Study on Performance of Hybrid Turbofan Variable-Cycle Engine with Intermediate Series Fan

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Abstract. In this paper, the cycle analysis and installation characteristics of the engine are analyzed, and the variable cycle mechanical structure is designed. The intermediate series fan variable cycle engine moves the fan of the traditional large bypass ratio turbofan engine back to the low and high-pressure compressor connection, so it becomes the intermediate series fan. The fan adopts CDFS (core engine fan) technology and has the characteristics of high speed and a large boost ratio. In front of the fan, the auxiliary air intake of the external culvert is designed, and the intake regulating device is installed to control the airflow of the external culvert and adjust the bypass ratio. The adjustment structure refers to the camera aperture adjustment mechanism and has the characteristics of a continuous adjustable opening and a stable intermediate process. The movement direction of blade adjustment is perpendicular to the direction of incoming flow, and the influence of incoming flow impact on blade movement can be minimized in the adjustment process. It is driven by a hydraulic actuator cylinder and has the advantages of a simple structure and easy realization. A mixed turbofan variable-cycle engine with an intermediate series fan can provide thrust for civil airliners with a flight speed of Mach 0~3 and has good economic performance. The proposed scheme has certain reference significance and value for the development of the next-generation supersonic airliner and the development of a military variable cycle engine.

Keywords: Bypass ratio, variable cycle engine, series fan

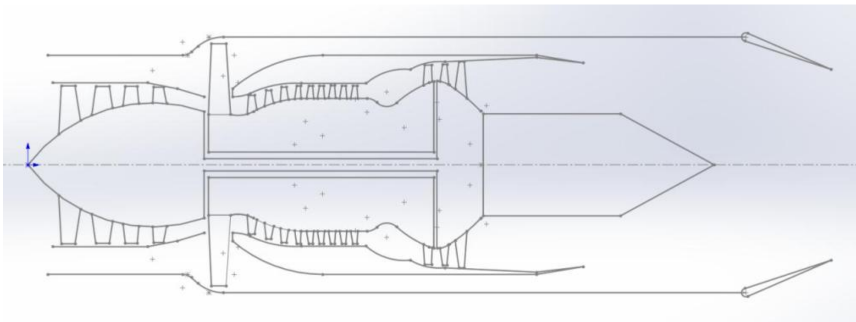
1 Introduction

Turbojet engines and turbofan engines are the types of engines used by current mainstream supersonic aircraft. Under subsonic flight conditions, the fuel consumption of gas turbine engines increases with the decrease in bypass ratio, so turbofan engines can show better fuel consumption performance at low-speed cruise. Under supersonic flight conditions, the fuel consumption of the engine will increase with the increase in bypass ratio. At the same time, the bypass ratio of the turbofan engine will increase with the increase in Mach number. These two factors lead to the deterioration of the fuel consumption performance of turbofan engines during supersonic cruise. Reducing engine fuel consumption and aircraft fuel consumption is of great significance for improving aircraft range and expanding economic benefits. Variable-cycle engine is a gas turbine engine that can fly in a wider envelope by changing the working cycle through the adjustment of variable geometry components. Variable-cycle engine is essentially a kind of aero-engine that can change the bypass ratio by adjusting the geometric components to meet the performance requirements of thrust and fuel consumption in different flight states. There is still a certain gap between domestic and foreign variable-cycle engine technology, which mainly focuses on performance analysis and simulation of variable-cycle engines. Zhou et al. established a mathematical simulation model for the overall performance of a dual-bypass variable-cycle engine and analyzed the control laws of 10 adjustable variables of a variable-cycle engine under typical flight conditions and their effects on installation performance and stability [1]. In the Nanjing University of Aeronautics and Astronautics, a nonlinear component-level model of a dual external bypass variable cycle engine was established, which can simulate the action/steady state and mode switching under the single and double bypass operating mode. The influence of adjustable components on the performance of the whole engine was analyzed, a joint adjustment scheme of multiple components was designed, and a preliminary open-loop adjustment scheme for mode switching was presented [2]. Jia from Northwestern Polytechnical University established the whole engine models of a dual external variable cycle engine and triple-external adaptive cycle engine with key components, studied the flight/engine integration and installation performance, and proposed a new method for optimal design of steady-state control rules [3]. Wang et al. [4], in order to study the variable geometry performance benefits of a single external variable cycle engine, established a simulation model of the overall performance of a single external variable cycle engine, and verified the calculation accuracy of the simulation model through a numerical example. Based on the performance calculation and simulation model of the adaptive cycle engine, Jiang et al. [5] combined the mode conversion and acceleration and deceleration process to realize the rapid thrust change process on the basis of relevant research. According to the mode conversion and acceleration and deceleration control law design, the performance analysis of the transition process of rapid thrust change under typical calculation examples was carried out and the feasibility of the control law design method was verified. Hou [6] summarized the research progress of the most promising combined power, especially the rocket ram combined power, analyzed the technological development characteristics and breakthroughs, and put forward the main development direction of the rocket ram combined engine in the future and the development suggestions of combined power technology. Ren et al. [7] proposed a new conceptual structure for a turboshaft-turbofan variable cycle (TSFVCE) engine for rotary wing VTOL high-speed cruise aircraft, which can operate in both turboshaft and turbofan modes. Wang et al. [8] carried out research on the advance/launch matching problem of adaptive cycle engines and proposed to use the FLADE (Fan on Blade) component unique to adaptive cycle engines to achieve advance/launch matching under sub-supersonic cruise tasks. Yu et al. [9] discussed the development history, layout position, and structural form of the rear bypass ejector of the variable cycle engine, analyzed the structural and functional characteristics of the rear bypass ejector, and pointed out the influence on the aero-thermal performance and structural size of the afterburner, as well as the influence on engine thrust and fuel consumption. Chen et al.

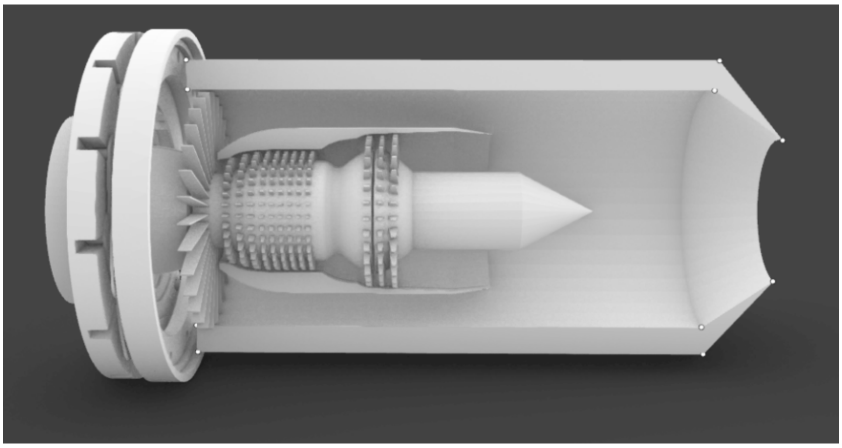
[10] studied the starting control law of double-external-cultural-cycle engines. Based on the component-level modeling method, taking into account variable geometry characteristic processing of adjustable components and low-speed characteristic extrapolation of rotating components, they adopted the flow balance method to construct common working equations and established the mathematical starting model of variable cycle engines.

2 Intermediate Series Fan Variable Cycle Engine Structure

The design scheme is a type of variable cycle engine with CDFS (core engine fan), which is composed of a compressor, series fan, double ring combustion chamber, turbine, and exhaust device, and is equipped with flow channel regulation and combustion regulation device, combined with the characteristics of turbojet engine and large bypass ratio turbofan engine, and has the characteristics of large thrust and low fuel consumption. The core geometric regulating component of the intermediate series fan variable cycle engine is the air intake regulating device of the auxiliary intake valve, which can continuously and stably control the opening of the auxiliary intake port of the engine outer bypass, thereby continuously changing the airflow of the outer bypass, increasing or reducing the engine bypass ratio, changing the cycle state, and realizing the purpose of the engine variable cycle. The regulating device is installed in front of the fan and is integrated with the engine compartment. The MR-01 low-pressure compressor blade does not compress the external bypass gas but adds a series fan in the middle of the high and low-pressure compressor to compress the external bypass air, and the series fan is connected to the high-pressure rotor, driven by the output power of the high-pressure turbine. In addition, the scheme adds a variable geometry engine casing before the series fan, and combined with the series fan, adjusts the intake volume of the external bypass by controlling the opening of the adjustable structure of the casing to change the engine bypass ratio, so as to achieve variable cycle, as shown in Figure 1.



(a) Schematic diagram of the principle of intermediate series fan engine.



(b) Three-dimensional structure diagram.

Fig. 1. Schematic diagram of intermediate series fan engine.

In the small bypass ratio mode, the airflow is divided into two streams after entering the engine inlet. One stream flows into the inner passage, is compressed by the compressor, enters the combustion chamber, burns, and expands in the turbine to work; the other stream enters the outer bypass, is compressed by the fan, and mixes with the first stream at the turbine outlet interface to enter the afterburner. In the high bypass ratio mode, the airflow is divided into three streams, one stream flows into the inner passage from the engine inlet, and the second stream flows into the outer passage from the engine inlet. The third stream flows into the outer passage through the auxiliary intake valve at the front of the fan and mixes with the second stream. After CDFS compression, it mixes with the first stream after combustion expansion, works, and flows into the afterburner together. Finally, it flows out through the tail nozzle.

Compared with the conventional turbofan engine with double bypass, the external bypass air flow rate is adjustable in this scheme, and the bypass ratio is increased by increasing the external bypass air flow rate, reducing fuel consumption, and meeting the thrust performance requirements of the conventional turbofan engine.

3 Estimation of Propulsion System Characteristics

In this paper, the performance of the intermediate tandem engine is estimated to a certain extent. Due to the lack of specific aircraft flight tasks, the component characteristics cannot be completely determined for the time being, and many statistical laws and existing engine statistical estimation models are referred to in the estimation process.

3.1 Installation Thrust Performance Estimation

In terms of propulsion system performance, the installed thrust of the engine is different from the non-installed thrust due to the installation losses of the engine, such as the additional resistance of the intake system, the overflow resistance of the intake system, the boundary layer discharge resistance of the intake system, the friction resistance of the rear body of the exhaust system and the pressure differential resistance. This must also take into account changes in the total intake pressure recovery coefficient and nozzle thrust coefficient, power extraction, external pilot air, intake resistance, and nozzle resistance. The following Equation (1) expresses the relationship between installed and non-installed thrust:

$$F_A = F - F_R - X_{IN} - X_{OUT} \tag{1}$$

where F_A: installed thrust; F: uninstalled thrust; FR: Compressor extraction power; X_{IN}: Intake system resistance; X_{OUT}: Exhaust system resistance.

3.2 Estimation of Engine Size and Weight

The weight and size of the propulsion system have a great impact on the performance of the aircraft, and the weight of the propulsion system in modern aircraft accounts for 7% to 14% of the total weight of the aircraft. The increase in propulsion system weight and impact on aircraft performance also affect life cycle costs, while the size of the propulsion system directly affects aircraft drag. Therefore, in the overall design of the propulsion system, the weight and size of the propulsion system must be estimated. However, in the project design stage, the structure of the propulsion system has not yet been determined, and its dimensions and weight can only be calculated by statistical methods.

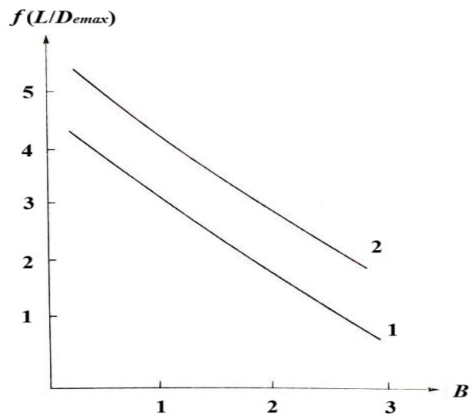


Fig. 2. Statistical curve.

3.2.1. Engine Size Estimation. One of the main parameters that affect the resistance and weight of the aircraft structure is the upwind area of the engine, that is, the maximum cross-sectional area of the engine. The maximum cross-sectional area of the intermediate series fan engine is located in the front section of the series fan, so the maximum cross-sectional area of the engine can be obtained by estimating the engine inlet area and the space occupied by the adjustable mechanical structure According to the results of cycle analysis, the front section diameter of the engine series fan is about 1.29 m. Considering the installation volume of the adjustable structure, the maximum diameter of the engine windward side is estimated to be 1.5 m. Engine length is generally determined by statistical analysis of available engine technical data.

$$L_e = D_{e\max} . f(L / D_{e\max}) \tag{2}$$

where L_e: Engine length; D_{emax}: Maximum engine windward diameter; f (L/D_{emax}): Statistical proportion coefficient. Figure 2 shows a simple example of a statistical curve for f (L/Demax).

3.2.2. Engine Size Estimation. Engine-delivered weight does not include engine accessories. The delivered weight of the engine is related to many factors such as engine thrust, design point cycle parameters, structural form, materials used, and the technical level at that time, so it is very difficult to get an accurate analytical equation for calculating the weight of the engine. At present, there are two widely used estimation methods:

(1) Calculating engine weight by parts. This calculation method can obtain higher precision of engine weight, but because there are many engine parts, it is difficult to know the weight of engine parts in the design stage. Therefore, this method is not suitable for the overall engine design stage.

(2) Using available engine statistics to estimate engine weight. There are many forms and methods of engine weight estimation models established by statistical methods. Moreover, the engine uses involved are different, the focus considered in the construction of the weight estimation structure is different, and the estimation model obtained is naturally different.

Estimation model:

$$W_e = C_t \cdot AFTF \cdot W_{aH} \cdot W_s \tag{3}$$

where C_t is the engine technical level parameter. For the value of the development technology level of different countries and the new technology level adopted in the engine, C_t=0.825; AFTF is the correction coefficient of turbine front temperature, and AFTF can be calculated according to the following equation:

$$AFTF = 0.6867 - 0.0347(T_4 - 1850)/150 \tag{4}$$

where W_{aH} is the design point engine internal airflow; W_s is the engine weight per unit flow and is determined by statistical method. According to the above model estimation and taking into account the weight of the mechanical regulating mechanism of the outer bypass, W_e =2676 kg.

3.3 Estimation of Installed Fuel Consumption

According to empirical estimates, for different engine uses, the installed fuel consumption rate is 5% to 10% higher than the non-installed fuel consumption rate. In the estimation of installation fuel consumption in this paper, this value is taken as 8%. First of all, according to the calculated fuel consumption value of 0.54 kg/(daN·Hr) at the engine design point, the unit fuel consumption rate at takeoff is first simply estimated, and the estimated result is 0.62 kg/(daN·Hr), which can still meet the target requirements.

With reference to the fuel consumption ratio of CJ828 in each flight stage as the weight to estimate the fuel consumption of the intermediate tandem fan engine installation, and the flight altitude of CJ828 combined with the variable cycle characteristics of the engine, the best flight speed and bypass ratio are selected at a given altitude, so as to determine the unit fuel consumption of the engine at this flight altitude. Finally, the weight is brought in to estimate the installation fuel consumption by weighted average. The planned mission is shown in Table 1:

Table 1. Thinking about the mission.

Flight Phase	Flight Altitude (m)	Flight Speed (Ma)	Thrust (kN)	Bypass Ratio	Unit Fuel Consumption (kg/(daN·Hr))	Weight	Average Unit Fuel Consumption (kg/(daN·Hr))
Take-off phase	0-450	0.4	122.4	4	0.62	0.03	1.02
Climb phase	450-10000	0.6	112.0	3	0.84	0.08	
Cruise stage 1	10000	0.7	97.2	4	0.80	0.25	
Stair climb	10000-12000	0.8	105.2	3.5	0.82	0.01	
Cruise stage 2	12000	0.8	95.4	4	0.82	0.2	
Glider stage	12000-4500	0.6	112.0	3	0.84	0.02	
Switching section	4500	0.6	94.7	4	0.79	0.09	
Stand-by stage	450	0.4	122.4	4	0.62	0.07	
Descent phase	450-0	0.4	122.4	4	0.62	0.015	

According to the above estimation method, the estimated result is 1.02 (kg/(daN·Hr), which is a bit too high for a civil airliner. However, it should be noted that when making the above estimation, the gas temperature in front of the turbine is always 1930 K, which will have a great impact on the fuel consumption of the engine. The gas temperature in front of the turbine is not always 1930 K. In the cruise and glide stages of the aircraft, the economic performance of the engine is to be pursued to the greatest degree. The thrust value shown in Table 1 is not needed at this time, and these values are much higher than the actual flight process, resulting in much higher fuel consumption. It is found that the fuel consumption rate in the three stages of cruise, glide, and transition is much lower than the value in the table, which can reduce the unit fuel consumption rate by 40% to 50%, so the final calculation result is corrected, and the correction result is 0.45 (kg/(daN·Hr), which is in line with the current engine performance requirements of civil aircraft. If the aircraft is flying supersonic in the cruise phase, the fuel consumption at maximum speed is 1.19 (kg/(daN·Hr), the speed is Mach 3, the speed is increased by 275%, and the fuel consumption is increased by 46.9%. The data show that the engine solution will make the next generation of supersonic passenger aircraft speed and economic performance improve significantly.

4 Conclusion

In this paper, the next-generation engine design of supersonic passenger aircraft is proposed. The MR-01 proposal provides enough thrust for a supersonic airliner to achieve sea-level take-off and supersonic cruise without an afterburner. Its simple variable geometry channel adjustment mode greatly reduces the difficulty of design and production of variable cycle turbofan engines, and the stable and continuous airflow control mode makes it highly feasible. The proposal of MR-01 provides some reference value for the research of variable cycle engines.

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