Angus Academic Press CSECEE 2025
ISSN: 3007-9640 DOI: https://doi.org/10.70114/acmsr.2025.5.1.P132

Modeling and Closed-Loop Transient Analysis Method of Large Bypass Ratio Turbofan Engine

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Abstract. As the core aerospace power unit, the high-bypass two-spool separate-exhaust turbofan engine, a typical aerothermodynamic coupling system, exhibits strong nonlinearity within the flight envelope due to dynamic changes in environmental parameters and operating modes, with transient control being a research difficulty for involving multi-steady-state switching and fault risks. This paper built its component-level model via the analytical method based on aerodynamic/thermodynamic principles, solving nonlinear common working equations with the Newton-Raphson method; validated against GasTurb, 6 key steady-state parameters had relative errors <2%, and dynamic errors <1.5%. A closed-loop controller integrating steady/transient control and anti-windup was designed: steady state used PI parameter interpolation to control corrected fan speed; transient state adopted high-low select logic to limit fuel commands and coordinate VSV/VBV; output regression suppressed integral windup. Tests showed steady-state tracking error <1% with 2%-3% overshoot, transient rise time ~8s with error <1%, and key parameters safe, supporting engine performance optimization.

Keywords: High-bypass turbofan engine; Component-level Modeling; Closed-loop Control; Variable Stator Vane (VSV); Variable Bleed Valve (VBV).

1. Introduction

In the aerospace field, the turbofan engine, as a core power device, is a highly complex aerothermodynamic coupling system. Within the flight envelope, the engine's operating characteristics exhibit significant nonlinearities as environmental parameters (e.g., altitude, Mach number) and operating modes (e.g., maximum thrust, cruise, afterburner) switch dynamically [1]. A precise control system is crucial for ensuring the engine's efficient operation and unlocking its performance potential.Engine operating states can be categorized into two main types: steady-state and transient-state. Steady-state control needs to suppress disturbances and maintain the target state when external conditions change. Transient-state control covers processes such as start-up, acceleration/deceleration, and afterburner operation. Due to the involvement of multi-steady-state point switching, strong nonlinear characteristics, and the risk of parameter over-limit, it has become a research challenge. Excellent transient-state control must not only unlock performance but also prevent faults such as surge, overspeed, and overtemperature.

Early aircraft engines adjusted their operating states only through single-variable open-loop control of fuel flow. Although simple in structure, this method had low control accuracy. With the improvement of classical control theory and the increasing demand for performance, the application of closed-loop feedback control has significantly enhanced control accuracy and dynamic performance. Among various approaches, N-dot closed-loop control, which adjusts fuel flow based on the rate of change of rotational speed, has become a mainstream solution in Europe and the United States. Jeffrey et al. [2] developed the "Tool for Turbine Engine Closed-Loop Transient Analysis (TTECTrA)", which achieves robust control across multiple operating points using a gain-scheduled PI controller, dynamically adjusting parameters to adapt to different flight conditions. With the development of modern control theory, several methods based on this theory

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have emerged, such as the Linear Quadratic Regulator (LQR) [3]. Howlett et al. [4] were the first to publish a research paper on the application of the LQR method to N-dot closed-loop control. Subsequently, Achgill and Zagaranski [5] also applied this method to the acceleration control of turboshaft engines. When designing and verifying the integration of engine steady-state and transient-state control, Wu Junfeng and Guo Yingqing [6] adopted a PI controller for steady-state control. Lu Jun et al. [7] proposed a dynamic stability method to address the design issue of optimal transient control laws for aircraft engines. Wang Rong et al. [8] put forward a model-based design method for fixed-state control laws. Additionally, Liu Zihe et al. [9] innovatively proposed to establish the full-envelope acceleration control scheme for engines based on the isotherm principle.

In addition, there are other methods for regulating engine status. The Variable Bleed Valve (VBV), located in compressor, is mainly used to regulate the airflow matching between the high-pressure and low-pressure compressors, preventing surge or blade damage caused by flow imbalance during engine acceleration and deceleration. The Variable Stator Vane (VSV) is one of the common anti-surge measures [10]; by adjusting the angle of guide vanes in the high-pressure compressor, it changes the airflow direction and optimizes the airflow angle of attack to adapt to different rotational speeds and operating conditions. The VSV adjustment mechanism uses adjustable single-stage or multi-stage vanes for airflow guidance, effectively increasing the surge margin [11].

This paper focuses on high-bypass-ratio turbofan engines; based on their high-precision models, it centers on VBV, VSV, and closed-loop control design methods, while balancing steady-state accuracy and transient performance to provide support for the performance optimization of aero-engines. The second part involves constructing a component-level model of the twin-spool turbofan engine using a thermodynamic variable specific heat algorithm, and verifying the model accuracy through steady-state and dynamic simulations to ensure the model's reliability; subsequently, the design of the engine's steady-state and transient controllers is carried out, including the control schedules for VBV and VSV. The third part conducts testing and analysis of the controller under different operating conditions to verify the reliability of the control strategy.

2. Methodology

2.1 Modeling Description

The modeling object, as shown in Figure 1, is a two-spool separate-exhaust turbofan engine. The low-pressure (LP) shaft connects the fan, intermediate-pressure compressor (IPC), and low-pressure turbine (LPT), while the high-pressure (HP) shaft connects the high-pressure compressor (HPC) and high-pressure turbine (HPT). The fan outlet is equipped with two ducts, namely the bypass duct and the core duct.

The throat area of the VBV is proportional to the valve position [12], with the valve position ranging from 0 to 1.

$$A_{VBV} = Pos_{VBV} \cdot A_{VBV,0}. \tag{1}$$

When the angle of the VSV changes, the parameters of the high-pressure compressor—including corrected flow rate, efficiency, and pressure ratio—change accordingly [13]. Therefore, these parameters need to be corrected.

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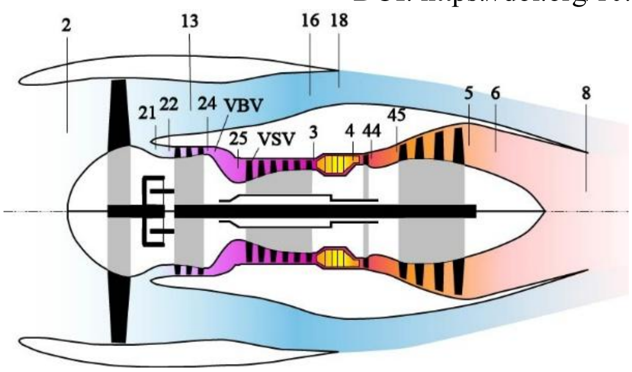

Fig. 1 Schematic diagram of turbofan engine structure

2.2 Model Validation

2.2.1 Steady-State Model Validation

To verify the steady-state accuracy of the engine model, this paper takes the turbofan engine in GasTurb as the reference model, and selects 5 steady-state operating points of the engine. The relative errors between the established engine model and the reference model are plotted based on 6 parameters, namely fuel flow rate at the inlet exit (W_2), total temperature at the fan exit (T_{25}), total pressure at the high-pressure compressor exit (P_3), total temperature at the combustor exit (T_4), total temperature at the high-pressure turbine exit (T_5), and total pressure at the core nozzle exit (P_8), as shown in Figure 2. It can be seen from Figure 2 that the relative errors of the 6 parameters of the engine model are all below 2%, and the relative errors of some parameters are below 1%.

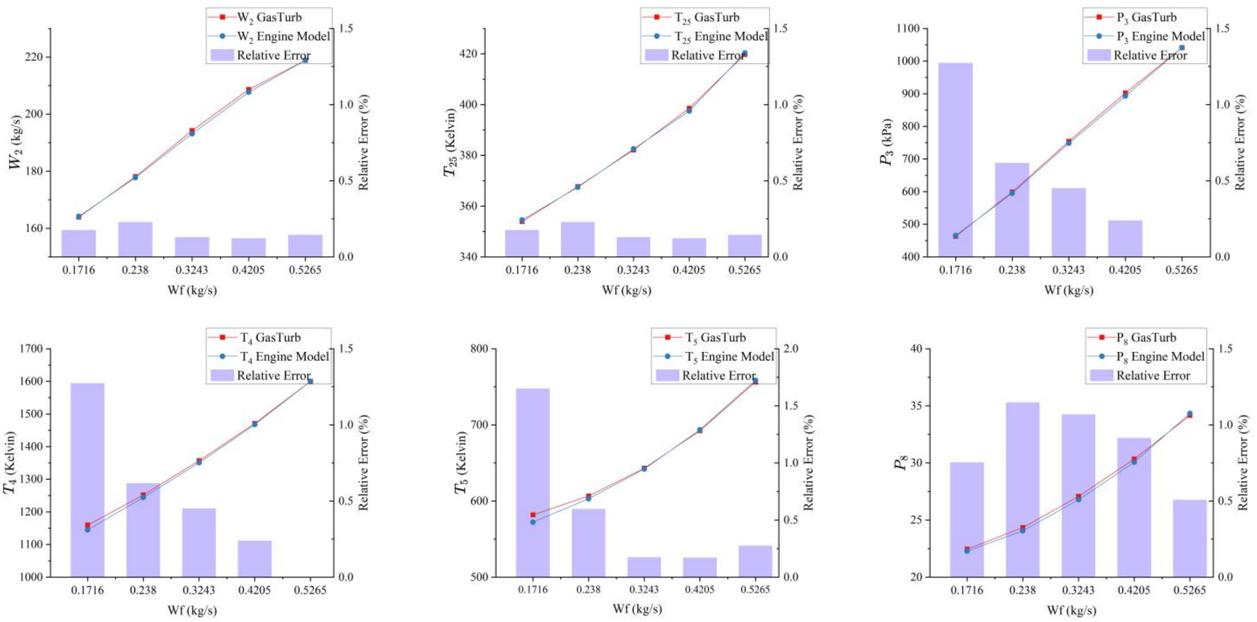

Fig. 2 Steady-state verification results of the engine model

2.2.2 Dynamic Model Validation

To verify the dynamic accuracy of the engine model, the time step is set to 0.1s, and the fuel supply rate varies with time as specified, as shown in Figure 3(a). Figures 3(b), 3(c), 3(d), 3(e), and 3(f) present the time-dependent variations of the following parameters—fan percentage speed (PCNF), high-pressure compressor percentage speed (PCNC), combustor exit temperature (T_4), HPC exit pressure (P_3), and HPC exit temperature (T_3)—for both the GasTurb reference model and the established engine model under the specified fuel supply rate, as well as the relative errors

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between the two sets of responses. It can be observed from the figures that: the relative errors of all parameters do not exceed 1.5%.

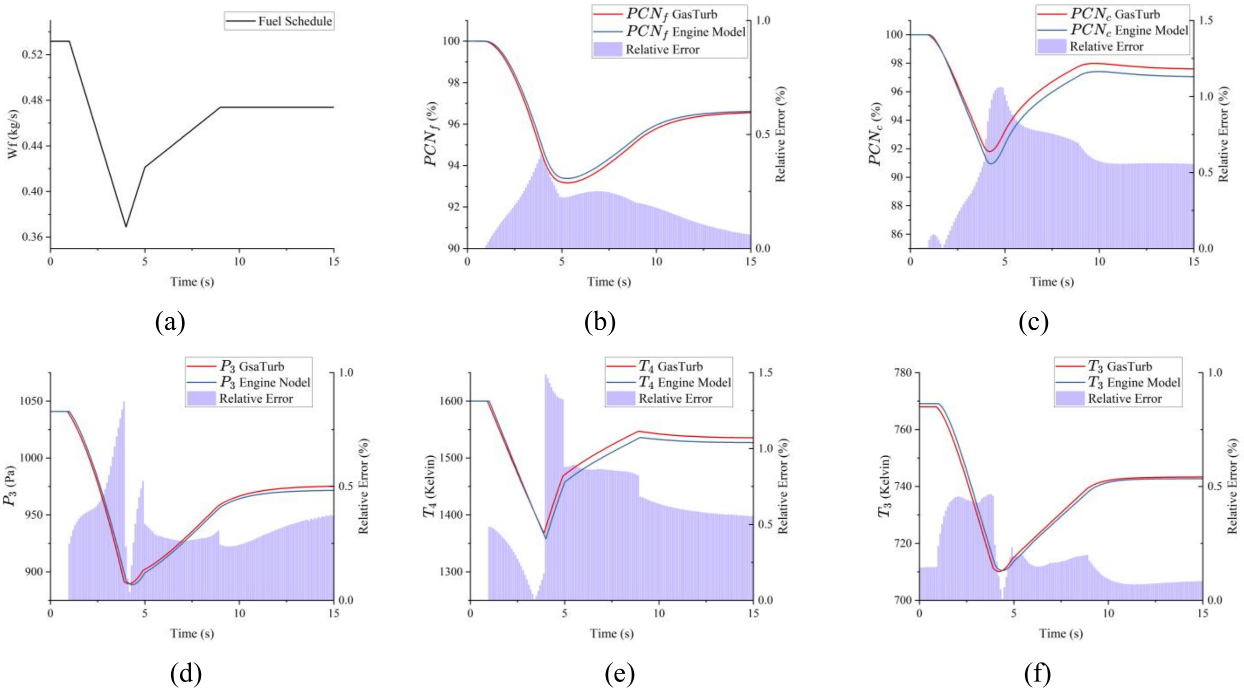

Fig. 3 Dynamic validation results of the engine models

2.3 Controller Design

2.3.1 Controlleler Description

In this paper, fuel flow rate is selected as the sole manipulated variable, and corrected fan speed is chosen as the controlled variable. The structure of the closed-loop controller designed in this paper is shown in Figure 4, and the controller consists of three parts: a steady-state controller, a transient-state controller, and a feedback module.

Among them, the steady-state controller adopts a classical PI (Proportional-Integral) control structure. It takes the error signal between the actual fan speed and the speed command as its input, and outputs the fuel command. The transient-state controller mainly focuses on the engine's acceleration and deceleration processes; it adopts a high-low select logic structure to limit the fuel command, so as to prevent issues such as acceleration over-limit and compressor surge.

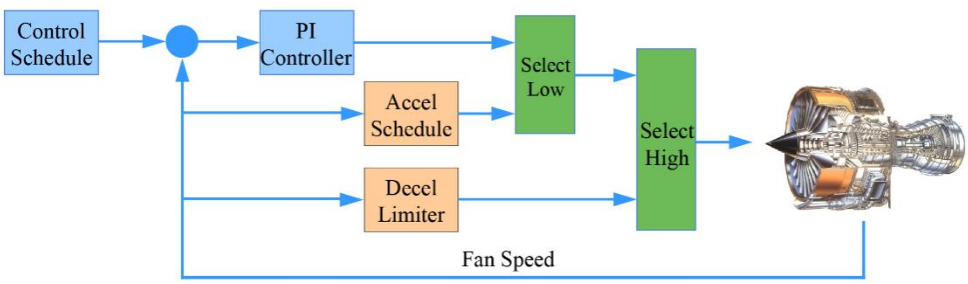

Fig. 4 Closed-loop control system structure diagram

2.3.2 Steady-State and Transient-State Control

Currently, linear control methods remain the most well-developed and maturely applied approaches in aircraft engine control [14]. When designing a steady-state controller, it is necessary to

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study the dynamic characteristics of the engine at steady-state operating points and establish a linear model for "small-deviation" dynamics. The underlying principle is to determine steady-state operating points using key engine parameters, perform small-step linearization around each steady-state point [15], and further establish a piecewise linearized state-space model.

For the multiple linear models established above, the corresponding PI controller parameters are designed respectively to meet the requirements. The unit step response of one operating point is shown in Fig. 5(a), with the rise time being approximately 1.070 s and the settling time approximately 2.005 s. The controller parameters at different operating points are plotted into an interpolation curve, as shown in Figure 5(b). During engine operation, the corresponding controller parameters are obtained via interpolation based on the fan speed.

2.3.3 Transient-State Control

Acceleration limits in the transient state of aircraft engines are key control parameters established to ensure safe engine operation and avoid component damage or performance degradation. These limits involve multiple factors, including thermodynamic, aerodynamic, mechanical, and control aspects.

During engine acceleration, the turbine inlet temperature rises rapidly. If the temperature gradient changes excessively fast, high-temperature components such as turbine blades may develop cracks or deformation due to excessive thermal stress. A rapid increase in compressor speed may lead to flow separation, exceed the surge margin, and cause reverse airflow—even resulting in compressor blade damage in severe cases. A rapid increase in fuel flow may lead to a too lean or too rich fuel-air ratio, which can cause combustion instability or even flameout. Additionally, the engine rotor speed increases rapidly, subjecting the rotor to greater forces and torque. Excessively fast acceleration may lead to excessive rotor vibration (resulting in bearing wear or blade fatigue) or exceeded torque limits (impacting the lifespan of the transmission system).

As shown in Figures 5(c) and 5(d), the controller adjusts VBV and VSV based on the fan speed. The engine's acceleration schedule is presented in Figure 5(e); for the deceleration process, the fuel-air ratio in the combustor is limited to prevent lean flameout.

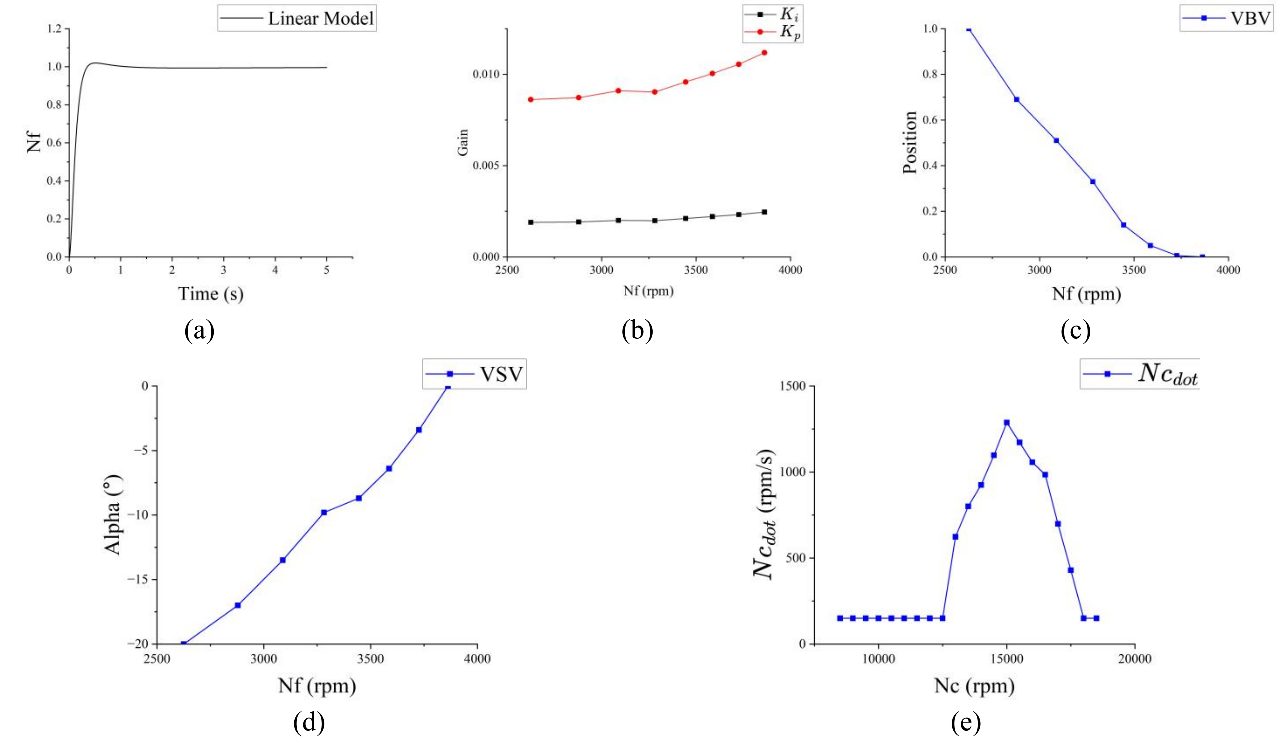

Fig. 5 Controller parameters and control plan diagram

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2.3.4 Anti-Integral Windup

The integral windup problem occurs during controller switching. If anti-windup measures are not applied to the integrators of inactive control loops, it will lead to integral accumulation beyond the expected range, ultimately resulting in abnormal control output and deterioration of the system's dynamic response.

To suppress the integral windup effect, the traditional approach involves constraining the integrators by configuring state switching conditions for controller activation/deactivation [16]. This paper adopts an output regression-based anti-windup strategy, which achieves more precise regulation by dynamically correcting the integral path.

3. Results and Discussion

3.1 Steady-State Controller Testing

When the target thrust increases slightly, the fan speed changes moderately and the engine operating state remains relatively stable. Under this condition, the steady-state controller is activated, while the acceleration/deceleration controller is in a restricted state. A target thrust command curve is given, and the corresponding curve of the controlled variable (i.e., fan speed) is obtained via interpolation. The response data of thrust, fan speed, combustor fuel-air ratio, and compressor surge margin (SM) during the test are plotted in Figure 6.

As can be seen from the figure, the steady-state controller can track the fan speed effectively, with a steady-state error of less than 1% and an overall overshoot of approximately 2% to 3%. During the test, the combustor fuel-air ratio and compressor surge margin are both within the allowable ranges, and the engine maintains stable operating conditions. These results indicate that the steady-state controller exhibits good performance and can meet the requirements for a certain level of steady-state accuracy.

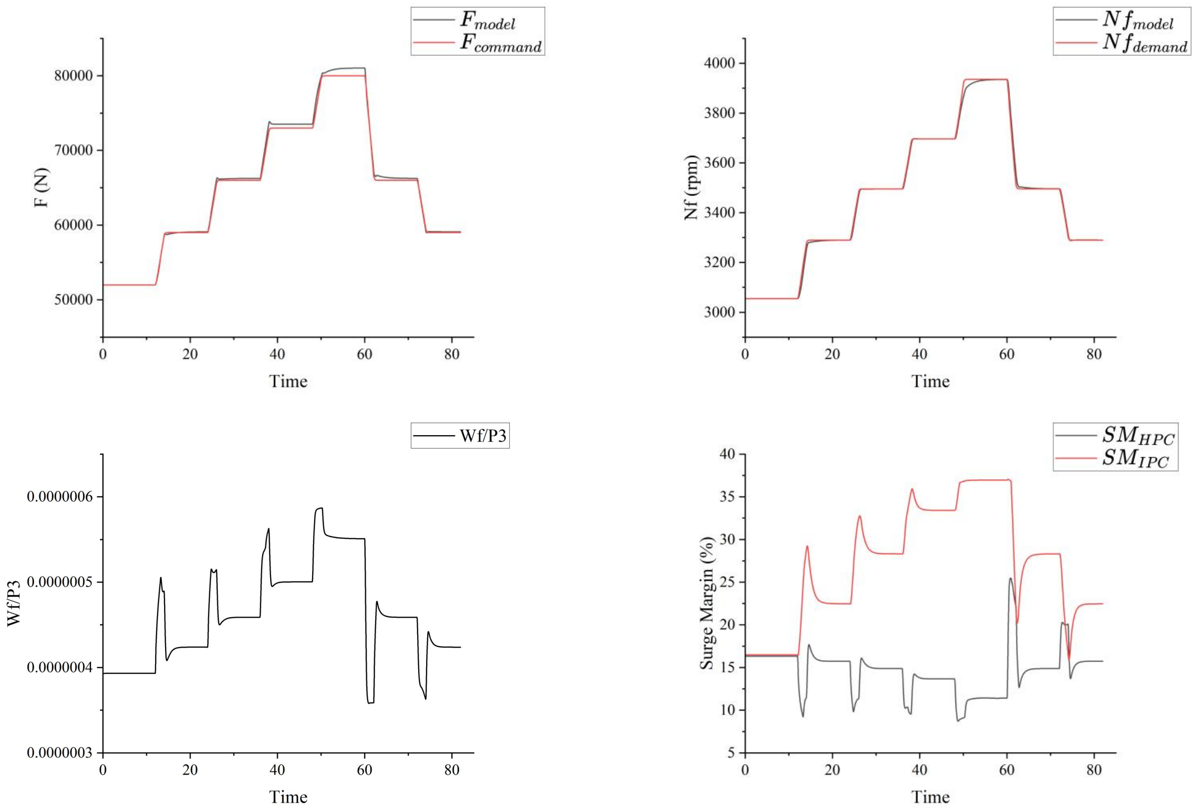

Fig. 6 Steady-state control test results

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3.2 Transient-State Controller Testing

When the target thrust increases significantly, the fan speed changes drastically and the engine operating state undergoes substantial variations. In this scenario, the transient-state controller is activated, while the steady-state controller is in a restricted state. A target thrust command curve is specified, and the corresponding curve of the controlled variable (i.e., fan speed) is derived through interpolation. The response data of thrust, fan speed, compressor surge margin, high-pressure shaft acceleration, and combustor fuel-air ratio during the test are plotted in Figure 7.

It can be observed from the figure that the transient-state controller is capable of tracking the fan speed dynamically, with a rise time of the controlled variable of approximately 8 seconds and a steady-state error of less than 1%. Throughout the test, the combustor fuel-air ratio, compressor surge margin, and HP shaft acceleration all stay within the allowable limits, and the engine operates in good condition. This demonstrates that the transient-state controller possesses a certain level of dynamic tracking capability.

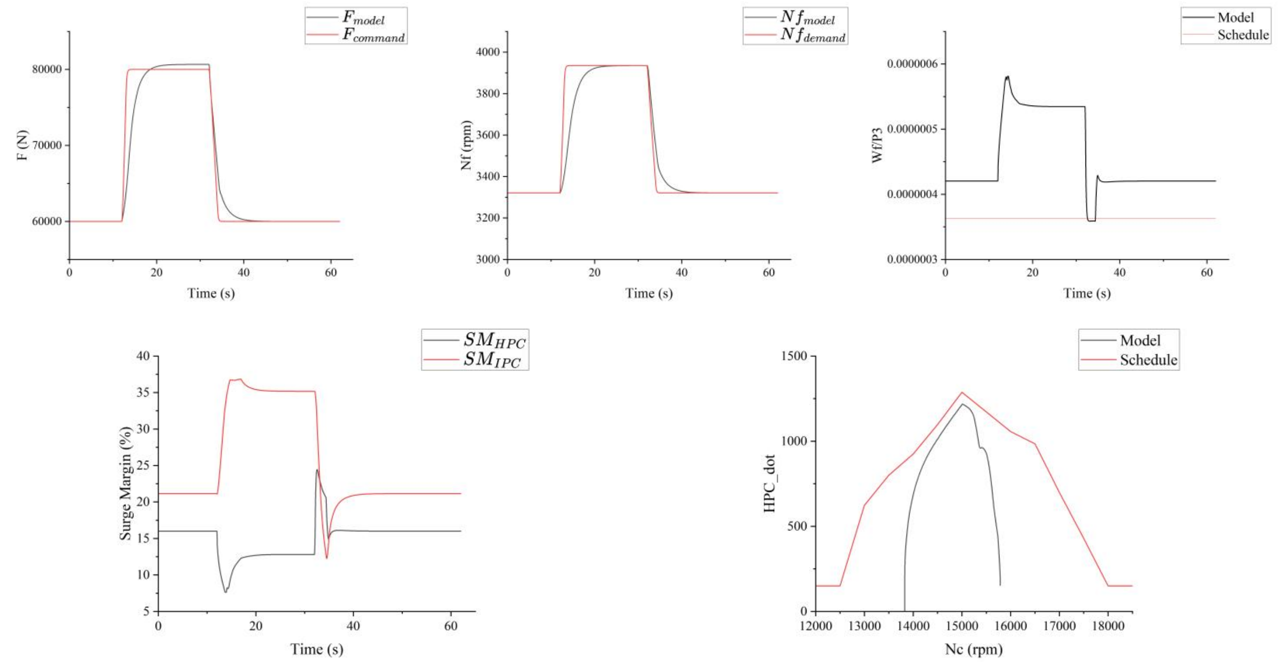

Fig. 7 Transition -state control test results

4. Summary

This paper conducts research on modeling and closed-loop control for the strong nonlinearity and transient control challenges of large bypass ratio twin-spool separate-exhaust turbofan engines: an analytical method is used to construct a component-level model for modeling, constraint relationships are established based on aerothermodynamic principles and nonlinear equations are solved via the Newton-Raphson method, and validation with GasTurb as the benchmark shows that the relative error of 6 key steady-state parameters is <2% and the error under dynamic conditions is <1.5%, meeting accuracy requirements; the controller adopts a "steady-state-transient-anti-saturation" architecture, where PI parameter interpolation curves are used to dynamically match control quantities in the steady state, high-low selection logic is applied to constrain fuel commands and VSV and VBV are coordinated to optimize airflow matching in the transient state, and an output regression strategy can suppress integral saturation; tests indicate that the steady-state rotor speed tracking error is <1% with an overshoot of 2%-3%, the transient rise time is approximately 8s with an error <1%, and parameters such as surge margin and acceleration all meet safety requirements. This study provides support for turbofan engine performance

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optimization, and intelligent algorithms can be integrated in subsequent work to improve wide-envelope robustness.

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