Design and implementation of aeroengine fault data simulation generator

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Abstract

As a core component of an aircraft, once the aeroengine occurs faults, its safety and reliability reduce during the flight. These faults cause unpredictable consequences. Therefore, it is necessary to study how to model the faults of the engine. Based on Simulink software, aeroengine simulation model is established from aeroengine mathematical model which can be derived from aerothermodynamics equations. This paper Simulates various typical faults to aeroengine simulation model, the simulation results show that the designed model can correctly obtain the engine aerothermodynamics export parameters and common faults data, verifying the rationality and effectiveness of the model. The simulation generator provides a visual tool for engine modeling, and supplies data support for aeroengine fault diagnosis and prediction.

Keywords Aeroengine · Simulink · Aerothermodynamics model · Component level modeling · Fault simulation

1 Introduction

The aeroengine is a highly complicated and precise non-linear thermodynamic system, it is the heart of the aircraft. Once the engine fails, it causes a serious threat to the performance and reliability of the aircraft. Therefore, it is of great significance to analyze and research the fault data of aeroengine in order to the safety of the aircraft during flight. Obtaining actual flight data of aircraft engines is difficult and impractical in different situations and various fault conditions. The engine running process can be simulated by this model to get these data, so modeling and simulation of aeroengine are valuable.

Aeroengines have been modeled and simulated by several researchers to obtain their dynamic and steady-state parameter data. Chun-Yang et al. [1] established a mathematical model of the equilibrium manifold of a nonlinear system based on the test data of a turbofan engine. The high-pressure speed is used as the scheduling

variable, and the coefficients of the model are obtained by polynomial least squares fitting. At any time, the similar performance parameters for each state can be obtained with the change law of the high-pressure rotor conversion speed, so as to simulate the turbofan engine. When using the equilibrium manifold model, test data is used as the data foundation. Fei et al. [2] used Matlab/Simulink to simulate the general component-level model of a certain type of twin-shaft turbofan engine. The S function and the algebraic ring problem in the model needed to be solved with Newton–Raphson iteration method, which complicates the modeling process. Foreign literatures on aeroengine mainly focus on the research of turboprop engine model [3, 4] and performance simulation [5, 6]. Due to the structural differences of turboprop engines and the confidentiality of design departments, the relevant literatures about the basic and more accurate aerothermal simulation calculation of turboprop engines have not been consulted [7], so the simulation research on fault data is even less.

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Literature [8], the integrated system is used to model the engine system, and the performance simulation of the engine under various working situations is realized. However, when applied to the 3D/2D interpolation algorithm, a large amount of experimental data is needed, yet it is difficult to obtain a large amount of engine experimental data actually. Literature [9], the CAT-P80 jet aviation gas turbine is used as the research object. The simulation model is established by using Matlab software. The simulation results can accurately reflect the steady-state performance of the gas turbine, but the simulation of the fault data is poverty. Ren Zhibin of Shanghai Jiaotong University [10] modeled and simulated the aero-engine tail nozzle based on Modelica/Dymola software, and realized the performance simulation under non-design speed and small flow conditions. Yao [11] of Nanjing University of Aeronautics and Astronautics used EcosimPro software to carry out component-based aeroengine modeling technology research. Based on a twin-shaft turbofan engine, steady-state simulation and dynamic real-time simulation research were carried out. The simulation results indicates that the engine mathematical model fully meets the real-time requirements and has good stable dynamic simulation accuracy. Sujie et al. [12] of the Institute of Automation, Chinese Academy of Sciences, based on the PROOSIS software to establish aeroengine airway parameter model, obtained the monitoring parameter data under different conditions. Although these softwares are great simple and high precise for modeling different types of aeroengines, this software is not universal and confidential, which is not conducive to scientific research. For aeroengine aerodynamic parameters modeling and simulation, most of the research is only for the simulation data under normal conditions, but few on the fault data simulation.

Due to the generality and openness of Matlab, and the Simulink module library included in the software, the system model can be highly visualized. Therefore, this paper uses the Simulink module library to model the aerothermodynamics equations of various components of the aeroengine and package them as sub-modules, which can realize the visualization of the normal operation process of the engine. The aerothermodynamics equations of the engine components are expressed as Simulink sub-modules, these components include the intake port, fan, compressor, combustion chamber, high pressure turbine, low pressure turbine, mixing chamber and tail nozzle. After sub-modules of these components are built, they are linked together by the common working equation of the aeroengine in the dynamic process, and constrains each other. The simulation parameters, simulation algorithm and other related parameters are set to get the simulation results under the normal operation of the engine. Because it is difficult to obtain the fault data in the process of aeroengine operation, it is crucial to analyze

and study the fault data of aeroengine in the actual process. The fault can be found to a certain extent to avoid the occurrence of the fault situation and the unpredictable disaster. Because of the importance of fault data for subsequent fault trend prediction, this paper obtains different fault simulation results by adding different faults according to different fault environments at the input of the aerothermodynamics model, so as to obtain different fault data.

2 Aeroengine component level simulation modeling

In order to simulate typical engine faults, a simulation model of its normally operating process must be established. In this section, the modeling process of engine component level based on Simulink is given in detail. The modeling methods commonly used in aeroengines are mechanism modeling and identification modeling [13]. Mechanism modeling is used in this paper, is also called component-level modeling. According to the working principle of aeroengine and aerothermodynamics equation [14], the component-level mathematical model is established. The components of the engine are connected together to obtain the dynamic and static characteristics by the common working equations of the engine power balance and flow balance. After the overall modeling of the engine is completed, the export parameter data of each component is obtained by setting the aerothermodynamics parameters and coefficients of the model.

2.1 Aerothermodynamics model and modeling process of each component

Independent component modules are built according to the aerodynamic equations of the aeroengine and its components. Due to the complexity of the aerodynamic thermal process inside the aeroengine, the aerothermodynamics model of each component is packaged as a subsystem module.

2.1.1 Aerothermodynamics mathematical model of the inlet and Simulink simulation module

For the calculation [13, 14] of the aerodynamic force of the inlet, only the case of the flight altitude $H \leq 11.0$ and the Mach number $M \leq 1$, the atmospheric temperature T_0 and atmospheric pressure P_0 are described as Eqs. 1 and 2 respectively.

$$T_0 = 288.15 - 6.5H. \quad (1)$$

$$P_0 = 1.013252 \times 10^5 \left(1 - \frac{H}{44.3}\right)^{5.225}. \quad (2)$$

It is assumed that the inlet is an adiabatic process and σ_1 is the total pressure recovery coefficient of the inlet, thereby obtaining the output parameters of the inlet. Atmospheric temperature T_0 and pressure P_0 are equal to the temperature and pressure entering the entrance of the inlet. When the air flows through the inlet, the temperature T_1 and pressure P_1 at the entrance of the inlet are obtained in Eqs. 3 and 4 [13] respectively.

$$T_2 = T_1(1 + 0.2M^2). \quad (3)$$

$$P_2 = \sigma_1 P_1(1 + 0.2M^2)^{3.5}. \quad (4)$$

The aerothermodynamics equation of the inlet can be modeled in the Simulink environment as Fig. 1.

2.1.2 Fan's aerothermodynamics calculation and Simulink simulation module

Knowing the fan rotating speed n_L and the fan's boost ratio π_{cl} , and the fan outlet pressure $P_{2.5}$, air flow $q_{m,a}$, and outlet temperature $T_{2.5}$ are calculated as Eqs. 5, 6 and 7 [15] respectively.

$$P_{2.5} = \pi_{cl} P_2. \quad (5)$$

$$q_{m,a} = W_{f0} \frac{P_2}{101325} \sqrt{\frac{288}{T_2}}. \quad (6)$$

where W_{f0} is the air flow into the fan.

$$T_{2.5} = T_2 \left(1 + \frac{\pi_{cl}^r - 1}{\eta_{cl}} \right). \quad (7)$$

where $r = (k - 1)/k$, k is the air adiabatic index.

The outlet pressure $P_{2.5ll}$ and temperature $T_{2.5ll}$ of the outer duct of the fan are equal to the outlet pressure $P_{2.5}$ and temperature $T_{2.5}$ of the fan.

The aerodynamic equation of the fan can be modeled in the Simulink simulation environment as Fig. 2.

Fig. 1 Simulation module for the inlet

Fig. 2 Simulation module for the fan

2.1.3 Calculation of aerothermodynamics of compressor and Simulink simulation module

The speed of the high pressure compressor and the pressure ratio of the high pressure compressor π_{CH} are known. The outlet pressure P_3 , air flow $q_{m,aH}$ and outlet temperature T_3 through the high pressure compressor are calculated as Eqs. 8, 9 and 10 [15] respectively.

$$P_3 = \pi_{CH} P_{2.5}. \quad (8)$$

$$q_{m,aH} = q_{m,a} \frac{P_{2.5}}{101325} \sqrt{\frac{288}{T_{2.5}}}. \quad (9)$$

$$T_3 = T_{2.5} \left(1 + \frac{\pi_{CH}^r - 1}{\eta_{CH}} \right). \quad (10)$$

When the high pressure compressor extracts cold air, at this time, the high and low pressure turbines are cooled, and the outlet flow rate of the high pressure compressor should be appropriately corrected.

K_{col} is the high-pressure compressor suction coefficient, then the amount of cooling air extracted from the high-pressure compressor $q_{m,a,col}$ [10] is expressed as Eq. 11.

$$q_{m,a,col} = K_{col} q_{m,aH}. \quad (11)$$

After the cooling air is extracted, the air flow at the outlet of the high pressure compressor is described as Eq. 12 [15].

$$q_{m,a3} = q_{m,aH} - q_{m,a,col}. \quad (12)$$

α_{col} is the pumping coefficient, then the total temperature of the extracted air is described as Eq. 13 [15].

$$T_{col} = \alpha_{col} T_3. \quad (13)$$

Fig. 3 Simulation module for a high pressure compressor

The aerothermodynamics equation of the high pressure compressor can be modeled as follows in the Simulink simulation environment as Fig. 3.

2.1.4 Aerothermodynamics calculation of the combustion chamber and Simulink simulation module

Assume that the fuel flow rate supplied to the combustion chamber the law of change with time.

$$q_{m,f} = q_{m,f}(t). \quad (14)$$

According to the energy balance principle of the combustion chamber, the outlet temperature of the combustion chamber T_4 can be calculated. Its energy balance equation [15] is described as Eq. 15.

$$q_{m,f}H_u\theta_b + q_{m,f}h_f(T_{f0}) + q_{m,f}h_a(T_3) = q_{m,f}h_f(T_4) + q_{m,a3}h_g(T_4). \quad (15)$$

where T_{f0} is the temperature of the fuel entering the combustion chamber. h_a , h_g , h_f are the enthalpy of 1 kg of air, gas and fuel, respectively.

The combustion total pressure recovery coefficient is σ_b , then the combustion chamber outlet pressure P_4 [13, 14] and fuel flow $q_{m,g4}$ are expressed as Eqs. 16 and 17 [15] respectively.

$$P_4 = \sigma_b P_3. \quad (16)$$

$$q_{m,g4} = q_{m,a3} + q_{m,f}. \quad (17)$$

The aerothermodynamics equation of the combustion chamber can be modeled in the Simulink simulation environment as Fig. 4.

Fig. 4 Simulation module for the combustion chamber

2.1.5 Aerodynamic thermal calculation of high pressure turbine and Simulink simulation module

Knowing the expansion ratio of the high-pressure turbine π_{TH} , the outlet flow $q_{m,gH}$, outlet pressure $P_{4.5}$, and outlet temperature of the high-pressure turbine $T'_{4.5}$ are described as Eqs. 18, 19 and 20 [15] respectively.

$$q_{m,gH} = q_{m,g4} \frac{P_4}{P_{4d}} \sqrt{\frac{T_{4d}}{T_4}}. \quad (18)$$

$$P_{4.5} = \frac{P_4}{\pi_{TH}}. \quad (19)$$

$$T'_{4.5} = T_4[1 - (1 - \pi_{TH}^{-r'})\eta_{TH}]. \quad (20)$$

In the formula, $r' = (k' - 1)/k'$, k' is the adiabatic index of the gas.

$K_{H,col}$ is the proportional coefficient used to cool the high pressure turbine in the high pressure compressor suction. Considering that the air flowing into the high-pressure turbine flows into the high-pressure turbine and is mixed with the gas stream, the high-pressure gas turbine outlet gas flow rate $q_{m,H,col}$ and temperature $T_{4.5}$ and the total flow of the high pressure turbine outlet $q_{m,g4.5}$ are expressed as Eqs. 21 [15] and 22 respectively.

$$q_{m,H,col} = K_{H,col} q_{m,a,col}. \quad (21)$$

$$T_{4.5} = \frac{q_{m,gH}T'_{4.5} + q_{m,H,col}T_{col}}{q_{m,gH} + q_{m,H,col}} = \frac{q_{m,gH}T'_{4.5} + q_{m,H,col}T_{col}}{q_{m,g4.5}}. \quad (22)$$

The aerothermodynamics equation of a high-pressure turbine can be modeled as follows in the Simulink simulation environment as Fig. 5.

Fig. 5 Simulation module for a high pressure turbine

2.1.6 Pneumatic thermal calculation and Simulink simulation module of low pressure turbine

The expansion ratio of the low-pressure turbine π_{TL} is known, and the outlet flow $q_{m,gL}$, outlet pressure $P_{s'}$, and outlet temperature T'_5 of the low-pressure turbine are described as Eqs. 23, 24 and 25 respectively [15].

$$q_{m,gL} = q_{m,g4.5} \frac{P_{4.5}}{P_{4.5d}} \sqrt{\frac{T_{4.5d}}{T_{4.5}}} \quad (23)$$

$$P_{s'} = \frac{P_{4.5}}{\pi_{TL}} \quad (24)$$

$$T'_5 = T_{4.5} [1 - (1 - \pi_{TL}^{-r'}) \eta_{TL}] \quad (25)$$

$K_{L,col}$ is the proportional coefficient used to cool the low pressure turbine in the high pressure compressor suction. Considering that the air flowing into the low pressure turbine flows into the low pressure turbine and is mixed with the gas stream, the gas flow $q_{m,L,col}$ and temperature T_5 at the outlet of the low pressure gas turbine and the total flow of the low pressure turbine outlet $q_{m,g5}$ are expressed as Eqs. 26 [15] and 27 respectively.

$$q_{m,L,col} = K_{L,col} q_{m,a,col} \quad (26)$$

$$T_5 = \frac{q_{m,gL} T'_5 + q_{m,L,col} T_{col}}{q_{m,gL} + q_{m,L,col}} = \frac{q_{m,gL} T'_5 + q_{m,L,col} T_{col}}{q_{m,g5}} \quad (27)$$

Fig. 6 Simulation module for low pressure turbine

The aerothermodynamics equations of the low-pressure turbine can be modeled in the Simulink simulation environment as Fig. 6.

2.1.7 Aerodynamic thermal calculation of the outer culvert of the inlet of the mixing chamber and the Simulink simulation module

At the entrance to the mixing chamber, the gas flow $q_{m,g5}$ [16] from the connotation into the mixing chamber is described as Eq. 28.

$$q_{m,g5} = K'_q \frac{P_5 A_{5l} q(\lambda_5)}{\sqrt{T_5}} \quad (28)$$

where A_{5l} is the mixed inlet intrinsic track area. $K'_q = \sqrt{\frac{k'}{R'}} \left(\frac{2}{k'+1} \right)^{\frac{k'+1}{k'-1}}$, k' is the gas adiabatic index, and is the gas constant. From this, $q(\lambda_5)$ can be calculated. In turn, you can solve λ_5 . And because $\pi(\lambda_5)$ is a relation between λ_5 and k' .

At the entrance to the mixing chamber, the pressure $P_{s,5}$ of the outer duct is expressed as Eq. 29 [15].

$$P_{s,5} = P_5 \pi(\lambda_5) \quad (29)$$

According to the mixed entrance, the static pressure of the inner and outer ducted airflow is equal, that is, $P_{s,5II} = P_{s,5}$, which can be obtained [15].

$$\pi(\lambda_{5II}) = \frac{P_{s,5II}}{P_{5II}} = \frac{P_{s,5}}{\sigma_{II} P_{2.5II}} \quad (30)$$

where σ_{II} is the total pressure recovery coefficient of the outlet of the outer culvert fan to the inlet of the mixing chamber. Can solve λ_{5II} . And because $q(\lambda_{5II})$ is a relation

between λ_{5II} and k . In turn, the air flow through the outer culvert $q_{m,all}$ [15] is described as Eq. 31.

$$q_{m,all} = K'_q \frac{P_{5II} A_{5II} q(\lambda_{5II})}{\sqrt{T_{2.5II}}}. \quad (31)$$

where $A_{5//}$ is the area of the outer duct of the mixing chamber inlet.

The aerothermodynamics equation of the outer culvert of the mixing chamber can be modeled in the Simulink simulation environment as Fig. 7.

2.1.8 Aerodynamic thermal calculation of the mixing chamber outlet and Simulink simulation module

The mixing chamber outlet pressure P_{cm} [14] is described as Eq. 32.

$$P_{cm} = \sigma_{cm} \left(\frac{q_{m,g5} P_5 + q_{m,all} P_{5ll}}{q_{m,g5} + q_{m,all}} \right). \quad (32)$$

where σ_{cm} is the total pressure recovery coefficient of the mixing chamber.

The mixing chamber outlet gas flow rate $q_{m,g,cm}$ [14] and total temperature T_{cm} [15] are expressed as Eqs. 33 and 34 respectively.

$$q_{m,g,cm} = q_{m,g5} + q_{m,all}. \quad (33)$$

$$T_{cm} = \frac{c_p T_{2.5ll} q_{m,all} P_{5ll} + c'_p q_{m,g5} T_5}{c''_p q_{m,g,cm}}. \quad (34)$$

where c_p, c'_p, c''_p is the entropy index of air, gas and fuel, respectively.

The aerothermodynamics equation of the mixing chamber exit parameter can be modeled as Fig. 8.

Fig. 8 Simulation module for the mixing chamber outlet

2.1.9 Aerodynamic calculation of the tail nozzle and Simulink simulation module

σ_{NZ} is the total pressure recovery coefficient of the tail nozzle. The aerodynamic thermal process of the tail nozzle, the total pressure P_8 [14, 15] of the nozzle outlet involved is described as Eq. 35.

$$P_8 = \sigma_{NZ} P_{cm}. \quad (35)$$

The total outlet temperature of the nozzle is described as Eq. 36.

$$T_8 = T_{cm}. \quad (36)$$

When the gas expands in the nozzle, the outlet velocity of the nozzle C_8 is described as Eq. 37.

$$C_8 = \sqrt{2C'_p T_8 \left[1 - \pi_{NZ}^{-(K'_q-1)/K'_q} \right]}. \quad (37)$$

The nozzle outlet flow rate $q_{m,g8}$, thrust F [16], exhaust speed v_8 are expressed as Eqs. 38, 39 and 40 respectively.

$$q_{m,q8} = K'_q A_8 P_8 q(\lambda_8) / \sqrt{T_8}. \quad (38)$$

Fig. 7 Simulation module for the entrance culvert of the mixing chamber

$$F = q_{m,g8}(C_8 - C_0) + (P_8 P_0 / P_{cm} - P_0) A_8. \quad (39)$$

$$v_8 = \sigma_{NZ} \lambda_8 a_{cr}. \quad (40)$$

In the above formula, A_8 is the nozzle outlet area, C_0 is the flight speed (0 in the interview vehicle), a_{cr} is the critical sound speed, and when the tail nozzle is in the critical state or supercritical state, the dense flow function can be selected as $q(\lambda_8) = 1$, $\lambda_8 = 1$, P_0 is static pressure.

The aerothermodynamics equation of the tail nozzle outlet parameter can be modeled in the Simulink simulation environment as Fig. 9.

2.1.10 The common working equation of aeroengine and the Simulink simulation module in the dynamic process

After the aerothermodynamics Simulink module of the engine components is built, the components need to work together and be constrained by each other. This restriction exists not only when the engine is stable, but also during the dynamic working of the engine. According to the flow balance and power balance in the dynamic working process of the aeroengine, the common working equation under the common working conditions can be obtained. This paper only considers the influence of engine rotor inertia on the dynamic characteristics of the engine, ignoring the influence of thermal inertia and component channel volume dynamics, and considers that the dynamic process component efficiency and total pressure loss coefficient remain unchanged. The tail nozzle is in a critical state above. Flight conditions are constant. Combustion delays and differences in gas and air flow are ignored.

The four flow balance equations [15] to be followed for the common working equation.

- (1) The air flow of the fan is equal to the equilibrium equation of the sum of the air flow through the high pressure compressor and the air flow of the outer culvert.

$$q_{m,a} - q_{m,aH} - q_{m,all} = 0. \quad (41)$$

- (2) The high-pressure turbine inlet gas flow rate is equal to the equilibrium equation of the sum of the high-pressure compressor outlet air flow and the fuel flow.

$$q_{m,gH} - q_{m,a3} - q_{m,f} = 0. \quad (42)$$

- (3) The equilibrium flow equation between the low pressure turbine inlet gas flow and the high pressure turbine outlet gas flow.

$$q_{m,g4.5} - q_{m,gL} = 0. \quad (43)$$

- (4) The gas flow rate of the tail nozzle is equal to the equilibrium equation between the sum of the air flow through the outer culvert and the gas flow at the low pressure turbine outlet.

$$q_{m,g8} - q_{m,all} - q_{m,g5} = 0. \quad (44)$$

The two power balance equations [15] to be followed for the common working equation.

- (1) High-pressure shaft power balance equation.

$$P_{TH} - P_{CH} - D_H \frac{dn_H}{dt} = 0. \quad (45)$$

where P_{TH} is the high pressure turbine power $P_{TH} = q_{m,g4} \pi_{TH}$, P_{CH} is the high pressure compressor power $P_{CH} = q_{m,aH} \pi_{CH}$, $D_H (dn_H)/dt$ is the dynamic term, the high pressure rotor accelerates the power $D_H = (\pi/30)^2 J_H n_H$.

- (2) Low-pressure shaft power balance equation.

Fig. 9 Simulation module for the tail nozzle outlet

$$P_{TL} - P_{CL} - D_L \frac{dn_L}{dt} = 0. \quad (46)$$

where P_{TH} is the low pressure turbine power $P_{TL} = q_{m,g4.5} \pi_{TL}$, P_{CL} is the fan power $P_{CL} = q_{m,a} \pi_{CL}$, and $D_L(dn_L)/dt$ is the dynamic term, the high voltage rotor accelerates the power $D_L = (\pi/30)^2 J_L n_L$.

The common working equations of aeroengines can be modeled in the Simulink simulation environment as Fig. 10.

2.2 Engine overall Simulink model

After building the Simulink module with the components and the balance relationship they follow, a complete aero-engine model needs to be established. The atmospheric environmental parameters are taken as the entrance parameters of the inlet. After the aerothermodynamics calculation of the inlet, the output is used as the entrance

parameters of the fan, after the aerothermodynamics calculation of the fan, the output is used as the entrance parameter of the compressor, and so on, until the export parameters of the tail nozzle are reached. However, there is also a link between the aerothermodynamics parameters of the different components, as shown in Fig. 11.

3 Simulation and analysis of fault impact

In this section, the aerothermodynamics simulation model of Section II is used. By setting the design point parameters involved in the model, the aerothermodynamics output parameter data of each component under normal operating conditions can be obtained. The fault environment is simulated by adding disturbances or changes to the inputs or models of the aerothermodynamics models of the various components to obtain fault parameter data during engine operation.

Fig. 10 Simulink module of the common working equation

Fig. 11 Engine overall Simulink model

3.1 Simulation environment and parameter setting

In this paper, the overall simulation model is built by utilizing the aerothermodynamics equations of engine components in the environment of MATLAB/Simulink software. Before simulating the Simulink model of the whole engine, it is necessary to set different coefficients, exponents, efficiencies, pressure ratios and expansion ratios involved in the aerothermodynamics model [7, 17], as shown in Table 1. Set the simulation start and end times to 0 and 50 respectively, set the simulation algorithm, select the variable step length Runge–Kutta continuous algorithm, the minimum, maximum step size and initial step size and error tolerance are default [18]. Limit the amount of output data to 10,000, and other parameters are default.

3.2 Simulation output of engine normal working process

After setting the parameters of the model, the parameters of the engine components in the normal working process can be obtained by simulation. In this section, the aerothermodynamics output parameters representing the state change process of compressor, combustion chamber and nozzle are selected. The output parameters of different components are simulated as shown in Fig. 12. The

simulation results are respectively the combustion chamber outlet temperature, and the tail nozzle outlet thrust.

Figure 12 shows the output curve of aerothermodynamics parameters of the compressor, combustion chamber and tail nozzle respectively. The model parameters set in Table 1 are substituted into the aerothermodynamics equations of each component to check the export parameters and models of each component. The output parameters after simulation are basically the same, which verifies the correctness of the model.

3.3 Fault simulation and results analysis based on component level model

Aero-engine is a kind of machine with multiple faults, which is expensive to manufacture. It is vulnerable to external environmental impact and abnormal changes and faults during operation. Because it is very difficult and unrealistic to obtain the fault data during flight, according to the different forms of failure, the fault can be simulated by superimposing disturbances or abnormal changes on the input or middle parts of the components of the aero-engine model established in Section II, depending on the manifestation of the different faults. Then adding faults and observing them at the output of each component,

Table 1 Design point paramaters in aerothermodynamics model

Parameters and coefficients (unit)	Values	Parameters and coefficients (unit)	Values
Height H (km)	3	Gas adiabatic index k'	0.03964
Mach number M	0.7	High pressure turbine efficiency η_{TH}	0.88
Inlet total pressure recovery coefficient σ_I	0.97	High-pressure compressor pumping capacity is used to cool the proportional coefficient of the high-pressure turbine $K_{H,col}$	0.03
Speed of the fan n_L (r/min)	100	High pressure turbine design point temperature T_{Ad} (K)	1100
Fan boost ratio π_{CL}	1.23	High pressure turbine design point pressure P_{4d} (P_a)	123,159
Air adiabatic index k	1.33	Low pressure turbine expansion ratio π_{TL}	2.1
High pressure compressor speed n_H (r/min)	160	Low pressure turbine efficiency η_{TL}	0.78
High pressure compressor boost ratio π_{CH}	2.716	Proportion coefficient for cooling low pressure turbine in high pressure compressor suction $K_{L,col}$	0.04
Compressor efficiency η_{CH}	0.85	Low pressure turbine design point temperature $T_{4.5d}$ (K)	1150
High pressure compressor suction coefficient K_{col}	0.05	Low pressure turbine design point pressure $P_{4.5d}$ (P_a)	110,000
Pumping coefficient α_{col}	0.045	Concentrated channel area at the entrance of the mixing chamber A_{Sj} (m^2)	0.29
Air enthusiasm h_f (kJ/kg)	1.5	Total pressure recovery coefficient of the outer culvert fan outlet to the inlet of the mixing chamber σ_{II}	0.93
Gas enthusiasm h_a (kJ/kg)	1.3	Outside tunnel area at the entrance of the mixing chamber A_{SII} (m^2)	0.29
Fuel enthusiasm h_g (kJ/kg)	1.4	Mixing chamber total pressure recovery coefficient σ_{cm}	0.98
Fuel calorific value H_u (kJ/kg)	42,900	Tail nozzle flow loss coefficient σ_{NZ}	0.93
Combustion chamber total pressure recovery coefficient σ_b	0.95	Tail nozzle outlet pipe area A_8 (m^2)	0.4
High pressure turbine expansion ratio π_{TH}	3	Critical speed of sound a_{cr} (m/s)	316.4

Fig. 12 Component level model export parameter simulation diagram

and obtain the simulation output result of common faults to realize the engine fault data generation.

Because the abnormal aerodynamic thermal parameters contain a large amount of fault information [19], the engine can operate stably in the normal state on the basis of the engine component level model in view of the occurrence of engine failure. At this time, several typical faults of the engine can be simulated by setting up at the input or the middle part of the model. Abnormal disturbances and changes are set at a certain time point to simulate abnormal changes according to the corresponding performance parameters of a fault decrease or increase, so as to simulate the characteristics of the fault and obtain the

changes of aerodynamic thermal parameters of the engine components at the inlet and outlet.

3.3.1 Compressor surge fault simulation

According to the performance of compressor surge fault, the faults are simulated. When surge failure occurs, the abnormal phenomena can be mainly manifested in the change of engine sound from sharp to low, strong mechanical vibration, large fluctuation of compressor flow, engine flame out, or even aerial parking, and the increase of engine exhaust temperature, the increase of exhaust thermometer indication, due to surge into the combustion chamber air. The quantity of gas decreases and the gas temperature at the exit of the combustion chamber rises [20]. Compressor surge is an unstable working state of compressor. It is a phenomenon of low frequency and high amplitude airflow oscillation along the compressor axis caused by the sudden decrease of air flow at the compressor inlet [21]. Therefore, the fault can be simulated by adding a large fluctuation vibration signal to the compressor flow.

In order to simulate the surge failure of compressor, the disturbance or abnormal change can be added to the input or middle part of the aeroengine component level model to simulate the surge failure by understanding the manifestation of the surge failure of compressor. When the compressor surges, two parameters will change significantly, and the flow rate will fluctuate greatly in a certain range. Air separation is the fundamental cause of engine surge, and the compressor temperature will rise to a certain extent. The process of simulating the abnormal change of air flow by adding disturbance at the outlet of fan, that is, the inlet of compressor, is shown in Fig. 13. The occurrence of surge fault will cause the increase of exhaust temperature of combustion chamber. Disturbance can be added to the model of compressor components to increase the exhaust temperature of combustion chamber for a period of time. The abnormal change process is simulated as shown in Fig. 14.

Since the surge failure of the compressor is manifested by a large fluctuation in the air flow, the low frequency and high amplitude air flow oscillation occurs along the compressor axis, and the gas temperature at the outlet of the combustion chamber rises. The simulation results are as follows.

Assuming that a surge fault occurs in the compressor, the simulation results of the flow and temperature changes at the compressor outlet are shown in Fig. 15. The compressor outlet flow oscillates greatly between 20 and 40 s, and the fault simulation ends after 40 s. When surge occurs, the outlet temperature of combustion chamber

Fig. 13 Anomalous variation of compressor air flow

Fig. 14 Simulation of abnormal change of combustion chamber outlet temperature in the case of surge fault

begins to rise from 10 s and then begins to decrease after a period of time.

3.3.2 Simulation of combustion chamber atomization failure

Carbon deposit in combustion chamber, or deformation, crack and block fall of fuel pipe will lead to poor fuel atomization, which is manifested by reduced combustion efficiency [19]. Local high temperature phenomenon may occur in combustion chamber, which may cause abnormal phenomena [22]. Therefore, the faults can be simulated on

(a) Compressor outlet flow oscillates greatly

(b) Outlet temperature of combustion chamber in case of surge failure

Fig. 15 Compressor surge fault simulation

the component-level model of aero-engine by the above-mentioned fault manifestations. The temperature of combustion chamber can be increased slowly from a certain moment. The process is shown in Fig. 16.

The performance of atomization failure from the combustion chamber can be characterized by a local increase in combustion chamber temperature. The simulation results are as follows.

As shown in Fig. 17, the temperature of the combustion chamber increases locally at 30 s to 45 s, and keeps steady state after 45 s, but the relative change of the value is slightly larger, which is consistent with the actual change after the failure.

3.3.3 Tail nozzle thrust drop failure

Bird impact is a common failure phenomenon during aircraft flight, and most of them occur during the take-off and landing phase of the aircraft. Bird impact will cause the thrust of the engine tail pipe to drop, and even cause aerial parking [23]. Therefore, this fault can be simulated by reducing the tail nozzle outlet thrust. The process of nozzle thrust descent can be simulated by simulating the

Fig. 16 Simulation of temperature rise in combustion chamber

Fig. 17 Simulation of local temperature rise in the combustion chamber

fault on the component level model of aeroengine and reducing the nozzle thrust in a certain period of time. The process is shown in Fig. 18.

The performance of the thrust failure from the tail nozzle can be characterized by a sudden drop in the thrust of the tail nozzle. The simulation results are as follows.

As shown in Fig. 19, before the simulation run for 30 s, the thrust of the tail nozzle did not change, the thrust suddenly decreased at 30–38 s, and the thrust increased after 38 s, but its magnitude was slightly smaller than the thrust change, after the actual engine failure, but not completely damaged.

In summary, when the system fails, the aerothermodynamics parameters of the model entrance and exit will change, which will destroy the operational stability of the original system. The simulation results show that the model can simulate the fault environment of the aero-engine well.

Fig. 18 Fault simulation of thrust drop in nozzle

Fig. 19 Simulation of tail nozzle thrust drop failure

4 Conclusion

Based on the aerothermodynamics equation of aeroengine, this paper establishes a component-level model of the aeroengine, including sub-modules of the intake port, fan, compressor, combustion chamber, outer duct, high-pressure turbine, low-pressure turbine and tail nozzle package. And through the common working equation to constrain and link each module, realize the overall model of the engine, and then set the corresponding parameters, add different fault types based on the component level model, and realize the problem that the engine normal and fault data are difficult to obtain, which can provide data foundation for fault diagnosis and fault prediction, and also provide a tool for visual modeling and Simulation of complex systems.

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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