts a steady-state form. The mechanism of the inlet unstart and the combustion mode transition was not considered before the MASTrim model. Even if the MASTrim model can represent the discontinuity of system parameters in the transition from sub-combustion to super-combustion, relevant research still needs to be performed.

6.2. Control issues on airframe/propulsion integrated system

Affected by the NASP [204], Hyper-X [206], and HyTech [26] plans, the control and optimisation issues focused by researchers in the past 20 years have also gradually evolved. Before the X-51A flight test accident, early research focused more on the use of advanced control methods to solve the control problems that existed during the cruise. Until now, the research has mainly focused on the static instability and the non-minimum phase of the vehicle's longitudinal attitude, tracking control of the altitude and velocity, elastic effect of the lightweight and long hypersonic vehicle, redundancy and saturation problem of the integrated control system, and the remarkable parameter varying problem and so on [320−331]. In addition, influenced by the wave of artificial intelligence technology, the design of aircraft control systems based on T−S fuzzy control [174,332−336] and NN control [337,338] has emerged. Due to the space limitations, the above research is not introduced. As a huge subject, several latest research progress of airframe/propulsion integrated control hardly can be completely covered in this study. We only analyse the particularity of this problem from the perspective of engine control.

The above-mentioned studies may passively inherit the limitation of the control-oriented model to describe the mechanism of the airframe/propulsion integrated system. Most of the research focuses on cruise control and neglects the special properties of the hypersonic airbreathing propulsion system. Although the problem of inlet unstart in the X-51A flight test has attracted attention, research on control and optimisation problems has gradually shifted from a single operating point cruise process to an accelerated climb process that spans a wide range of flying Mach. Based on the 3-DOF and 6-DOF integrated models, Serrani et al. [339,340] performed an optimal trajectory planning study for the aircraft to maintain the longest glide time after the inlet unstart within the set flight envelope, and designed a suboptimal trajectory tracker based on an adaptive algorithm. Driscoll et al. considered the problems of inlet unstart and ramjet/scramjet mode transition, optimised the acceleration trajectory to save fuel [341], and found the discontinuity of the thrust in the mode transition [342]. In addition, the variable geometry inlet extends the operation range and improves performance of hypersonic vehicles. Dou et al. [343,344] considered variable geometry inlet in airbreathing hypersonic vehicle model and designed sliding mode controller with fuzzy logic systems. Liu et al. [345] managed a reinforcement learning control for the vehicle with variable geometry inlet to external disturbances and diversified uncertainties.

In summary, early research on the integrated control of hypersonic vehicles is limited by the complicated mathematical model of the propulsion system, which focuses more on solving vehicle control problems. The X-51A flight test has attracted increasing attention from researchers to the control of the accelerated climb process of the airframe/propulsion system. It has also led to research in the past 10 years focussing on the optimisation of the parameters of hypersonic vehicles in a wide range of flight Mach. Compared with the clear development of the airframe/propulsion integrated model construction, the control of the integrated model system shows the difficulty of cross-disciplinary research. It is an important part of the control of hypersonic vehicles to understand and analyse the complex processes of propulsion systems, such as inlet unstart and mode transition.

7. Conclusions

This study is organised according to the important control issues of airbreathing aero-engines, the control of aircraft GTEs, ramjets and scramjets, combined cycle engines, and a hypersonic airframe/propulsion integrated system. First, various advanced control algorithms are mainly introduced in the summary of aircraft GTE control. The discussion of ramjet, scramjet, and combined cycle engine control mainly focuses on specific control issues. By analysing the literature cited in this paper, the research directions of airbreathing aero-engine control that need future attention are as follows:

(1) The use of advanced control methods to further improve the performance of airbreathing aero-engines in a wide range of envelopes should be studied. High-performance engines must have considerable regulation means, which makes the precise modelling of engine control-oriented more difficult and the design of engine control systems more complex. Although control research on aircraft GTEs is more abundant than other airbreathing engines, it is particularly difficult to obtain a controller with the ability of anti-interference, multi-variable regulation and fault-tolerant control in a large flight envelope, and the controller needs to show good control effect. The five air-breathing aeroengine control problems summarised in the article are the basis for ensuring safe and efficient operation of the engine. Each control problem for different types of airbreathing aero-engines should be focused for more in-depth substantive research;

(2) The application of these advanced control algorithms to the actual airbreathing aero-engines control system should be considered. There is a serious disconnection

between theoretical research and practical engineering needs. For the control of aircraft GTEs, there have been attempts of various advanced control algorithms, but they are rarely used in practice. This is also the reason why DCSs, a hardware-biased research direction, have become an important control problem for air-breathing aero-engines. In addition, this problem is not only significant for aircraft GTEs but also for other airbreathing aero-engines. At present, there are few studies on the control of ramjets, scramjets, and combined cycle engines, thus researchers should improve the advanced control algorithm and avoid situations that do not consider actual engineering problems;

(3) For the dual-mode scramjet, control problems such as inlet unstart, combustion mode transition, multi-objective control, and integrated system, which are introduced in detail in this paper, must be faced in the design of the control system. At present, various advanced control algorithms are rarely used in ramjets and scramjets. The reason is that considerable research is still focused on the performance optimisation of key components, and the control design is more in the pre-development stage. Predictably, after solving the design and control problems of key components, the effective control system of scramjets in a wide range of flight envelopes will also become the focus of attention;

(4) In addition to solving the control difficulties faced by each sub-engine such as turbine and ramjet, research on the mode transition of the combined cycle engine is necessary. Establishing an accurate and effective combined cycle engine model and using control methods to solve problems such as thrust pinch that may occur in mode transition are current difficulties. In addition, the combined cycle engine brings a wider flight space owing to its special structure, which also introduces higher requirements for the control system design. In different operating modes, it may be necessary to design different control systems to accomplish different control goals of airbreathing aero-engines through switching control, which leads to new problems in the application of control systems;

(5) Hypersonic airframe/propulsion integrated systems require more attention to special control issues of airbreathing aero-engines. At present, research is focused on the problem of the vehicle. It is a new challenge to design an integrated control system that considers the performance and safety of propulsion by coupling the characteristics of the airbreathing engine into the aircraft model. From the extensive literature review, it can be seen that studies on hypersonic aircraft itself are sufficiently complicated. If we further consider the control problems of various air-breathing aero-engines, the work will be full of challenges.

Acknowledgements

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