RESEARCH ARTICLE

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Enhancing Aero Engine Design Through Advanced Computer Simulation Techniques

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Abstract

This paper provides a comprehensive review of the application of computer simulation in analyzing the performance of gas turbine engines. It introduces a novel three-tiered approach to simulate jet engine performance, enhancing understanding and optimization of design parameters. Utilizing a specialized computer simulation program, the study investigates the thermodynamic cycle at the design point and assesses performance at off-design points. Results underscore the pivotal role of computer simulation techniques in refining the design and efficiency of turbofan engines, offering significant insights into the development of more advanced gas turbine systems.

Keywords: Performance simulation, Design performance, Off-design performance, Gas turbine engine.

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1 Preface

As everyone knows ,the birth of turbojet engine is an important milestone in the development of modern aviation technology.More than half a century since the birth of turbojet engine,avation gas turbine engine as a technology intensive modern high-tech thermal fluid machinery has developed rapidly.Many aeroengines with high thrust to weight ratio and low fuel consumption have been widely used.Many forms of turbojet engines have been derived,such as turbofan engine,turboshaft engine,turboprop engine and turboprop fan engine [1–3].

The early design, calculation and research of aviation gas turbine engine were based on simple formulas and empirical data and completed by manual calculation. This design and calculation method requires a lot of human resources, has low calculation accuracy, and can not ensure the optimization of engine design parameters. With the rapid popularization and development of computer technology and computational mathematics, As an important research method, computer simulation technology has penetrated into many scientific and technological fields [10–15]. Similarly, computer numerical simulation of aviation gas turbine engine design and calculation has become one of the main technical means in the research field of aviation gas turbine engine [1].

Overall performance computer simulation technology [16, 17] is an important content of aeroengine computer numerical simulation research. In the engine design stage, based on the engine performance computer simulation, the overall performance parameters can be optimized, the engine cycle parameters and component design indexes can be determined, the engine control law can be optimized, and the engine control law can be determined. "In the engine development and use stage, various engine characteristics (height characteristics) can be determined through the engine performance computer simulation, Speed characteristics and throttle characteristics) to conduct aircraft/engine matching research, and quantitatively analyze the impact of various service conditions on engine performance.

By reviewing the research on the computer simulation technology of aviation gas turbine engine performance in the past years, this paper summarizes the research methods and development of engine performance simulation technology from the aspects of mathematical physical model and calculation software. Taking a turbofan engine as an example, using the computer simulation software of engine performance, from the two aspects of engine design and use, It shows that computer simulation technology plays an important role in the development of aeroengine.

2 Mathematical and Physical Model of Computer Simulation of Engine Performance

The establishment of mathematical and physical model of working process of aviation gas turbine engine is the basis of computer simulation of engine performance. Engine mathematical model is about the mathematical relationship between engine design parameters, service conditions and engine performance parameters.

2.1 Description of Thermodynamic Process of Gas Turbine Engine

As the propulsion device of aircraft, aviation gas turbine engine is actually a kind of thermal machinery from the perspective of physics. Its working process parameters and performance parameters are determined by the processes of variable compression, heating, variable expansion and isobaric heat release experienced by its internal circulating working medium (gas). On the other hand, the gas turbine engine is composed of many components. In the working process of the engine, each component must work in coordination. The matching of thermodynamic process and various components is the physical basis of gas turbine engine performance simulation.

Engine performance simulation is generally divided into design-point performance simulation and non-design-point performance simulation.The performance simulation of design point is to calculate the air flow parameters in each main section of the engine and the unit thrust and fuel consumption rate of the engine according to the Mach number (Ma) of flight at the selected design point, flight height and selected engine cycle parameters, including compressor boost ratio, total gas temperature in front of the turbine, boost temperature, bypass ratio, fan boost ratio, etc.It also includes the selection of efficiency and loss coefficient of components, the selection of cold air flow, etc., and determines the total thrust of the engine and the geometrical dimensions of each main section according to the air flow rate of the engine.The mathematical model of engine design point performance is essentially a thermodynamic calculation mathematical model for working fluid in the engine. The main mathematical relationship is the basic relationship of aerothermodynamics. The calculation model is simple [1].

Engine non-design point performance simulation is the calculation of engine thrust and fuel consumption at given flight envelope Mach number, flight height and throttle position.In the calculation and Simulation of engine non-design point performance, besides the service conditions of engine, the output parameters of engine design point performance calculation, the control scheme of engine and the characteristics of engine components under non-design conditions are also known.At this point, in addition to the internal working fluid of the engine must comply with the basic thermodynamic relationship, the working conditions of each component must also be met.Computer simulation of engine performance is developed around non-design point performance simulation.

2.2 Three Levels of Mathematical Model for Engine Performance

Because engine performance calculation needs to know the internal characteristics of each component while the main components of the engine are very complex fluid and thermal machinery, there are often different methods to obtain the characteristics of each component of the engine, according to the differences and complexity of the description methods for the characteristics of each main component of the engine in the overall engine performance simulation.The mathematical model for engine performance calculation can be divided into three levels.

2.2.1 Mathematical Model of the First Level

This engine model describes the performance of the engine by various fitting or empirical relationships. The whole engine acts as a "black box", and the specific working state of each component is not described in the model.Many engine manufacturers use this model to provide users with engine speed, height and throttling characteristics.

2.2.2 *Mathematical Model of the Second Level*

Each component of the engine acts as a "black box", giving the characteristics of each component without describing the detailed working conditions inside each component, and then determining the common working point of the engine according to the common working relationship of each component to complete the engine performance calculation.

2.2.3 *Mathematical Model of the Third Level*

This type of model describes every detail of the flow process of working fluid in the engine. There is no "black box" model in the whole flow path of the engine. Establishing this type of model is the goal of aero-engine numerical simulation at present.

In the above model, the first-level mathematical model can only predict the performance of a specific engine model, which is not suitable for engine design. The second-level mathematical model is a widely used engine performance mathematical model at present. Its characteristic is to select the engine control scheme according to the existing component characteristics.Given the flight conditions and engine operating conditions, and after determining the common operating points according to the common operating conditions of the components, the engine performance parameters and the flow parameters of each main section can be calculated.The third-level mathematical model is still under development due to the enormous amount of work involved in the numerical simulation of the flow process in very complex engine components.

2.3 Thermal Parameter Calculation Model

The specific heat and adiabatic index of gas are both functions of gas composition and temperature. Because the flow of gas in the engine passage changes the gas composition and temperature, in order to calculate the engine performance accurately, changes in the thermal properties of gas must be taken into account, which is commonly referred to as the calculation of variable specific heat.

The calculation of specific heat of air flow inside the engine is completed by iteration, which takes a certain amount of calculation time.In the early stage of engine performance simulation, due to the limitation of computer conditions, many researchers have used the methods of Overdetermined specific heat, average specific heat and sectional average specific heat.Nowadays, with the rapid development of computer technology, such methods have been gradually eliminated.Variable specific heat calculation has become the basic content of various engine performance simulation software.

2.4 Methods for Calculating Common Work Processes

Engine performance calculations are performed sequentially for each component along the gas flow path.Connecting the outlet of the previous component to the inlet of the next component draws the power and flow channels through the engine.The connection point between the exit and the entry is called a "node". Whether it is design point calculation or non-design point calculation, it is part-by-part calculation, which inputs the flight conditions to the engine inlet node and transmits information to the inlet node of each component one by one.When a component is calculated, its outlet gas flow parameters and some component characteristics are transferred to the next node.So, the functions of the system independent variables and the characteristics of the particular components, the air entrainment and the charts, are related to each other.Component calculations produce a set of equations that couple algebraic transcendental equations and partial differential equations.

Due to the restriction of each component in the work and the use of variable specific heat calculation, some parameters for determining the working state of components can not be obtained directly.Therefore, it is necessary to adopt a compact method for calculation of non-design point performance.The appropriateness of the test values can be checked according to the common working conditions that must be met between the components and the selected control scheme.The number of test parameters should be as small as possible and of course the calculation of parameters along the engine flow must be guaranteed. Therefore, when determining the common working point of the non design point of the engine, set the number of parameters to m, and its value is: $x_1, x_2, \cdots, x_m$. Then calculate the parameters along the engine flow. Check whether the corresponding check equation meets the common working conditions and the selected control scheme. If the check equation meets, the working point of each component corresponding to the test value is the common working point of the engine. If the check equation is not satisfied, a set of residual equations is obtained.

If:

$$X = (x_1, x_2, \ldots, x_m)^T$$

Residual quantity Z :

$$Z = (z_1, z_2, \ldots, z_m)$$

Obviously:

$$Z = F(X)$$

This system of equations is a system of multivariate nonlinear equations, which can not be expressed explicitly. Determining the common working point is transformed into solving the equations:

$$F(X) = 0$$

At present, Newton-Raphson method is widely used to solve nonlinear equations in most engine performance calculation software.

For a two shaft and two duct turbofan engine, it is usually necessary to solve the nonlinear equations composed of six residuals. At this time, the nonlinear equations can be written as:

$$E_i\left(V_1, V_2, \ldots, V_n\right)(i = 1, 2, \ldots, 6)$$

If $V = (V_1, V_2, \ldots V_n)$, assume the initial value is

$$V^{(0)} = \left(V_1^{(0)}, V_2^{(0)}, \ldots, V_n^{(0)}\right)$$

When iterating to step K,

$$V^{(k)} = \left(V_1^{(k)}, V_2^{(k)}, \ldots, V_n^{(k)}\right)$$

Then the partial differential equations of nonlinear equations near $V^{(k)}$ are

$$dE_i = \sum_{j=1}^{n} \frac{\partial E_i}{\partial V_i} dV_j (j = 1, 2, \ldots, 6)$$

If the differential is replaced by difference, the above formula becomes:

$$\Delta E_i = \sum_{j=1}^{n} \frac{\Delta E_i}{\Delta V_i} \Delta V_j$$

The above formula can also be rewritten as:

$$\Delta V = M^{-1} \Delta E$$

M is the n-order coefficient matrix $\left(\frac{\Delta E_i}{\Delta V_i}\right)_{n \times n}$;

ΔV is the solution vector;

ΔE is the column vector.

After ΔV is obtained from the above formula, Then the variable value of $K + 1$ approximation is

$$V_j^{(K+1)} = V_j^{(K)} + \Delta V_j$$

Iterate over and over until the error meets the accuracy requirement.

3 Development of Computer Simulation Technology for Engine Performance

3.1 Basic Information

The application of computer numerical simulation technology in the design, development and use of aviation gas turbine engine began in the late 1940s. In 1967, SMOTE/SMITE, the steady-state performance calculation software of turbofan engine developed by NASA research center with the support of the U.S. air force, is the first mature and perfect computer simulation software for overall engine performance. After that, NASA launched the steady-state performance computer simulation software of turbofan engine named GENENG/GENENG2 with multi rotor and multi structure in 1972.DYNGEN, a turbofan engine performance calculation software that can calculate dynamic performance, was launched in 1975. In these calculation software, the variable specific heat calculation method is widely used, and the Newton-Raphson method is used to calculate the common working equation.

Based on the above research work, in the early 1980s, foreign research institutions developed variable geometry engine performance calculation and simulation technology, combined with the performance of engine components (compressor, combustion chamber and turbine)

In the early 1990s, Arnold Engineering Development Center developed the calculation software ATEST [4–8] which can calculate the engine performance under any working condition from zero speed to maximum speed.

The domestic research on computer simulation of aeroengine overall performance began in the late 1970s. At that time, the American GENENG / GENENG 2 and DYNGEN software had been published. Based on these software, domestic researchers successfully developed engine performance calculation software. After more than 20 years of development, especially with the rapid popularization and improvement of computer technology in China, the relatively perfect and mature engine performance simulation software has been successfully applied and developed.

3.2 Basic Framework of Computer Simulation Software for Engine Performance

According to the above mathematical models and calculation methods, the performance calculation software of aviation gas turbine engine is successfully developed by referring to relevant foreign software technology. The software can calculate the design point and non design point performance of single shaft or double shaft turbojet and turbofan engines, and the engine can be mixed exhaust or separate exhaust, The software has been applied to many aviation gas turbine engines in China.

4 Overall Design of Engine Based on Computer Simulation Technology

The overall design of engine is the first step in the development of aeroengine. At this stage, it is necessary to analyze the task of the background machine to be used by the engine. On this basis, the overall performance design of the engine is completed by using computer simulation software, and the overall cycle parameters, control laws and design indexes of various components of the engine are determined.

4.1 Cycle Analysis of Engine Design Point

The purpose of cycle analysis of engine design point is to determine the type and value range of engine. The method is to select the important flight segments of the aircraft, use the engine thermal calculation method and software to calculate the variation law of unit thrust and fuel consumption rate with cycle parameters, and select the best cycle parameter range of each flight segment. Finally, by synthesizing the calculation results of each leg, after comparison and screening, the value range of engine design Mach number, design altitude and cycle parameters are determined.

It must be noted that there are two criteria for selecting the best cycle parameters of the engine: one is low fuel consumption and the other is high unit thrust. However, it can be seen from the calculation results in the figure that the two selection criteria are contradictory. Therefore, the best cycle parameters cannot be selected through cycle analysis, and only the value range of cycle parameters can be given. To finally determine the cycle parameters of engine design point, it is also necessary to calculate and analyze the performance of engine non design point, and select the appropriate cycle parameters after comprehensively weighing various factors such as material, process, reality and feasibility.

4.2 Engine Off Design Performance Analysis

When the engine design point cycle parameters are determined, the purpose of non design point performance analysis is to optimize the best adjustment scheme of the engine and check whether the engine can work normally in the whole flight envelope. The engine off design performance calculation mainly includes height characteristics, speed characteristics, idle characteristics and throttling characteristics.

Obviously, the engine performance is constantly changing with the change of flight conditions, and these changes are not simple linear changes. Therefore, in the process of engine cycle parameter design, we must take into account the engine performance in the whole flight envelope. Sometimes, in order to compromise, the flight conditions of the engine design point are often adjusted to make the engine performance more reasonable in the whole flight envelope. Usually, this process is a complex and time-consuming process, but with the help of computer performance simulation software, the design task can be completed very quickly.

4.3 Control Law Analysis

During the use of the engine, different working states must be realized by controlling one or a group of physical parameters of the engine, such as maximum state, intermediate state, cruise state, etc. Therefore, the selection of control law in the process of engine design has a direct impact on engine performance. Under the general combined control law, the performance of the engine is relatively good. At present, advanced turbine engines generally adopt combined control law.

5 Study on the Influence of Service Conditions on Engine Performance

During the use of aeroengine, many changing factors may be encountered, or the same engine may work in different aircraft models and different service environments. How much impact these different service conditions will have on the performance of the engine is a problem that the engine often encounters and needs quantitative analysis in the process of design and use. Computer simulation software of engine performance is an important technical means to study this kind of problem.

5.1 Calculation of Influence of Non-standard Atmospheric Conditions on Performance

The standard atmosphere specifies the relationship between atmospheric temperature and atmospheric pressure with altitude. However, due to different geographical locations and seasons, the atmospheric temperature changes greatly, and the temperature of the engine environment has a great impact on the engine performance, and the impact of the ambient temperature on the engine performance increases with the increase of flight Mach number. In the past, empirical data correction method was often used to analyze the influence of ambient temperature on performance in engineering practice. Nowadays, the computer simulation software of engine performance provides conditions for this analysis. Based on the computer simulation technology, the analysis of engine performance under non-standard atmospheric conditions can be realized conveniently, quickly and accurately.

With the increase of engine intake temperature, the thrust of the engine decreases! Fuel consumption increased. However, the degree of this effect is different under different flight conditions.

5.2 Reynolds Number

With the expansion of the application range of aeroengine, the change of Reynolds number has a greater and greater impact on the characteristics of engine components. Reynolds number mainly affects the flow capacity and work capacity of compressor and turbine components. When the engine flies at low Mach number at high altitude, the Reynolds number is in the non self mode region, which is far lower than the critical Reynolds number, resulting in serious deterioration of engine performance. Based on the engine performance simulation software, we can know the effect of Reynolds number on engine performance. In addition, because the change of Reynolds number is related to the geometric dimensions of engine components, the influence of Reynolds number will be more obvious for small engines.

5.3 Compressor Bleed

Engine bleed includes two cases: one is for engine turbine cooling, which requires bleed from compressed parts, and the other is for aircraft cockpit and anti ice treatment. The first bleed finally returns to the engine flow channel and is ejected from the engine nozzle. No matter what kind of bleed, it will inevitably cause the loss of engine performance. That is, the engine thrust is reduced and the fuel consumption rate is increased due to air bleed. At different operating points, the engine performance reduction caused by air bleed is different. Under the same flight altitude, the higher the flight Mach number, the greater the impact of air bleed on the engine [9].

5.4 Power Extraction

When an engine is used in an aircraft, it is often necessary to extract power from the engine. This power extraction will inevitably lead to the change of gas thermal process in the engine, which will affect the engine performance. Power extraction has a great impact on the thrust of the engine, which reduces the thrust of the engine, but has no obvious impact on the fuel consumption rate of the engine. In different flight conditions, the same power extraction has different effects on the engine.

To sum up, in the process of engine design and use, it is necessary to comprehensively analyze various factors affecting engine performance in order to ensure the normal operation of the engine in the whole flight envelope.

6 Conclusion

1. By reviewing the computer simulation technology of aviation gas turbine engine performance in the past 30 years, this paper summarizes the research methods of engine performance simulation technology, analyzes the current situation of engine simulation technology, and puts forward the concept of dividing and developing engine performance computer simulation technology according to three levels.

2. Engine design based on engine performance calculator simulation technology can quickly and accurately determine the optimal overall engine

cycle parameters, control laws and component design indexes; Based on computer simulation technology, it can also improve the design efficiency, find out the optimal design parameters and improve the engine design level.

3. Based on computer simulation software, it can accurately quantify the impact of various factors on engine performance, and provide technical support for engine design and users.

4. At present, the second level mathematical model based on component characteristics is widely used in engine performance computer simulation technology. This model can not simulate the detailed working process of each component of the engine; The engine design system with the ultimate goal of engine simulation design needs to develop the engine performance simulation method and software of the third-level mathematical model, which is an important research direction of engine performance simulation in the future.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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