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Optimization for the Starting Process of Turbofan Engine Under High-Altitude Environment

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ABSTRACT The control of the starting process for turbofan engine is a difficult task, especially under high-altitude and low-temperature environment, where its characteristics are more complex and strongly nonlinear. In this paper, the working characteristics of the starting process were analyzed and the corresponding mathematical model was established first. In the starting process control problem, since the fuel supply act as the main control parameter, the model of the fuel regulator system was also built. Then, according to the control requirements and combined with models, an optimization expression for minimization of starting time with working and physical constraints was given. The genetic algorithm was utilized to solve the constrained optimization problem and the performance was compared with the classical one that is acquired from actual flight test data. Without exceeding the temperature bound, the starting time can be shortened by about 30%. Moreover, during the unloading process, the starting time in the plateau state and the highest exhaust temperature are reduced by 18.2% $\sim$ 29.3% and 4.7% $\sim$ 8.6%, respectively.

INDEX TERMS Aircraft turbofan engine, starting process, high altitude environment, fuel supply optimization.

I. INTRODUCTION

Modern military and commercial aircrafts is mostly started by a gas turbine starter. Under high-altitude environment, owing to complex air conditions such as the unpredictable wind direction, the thin air and the reduced air density, one of the key issues for aircraft engine is the starting problem. When the aircraft starts, the air mass that flows into the engine is reduced. Hence, the total excess air coefficient decreases, which lead to the rich extinction in combustor of the engine easily. This will result in the difficulty of ignition and increase the temperature after the combustion chamber. Finally, it could cause the overheat of the starter and engine [1]–[4].

The engine starting process of modern aircrafts equipped with turbofan engines is generally divided into three stages. At the first stage, the main combustion chamber of the engine does not supply fuel. The rotor of the engine is driven to the ignition speed by the starter rotor. At the second stage, the main combustion chamber of the engine finishes the ignition with enough fuel. Then, the turbine starts to generate power and the starter turn the engine rotor belt to the minimum balance speed jointly. At the third stage, the engine speed reaches the disconnect speed of the starter. Then, the starter is disconnected and the engine is accelerated to the idle state by the turbine power independently [5]–[7]. Furthermore, with the introduction of some advanced control methods and theories, such as switch control, there are new research directions and possibilities for aero engine control in the plateau conditions [8]–[10].

The starting process of turbofan engine is a complex dynamic process. It is correlated with the starting fuel supply law, the starter power output, the atmospheric environment of the air intake and the electro-hydraulic load (such as the hydraulic pump). In addition, since the engine always start in airport, the noise of engine is also a critical issue.

There are many references related to the engine starting performance in plateau environment. Qiao and Xia [11] studied how to improve the engine starting performance, and pointed out that adjusting the start fuel supply is an effective way. Moreover, Jiang *et al.* [12] and Miao *et al.* [13] investigated the starting fuel supply of a certain type of aircraft engine and analyzed the required fuel supply theoretically. Jiang *et al.* [12] improved the ground starting performance of the engine in a high-altitude platform, especially focused on the adjustment of the fuel regulator. However, all above references did not provide the starting rules and the adjustment method of turbofan engine. Ommi and Azimi [15], Azimi [16], Adam [17], and Azimi *et al.* [18] studied the noise of turbofan engine and its reduction methods.

Usually, the basic control requirements for the engine start-up process includes short start-up time without exceeding temperature limit bound, which is critical for the turbofan engine. The first and second stages of the engine start-up process form the main part of the starting time. The acceleration process in the two stages depends mainly on the starting torque (power) and the starting fuel law. Therefore, in order to adapt to the high-altitude environment, the optimization of engine start fuel supply law is important for improving the success rate of starting.

In fact, the ideal starting process of the turbofan engine can be theoretically attributed to the matching and optimization of the fuel supply law. Moreover, under different environmental conditions, the starter output power of the fuel regulator is also critical. The above studies are mostly based on the theoretical analysis, the practical optimal solution is still unknown.

In this paper, the turbofan engine starting process and the fuel regulator are modeled. Then an optimization approach is provided to adjust the fuel supply in different environments on the plateau. All the proposed modeling and optimization methods are verified by the experiments.

II. CHARACTERISTICS ANALYSIS OF THE ENGINE STARTING PROCESS

The engine starting process is a dynamic process which is the result of the interaction among the power generated by the turbine, the output power of starter and the compressor consumption. During the starting process, engine was accelerated from a stand still state to idle state, it is generally divided into I,II, III three stages and the torque variation of the compressor, the turbine and the starter are shown in Fig. 1.

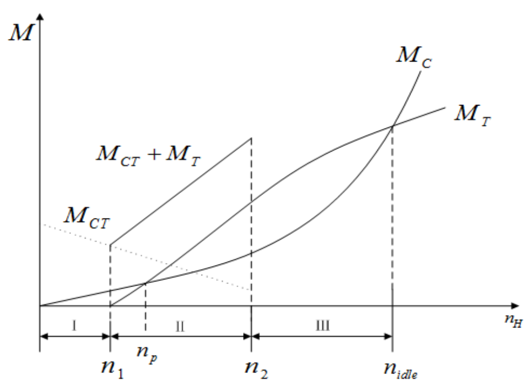

FIGURE 1. The torque characteristics of the engine starting process.

In Fig.1, n_H is the high pressure turbine rotor speed of engine, M is the starting torque of the engine, M_{CT} is the starter torque, M_C and M_T are the engine compressor and turbine torque respectively. n_1 is the engine ignition speed, n_2 is the disconnection speed of the starter, n_p is the minimum balance speed of the engine, and n_{idle} is the idle speed.

A. STAGE I: THE STARTING BELT PHASE

The starter drives the high pressure turbine rotor of the engine up to the ignition speed n_1 when the turbine starts working. At this stage the output torque of the starter is greater than the torque required by the high-pressure compressor to accelerate the engine high-pressure rotor. The torque balance equation for this stage is

$$M_{CT} - \frac{M_C}{\eta_m} = J\frac{d\omega}{dt} \tag{1}$$

The starter torque required at this stage is

$$M_{CT} = \frac{W_a L_C}{\omega \eta_m} + J\frac{d\omega}{dt} \tag{2}$$

Where ω is the rotor angular velocity, J and η_m are the moment of inertia and mechanical efficiency of the rotor respectively, and W_a and L_c are the compressor mass flow and power respectively.

B. STAGE II: ENGINE IGNITION STAGE

The period from the combustion chamber ignition speed n_1 to the starter disconnect speed n_2 is the Stage II of the engine starting process. With fuel ignition, the turbine is put into operation, and the engine is supplied with fuel according to the control plan as the speed increases. At this stage, the power generated by the turbine companied with the power of the starter is greater than the power consumed by the compressor. Turbine inlet temperature is mainly restricted by the allowable values of the high pressure compressor surge boundary and the maximum turbine inlet temperature $T^*_{4\max}$. Usually it is kept as this value.

At stage II, the turbine power increases rapidly as the speed increases. When the engine high pressure turbine rotor speed is greater than the minimum balance speed, the turbine power has been greater than the power consumed by the compressor. At this time, theoretically, the turbine can be driven only by the turbine, and the starter can be disconnected. However, in order to reduce the starting time and ensure the reliable starting of the engine, in general, the starter continues to rotate until the high pressure turbine rotor reaches n_2. When the turbine power is greater than the compressor power, the starter stops working.

The equation of the torque balance at this stage is

$$M_{CT} + M_T - \frac{M_C}{\eta_m} = J\frac{d\omega}{dt} \tag{3}$$

C. STAGE III: THE STAGE WHEN THE STARTER IS OFF

The third stage is the process when the high pressure turbine rotor speed rises from the speed n_2 to the idle speed n_{idle}. At this stage, the rotor acceleration is carried out by the residual power of the turbine, and the rotor angular acceleration is maximized. When the speed is reach to the engine idle speed, the control system reduces the remaining amount of fuel so that the rotor angular acceleration gradually decreases to zero, that is the system achieves a stable idle state and the engine running at idle state.

The engine working line in the whole start-up process shows in Fig. 2, along the curve labeled by 0-1-2-3.

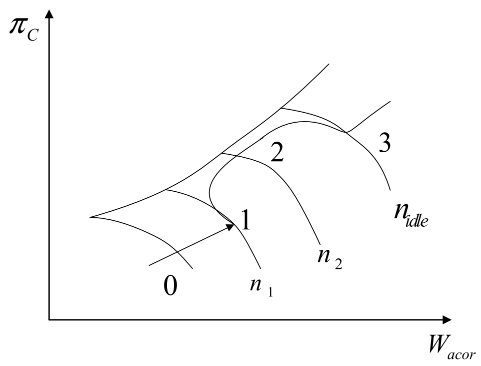

FIGURE 2. **Schematic diagram of the engine working line during the whole start-up process.**

III. MODELING AND SIMULATION OF THE ENGINE STARTING PROCESS

A. MODELING OF THE ENGINE STARTING PROCESS

1) START MODELS OF THE FIRST STAGE

The analysis of the starting process shows that the engine in the first stage is only driven by starter power with the high pressure turbine rotor such that the rotation speed is accelerated from zero to the ignition speed. The dynamic model is as follows.

$$\frac{dn_H}{dt} = \left(\frac{30}{\pi}\right)^2 (N_{CT} - N_C/\eta_m) / (n_H \cdot J_H) \tag{4}$$

2) START MODELS OF THE SECOND AND THIRD STAGES

The second and third stages of the engine start process are characterized by the fact that the combustion chamber has begun to work, the difference is that in the second stage the starter is still carried while in the third stage the engine is operating independently. The method of component can be adopted according to the principle of the joint operation. The difference between the two phases in the model is whether the power balance equation of the high pressure shaft increases the power of the starter.

To be more specific, the dynamic equation of the high pressure turbine rotor is

$$\frac{dn_H}{dt} = \left(\frac{30}{\pi}\right)^2 (N_T + N_{CT} - N_C) / (n_H \cdot J_H) \tag{5}$$

3) STARTER CHARACTERISTICS

The characteristics of the starter are important for the engine starting model, which can be determined by the magnitude of the torque and power provided to the engine. Usually for the characteristics of the starter, its torque characteristics are given, based on which the power characteristics can be deduced. The torque generated by the starter changes as the speed changes. A large number of experimental results have shown that, for the gas turbine starter, the output torque (converted to the engine high pressure turbine rotor) and the engine high pressure turbine rotor speed demonstrated approximately a linear relationship.

$$M_{CT} = M_{CT,0} - C \cdot n_H \tag{6}$$

Where C is a constant if the ratio of the starter shaft to the engine axial transmission is fixed for a given type of starter.

The torque characteristic of the starter can be used to derive the power characteristics of the starter:

$$N_{CT} = M_{CT} \cdot \omega = \frac{\pi}{30} \left(M_{CT,0} - C \cdot n_H\right) n_H \tag{7}$$

4) THE STARTING LOAD OF THE AIRCRAFT

On the airplane, in order to control the rudder and the landing gear, it is necessary to provide a hydraulic source at the start of the engine. The engine attachments are usually attached to the engine high pressure turbine rotor via a gear box. During the starting process of the engine, the hydraulic source does not relate to the aircraft work. But for the engine, it is treated to be a starting load. If the load is removed during the starting process, it can accelerate the starting speed of the engine.

5) RESTRICTED PARAMETERS

Limit the maximum turbine inlet temperature, surge margin and so on.

B. THE ENGINE START FUEL REGULATOR MODEL

In the above engine starting model, the core parameter that affects the starting process is the starting fuel supply, especially in start stage II and III, which is determined by the fuel regulator according to the environmental conditions and the running state of the engine. We can adjust the parameters appropriately through the adjusting screws on the fuel regulator. In order to explore the most suitable fuel supply pattern in the low altitude environment, in this section the model of the starting fuel regulation system is analyzed.

The principle and structure of the typical starting fuel regulator is shown as Fig. 3.

The fuel supply of the engine starting process is composed of two lines. One is the fuel flows through the throttle switch of the main pump and the slow-moving valve. After the automatic starter releases the fuel control, it enters the main auxiliary fuel line and the combustion chamber. The other is the fuel flow does not go through the throttle switch after through the main pump in the regulation of the fuel. Then the fuel flows through the fuel valve and directly goes into the auxiliary fuel line and the combustion chamber.

The operating principle of the starting fuel regulator is to adjust the fuel flow of the low pressure through the nozzle baffle, and control the actual fuel supply by adjusting the fuel volume of the fuel chamber. At the beginning of the starting process, the pressure after the compressor is low,

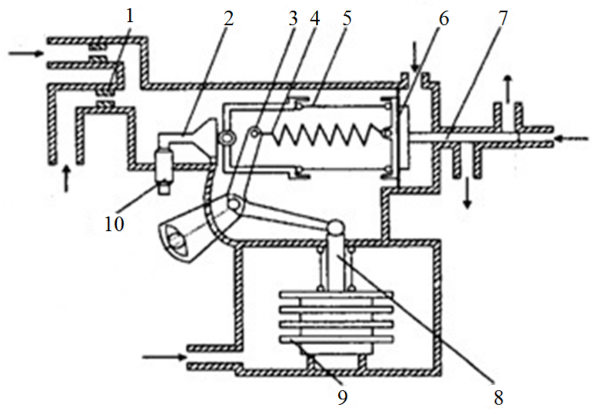

FIGURE 3. **The principle and structure of the typical starting fuel regulator. 1. Limit orifice 2. Adjust lever 3. L- lever 4. Sping 5. Spring Adjust lever 6. Spring seat 7. vavle 8. Push lever 9. Governor bellows.**

the fuel pressure acting on the left side of the nozzle of the fuel regulator is higher than the spring force and the air pressure acting on the right side of the baffle. The nozzle baffle is opened, and pushed the fuel in the throttle switch and part of the fuel line after the slow valve into the low pressure chamber. At the end of the starting period, with the increase of the speed, the pressure of the compressor is increased. The nozzle baffle is gradually shut down. The idle fuel flows through the throttle switch and the idle door fully, and then enters the engine.

When the engine starts, the throttle lever is in the slow position, and the engine is driven by the turbine to drive the high-pressure rotor. At the beginning of the starting period, the air pressure after the high and low pressure compressor is very small. Under the influence of the fuel pressure on the right side, the plunger valve pushes the film to the left. The plunger valve opens the fuel return fuel circuit after the throttle switch, so that parts of the fuel adjusted by the quantitative switch return to meet the requirement of less fuel in the initial stage. At this point, the amount of the returned fuel depends on the force of the spring acting on the film. With the increase of the high pressure turbine rotor speed, the air pressure of the high and low pressure compressor gradually increases. The partial pressure after the high pressure compressor in the left cavity of the film increases, which makes the ejector bar move right, reduces the fuel return after the throttle switch, and increases the starting fuel supply to the combustion chamber. When the engine high pressure turbine rotor speed reaches 40%, the air pressure after the high-pressure compressor pushes the valve rod to move right through the film. It completely cuts off the return circuit after the throttle switch, so that the quantity of fuel supplied by the quantitative switch completely goes into the combustion chamber. The start fuel regulator stops working, and the starting process of the engine is controlled by the accelerator regulator.

The mathematical model of starting fuel regulator is obtained according to the following continuous equation of the flow and the force balance equation.

1) THE MATHEMATICAL MODEL OF THE FILM

$$F = \frac{\pi}{16}(p_3 - p_6^*)(D_1^2 + 2D_1D_2 + D_2^2) \tag{8}$$

where p_3 is the air pressure of the left cavity of the film, p_6^* is the air pressure after the low pressure compressor, D_1 is the outer diameter of the film, and D_2 is the diameter of the film center.

2) THE MATHEMATICAL MODEL OF THE PRESSURE RELEASE VALVE

$$p_3 = \frac{A_a^2 p_2^* + A_b^2 p_6^*}{A_a^2 + A_b^2} \tag{9}$$

$$p_2^* = C_{n1} n_2 \tag{10}$$

$$p_6^* = C_{n2} n_2 \tag{11}$$

Where A_a, A_b are the circulation areas of the limited flow nozzle (1) and (P40) respectively, and p_2^* is the air pressure after the high-pressure compressor.

3) THE MATHEMATICAL MODEL OF THE EJECTOR VALVE

$$Q_y = C_y \pi d(x_0 - y)\sqrt{\frac{2}{\rho}(p_s - p_y)} \tag{12}$$

where Q_y is the return fuel of the valve port, p_s is the quantitative adjustment of the fuel pressure, p_y is the fuel pressure after the back of the valve, C_y is the flow coefficient of the valve, d is the diameter of the valve rod, y is the displacement of the valve stem (the output displacement of the film), and x_0 is the initial opening of the valve port.

According to the above model, there exist

$$p_{s0}A_1 = F_0 + K_{y1}x_{20} - K_{y2}x_{30} \tag{13}$$

$$F(s) = (M_y s^2 + Bs + K_{y2} + K_{y1})Y(s) + A_1 P_s(s) \tag{14}$$

$$p_s = C_{n3} n_2 \tag{15}$$

where p_s is the fuel pressure at the start of the throttle valve back to the fuel, and A_1 is the area of the fuel pressure on the right side of the valve, F0 is the output force of the film at the beginning of the start, K_{y1} is the stiffness of adjusting spring (5), x_{20} is the pre-compression of adjusting spring (5), K_{y2} is the stiffness of spring (4), x_{30} is the pre-elongation of the tension spring (4), M_y is the equivalent mass of the valve and the film, B is the viscous damping coefficient, and F is the output force of the film.

The mathematical models of the above-mentioned thin film, the pressure release valve, and the ejector valve can be used to derive the structure of the mathematical model of the fuel regulator when the engine starts (i.e., the high turbine rotor speed is less than or equal to 40%), which is shown in Fig. 4.

IV. SIMULATIONS OF THE ENGINE STARTING PROCESS

The above two parts analyzes the calculation method of the engine starting process modeling. In the case of a given starting fuel and starter input power, the core of the model is

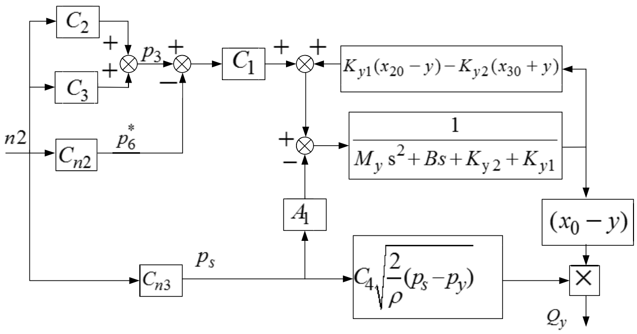

FIGURE 4. The structure of the starting fuel regulator at engine starting.

equivalent to solving the co-operation equations of (4) – (7) in the engine starting phase.

From the mathematical point of view, the starting model can be converted to solve the nonlinear implicit equations including differential equations. The equations could be solved by the Newton-Raphson method. The differential equations of the speed are calculated by the improved Euler method as shown in the following equation.

$$n^{(k+1)} = n^{(k)} + \left(1 + \frac{n^{(k)}}{n}\right) \dot{n}^{(k)} \Delta t \tag{16}$$

where $n^{(k)}$, $n^{(k+1)}$ are the rotor speed of current sampling time and next sampling time.

Simulations are run on a turbofan engine under the ground standard atmospheric conditions. The starting fueling speed of the combustion chamber is 15%, the disconnect speed of the starter is 53%, and the compressor surge margin should be less than 10%. The simulation results of the starting process are shown in Fig.5- Fig. 7.

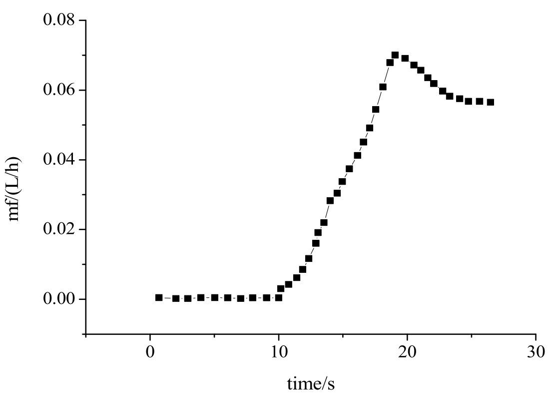

FIGURE 5. Fuel supply varies over time.

Fig. 5 - Fig. 7 present the variations of the main parameters of the engine during the starting time. It can be seen that the temperature of the turbine before the first stage is very low, which is similar to the outlet temperature of the compressor; the rotor speed of the high and low pressure is very low; the combustion chamber does not start the fuel supply ignition, and the fuel supply is zero.

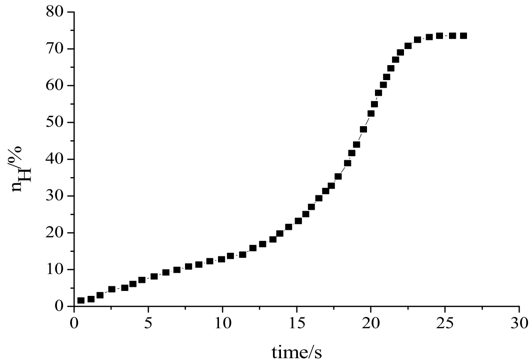

FIGURE 6. The high pressure turbine rotor speed overtime.

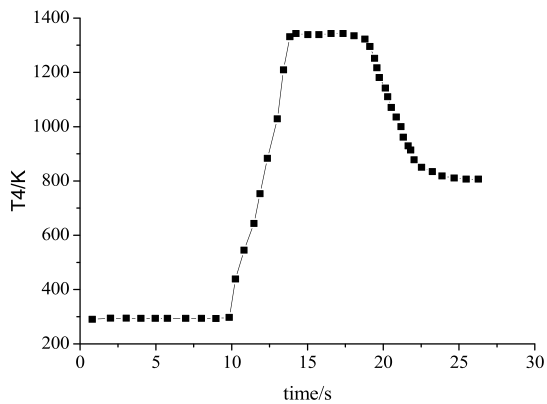

FIGURE 7. Changes of the temperature T4 in the turbine entrance over time.

In the second starting stage, the rotation speed of the high and low pressure rotor increases rapidly, and the temperature before the turbine rises sharply, reaching the maximum, and the fuel supply rises rapidly.

In the third phase, the high pressure turbine rotor speed increases slowly, while the low voltage rotor speed still increases rapidly. The temperature before the turbine keeps the maximum value for some time and then drops rapidly.

V. OPTIMIZATION OF THE ENGINE STARTING FUEL SUPPLY

A. THE OPTIMIZATION MODEL

Based on the above analysis, we can see that adjusting the screw can change the pre-tightening force of the spring on the left side of the starting fuel regulator film. Then it changes the engine starting fuel supply, and hence adjusts the engine starting time. The starting performance of the turbofan engine is characterized by the full start-up time (the time elapsed from pressing the start button to the high pressure turbine rotor speed n_H reaching the specified speed). Within the specified range, the smaller the value of full start-up time, the better the starting performance. The starting time can be calculated as follows:

$$t_{st} = (\frac{30}{\pi}) \int \int_0^{n_H^*} \frac{J}{\Delta N} n_H dn_H \tag{17}$$

where J is rotor moment of inertia, and ΔN is extra power of rotor. Therefore, in order to achieve the desired starting process in the low altitude environment, it boils down to the following problem: adjusting the fuel regulator, changing the fuel supply law of the starting process, and without causing overheating and surging, thus minimizing the starting time. The specific optimization model can then be described as follows.

The objective function of the optimization problem:

$$min\ t_{st} = (\frac{30}{\pi}) \int \int_{t_0}^{t_f} \frac{J}{\Delta N} n_H dn_H \tag{18}$$

Where t_0 and t_f are the start and the end times of the starting process respectively.

Constraints: The turbine inlet temperature is not exceeding a specified temperature

$$max(T4) \leq T4_{max} \tag{19}$$

The high pressure compressor does not surge

$$min(SMC) \geq SMC_{min} \tag{20}$$

The controlled rotor speed does not over speed

$$max(nh) \leq nh_{max} \tag{21}$$

The combustion chamber is not greased

$$max(far) \leq far_{max} \tag{22}$$

B. OPTIMIZATION METHODS

The genetic algorithm is an optimization algorithm based on the biological evolutionary principle. It is especially suitable for nonlinear multivariate implicit optimization problem, which is widely used in engineering [26], [27].

The genetic algorithm generally includes five steps: individual coding, generating initial population, fitness calculation, repeated artificial genetic selection, crossover and mutation operation according to a given genetic probability, and the optimization termination conditions test. In this paper, the genetic algorithm is utilized to solve the above optimization problem, in order to obtain the optimal fuel supply law. In the above five steps, the individual uses the binary coding. The selection, crossing, and mutation are respectively using roulette wheel method, a little crossover and uniform mutation. In addition, when the optimal individual fitness of multiple consecutive generations does not change the termination condition is satisfied. Based on the mathematical model of the starting process, the optimization process algorithm is shown in Fig. 8

C. EXPERIMENTAL DATA PROCESSING METHODS

The ground starting test is carried out based on a type of aircraft equipped with a turbofan engine at an airport of 2900m altitude. The relative time and relative temperature are obtained by non-dimensionalizing the maximum allowable time t_s and the inlet ambient temperature t_0, which are data derived in the standard atmospheric condition at the altitude in the start process.

TABLE 1. Conditions of the starting fuel supply in the plateau environment.

	Automatic starter adjustment p_m	Start acceleration adjustment p_n
Program A	Y	N
Program B	N	Y
Program C	Y	Y

D. INFLUENCE ON THE START-UP PERFORMANCE AFTER OPTIMIZING THE START-UP FUEL SUPPLY

In the engine fuel control system, the components that can moderately adjust the starting fuel supply include the automatic starter adjustment pin p_m and the starting acceleration adjustment pin p_n. There are some differences in the effects of different adjustment parts on the fuel supply in different starting stages. The automatic starter adjustment pin p_m mainly affects the fuel supply during the start-up process, and the starting acceleration adjustment pin p_n affects the fuel supply with a large speed. According to the above method, the fuel supply regularity of the engine is optimized and adjusted. The adjustment schemes center around the adjustment pins p_m and p_n and the combined adjustment schemes are shown in Table 1.

According to the engine starting fuel supply regulation without adjustment and with above three kinds of adjustment structures of Table 1, the starting tests of the engine in the plateau environment are carried out.

Fig. 9 and Fig. 10 show the curves of the high pressure turbine rotor speed and the engine exhaust temperature over the starting time in the test process.

It can be seen from the test results of the comparisons between the fuel supply without adjustment and with the optimization program A that the acceleration characteristics of the first half of the engine are significantly improved. At the time of the engine's high pressure turbine rotor speed reaching 40%, the relative time of the engine is reduced by 0.25 relative time, and the relative time of the engine is reduced by 0.7 reaching the 72% slow state. The highest exhaust temperature drops 0.02 relative temperature, but the exhaust temperature has less residual margin. Compared with the limit value, it is only 0.09 relative temperature, where there is still some space for improvement.

Comparing the results of the optimization schemes A, B and C, when adopting the B scheme, it can be seen that the slope of the acceleration curve of the engine is slightly lower than that of A scheme. When the engine high pressure turbine rotor speed is 40%, B scheme has a lag of about 0.13 relative time compared with A. It takes 0.26 less relative time to reach 72% of the idle state, but the maximum exhaust temperature drops 0.033 relative temperature. As a result of the starting acceleration adjustment, p_n mainly affects the fuel supply at high speed. In the B scheme, when the speed reaches 55%, the slope of the engine's high speed rise is reduced to some

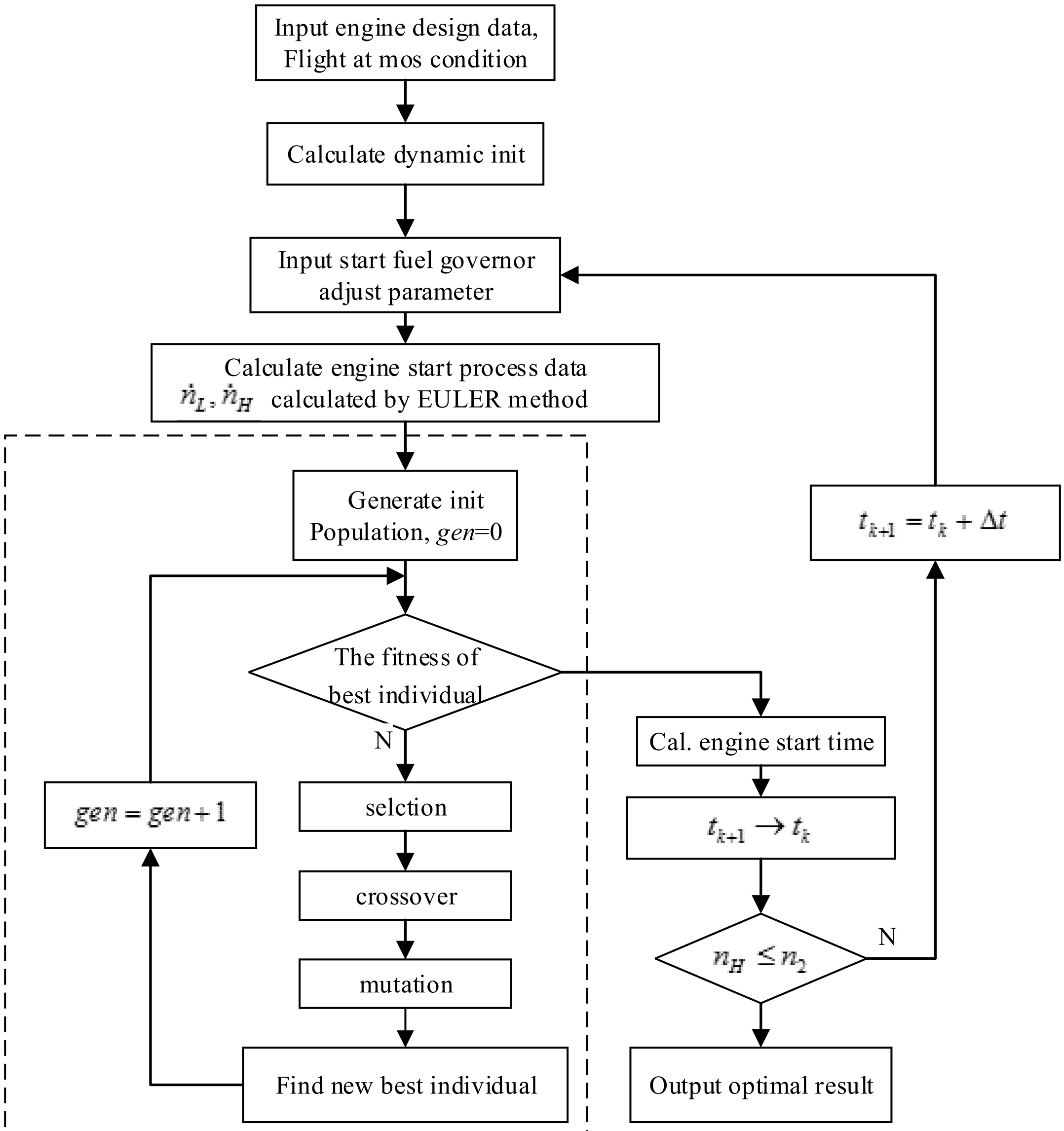

FIGURE 8. The engine starting process with a genetic algorithm and the flow chart of the fuel supply law.

extent, and thus affecting the starting acceleration time The C scheme adopts the combination adjustment method. Compared to A, B, the highest exhaust temperature in the starting process of the engine decreases by 0.088 and 0.055 relative temperature, and it increases 0.1 units of time to reach 72% of the idle state compared with the B scheme.

From the performance of the engine starting process with the adjustments, C scheme combines the advantages of A scheme and B scheme, although the start time is slightly less than the A scheme. But the highest exhaust temperature is a clear advantage. The relative time is increased by 0.55 when we compare the starting time, with the case when the fuel supply is not adjusted, The engine exhaust temperature has a large residual margin, which can effectively improve the structure life of the high temperature heat components of the engine. The plateau start test proves that the adjustment program is correct. If the altitude continues to increase, the C scheme still has some adjustment margin, which can be further optimized according to the reduction of atmospheric pressure and environmental change conditions.

E. INFLUENCE OF THE AIRCRAFT LOAD ADJUSTMENT OPTIMIZATION ON STARTING PERFORMANCE

According to the study, when the aircraft starts on the ground in the plateau environment, at the initial stage of starting the engine, the engine starting process hydraulic load can be released by the aircraft unloading hydraulic system. When the engine high pressure turbine rotor speed reaches a certain range (usually more than 53%), the engine has enough power to run via self-acceleration to the idle state. The aircraft system can restore the hydraulic system pressure. The adjustment measures can effectively reduce the extraction power of

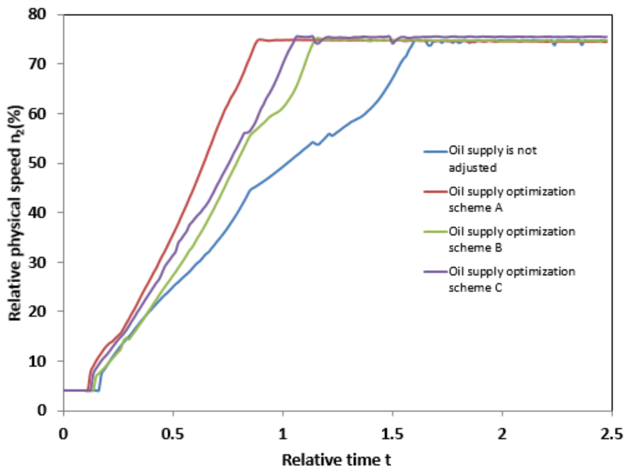

FIGURE 9. Influence of different schemes of fuel supply rules on the high turbine rotor speed of the starting process.

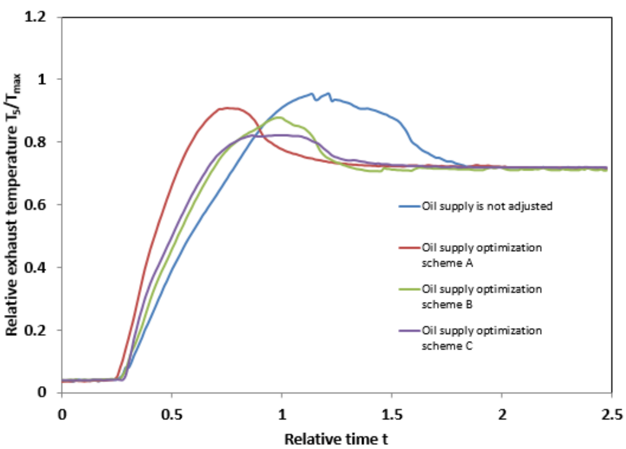

FIGURE 10. The effects of different schemes of fuel supply rules on the exhaust temperature of the starting process.

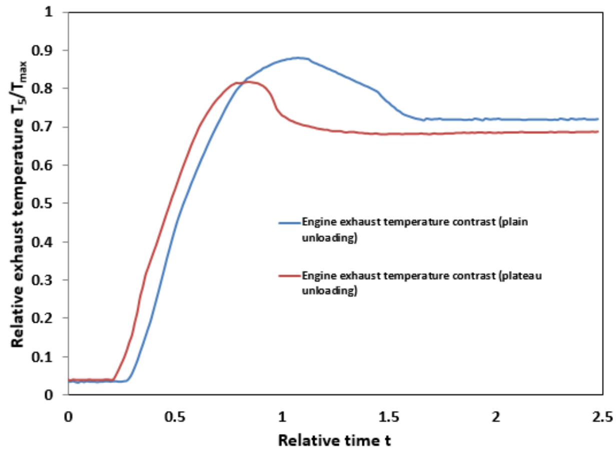

FIGURE 11. Comparison of n_H in the unloading control mode between the plain and the plateau environment.

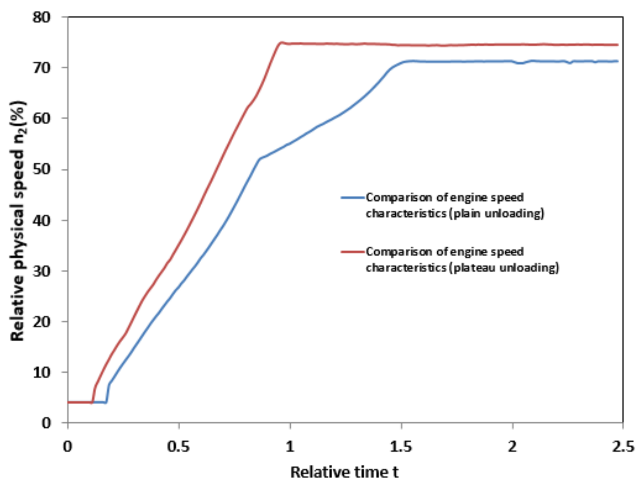

FIGURE 12. Comparison of the exhaust gas temperature in the unloading control mode between the plain and the plateau environment.

the starting process without affecting the normal operation of the hydraulic system, which can improve the starting residual power and ensure the success rate of starting. The influence of the aircraft load change on starting performance are shown as Fig. 11 and Fig. 12.

It can be seen from Fig. 11 and Fig. 12 that under the starting unloading condition, the ignition time of the engine in the plateau environment is slightly increased compared to that in the plain. Without adjusting the starter, the starting ignition time is increased by 0.065 relative units. The ignition speed of the plateau is 2.1 percent higher than the state of the plain, and the highest exhaust temperature decreases by 0.065 relative exhaust temperature. When the engine reaches the steady state of the idle state, the temperature of the exhaust gas in the plateau and the plain state is 0.685 and 0.723 respectively, and the relative physical speed is 74.7% and 71.4% respectively.

Fig.12 Comparison of the exhaust gas temperature in the unloading control mode between the plain and the plateau environment

It also can be seen that the hydraulic unloading method has obvious advantages during the second half stage of the engine starting in the plateau state, the maximum exhaust gas temperature is reduced. It is helpful to reduce the turbine starting load, which can ensure that the engine is not overheating during the start.

F. THE EFFECT OF THE INTEGRATED ADJUSTMENT MEASURES ON THE STARTING PERFORMANCE

Experiments show that in the plateau environment, the engine starting fuel supply adjustment optimization scheme C and aircraft load control comprehensive adjustment measures can effectively improve the engine ground starting performance, Fig. 13 and Fig.14 demonstrate the starting performance with and without the optimization of the integrated adjustment scheme for the engine.

It can be seen that the starting success time with optimization is 0.5375 relative time earlier, and the highest exhaust temperature decreases 0.12 relative temperature. After a large

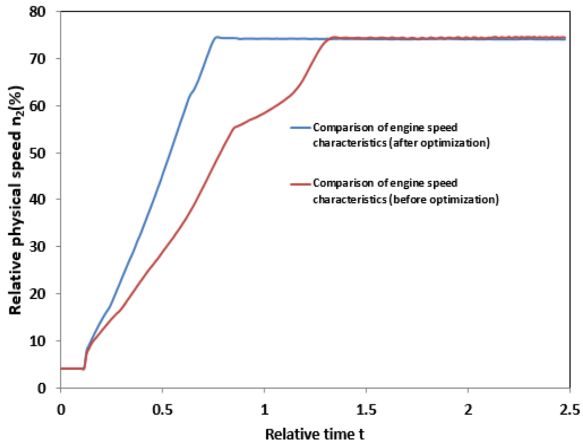

FIGURE 13. Comparison of speed n_H in the integrated adjustment mode.

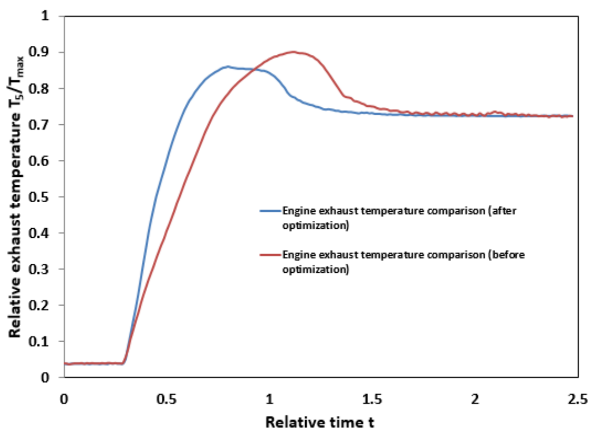

FIGURE 14. Comparison of the exhaust temperature in the integrated adjustment mode.

number of ground tests, the starting time can be significantly reduced by 20% ∼ 32% after the use of comprehensive adjustment measures, and the maximum exhaust temperature is reduced by about 7.3% ∼ 13.2%. It can be seen that the comprehensive adjustment measures can effectively improve the ground starting performance of the engine on the plateau.

VI. CONCLUSIONS

According to the characteristics of the starting process, combining with the working principle of the starting fuel regulator, the power of starter and the power change of aircraft accessories, the mathematical model of the turbofan engine starting process in high-altitude environment has been established. The genetic algorithm has been used to optimize the starting fuel supply law. Based on simulation results of the starting process at different altitudes, effective methods to improve the engine starting performance have been provided. Some advantages about the proposed schemes are as follows:

1. The proposed engine starting fuel supply scheme after corresponding optimization can reduce the maximum exhaust temperature during the engine starting process. Moreover, under the premise of not exceeding the temperature bound, the starting time can be shortened by about 30%. The remaining temperature margin in the plateau environment still has a certain space for further optimization.

2. Using aircraft load control method can increase the residual power in the starting process. Under the unloading conditions, the starting time in the plateau state is reduced by 18.2% ∼ 29.3%, and the highest exhaust temperature decreased about 4.7% ∼ 8.6% compared with that in plain state.

3. In order to shorten the starting time and improve the starting performance, the optimal adjustment of the fuel supply and the aircraft load control have been adopted. The results show that the starting time can be shortened by about 22.3% ∼ 32%, and the maximum exhaust temperature is reduced by about 7.3% ∼ 13.2%.

REFERENCES

[1] Z. Wang, Y. Huang, and S. Li, "Study on the starting fuel supply of a certain type of aircraft engine on the plateau," *Aircr. Engine*, vol. 40, no. 4, pp. 30–33, 2014.

[2] T. Guo and Z. Yang, "Discussion on high and low temperature start-up and altitude start-up test technology of aeroengine," *J. Aeronaut. Dyn.*, vol. 18, no. 3, pp. 327–330, 2003.

[3] L. Wu, J. Li, and S. Xie, "Establishment of mathematical model for start-up process of a certain type of engine on the plateau," *J. Aeronaut. Dyn.*, vol. 19, no. 1, pp. 58–60, 2004.

[4] Y. Li, Y. Wang, and Z. Lei, "Experimental study on altitude startup of a turbofan engine," *J. Aeronaut. Dyn.*, vol. 18, no. 5, pp. 599–603, 2003.

[5] A. G. Pascoe, "Start systems for aero gas turbines," *Aircr. Eng. Aerosp. Technol.*, vol. 77, no. 6, pp. 448–454, 2005.

[6] Y. Li and J. Liu, "Research on start-up performance estimation of turbofan engine based on support vector machine," *J. Aeronaut.*, vol. 26, no. 1, pp. 32–35, 2005.

[7] J. Wan and Y. He, "Discussion on starting process of aero gas turbine engine," *Sci. Technol. Inf.*, vol. 32, no. 1, pp. 3791–3799, 2013.

[8] Y. Shi, J. Zhao, and Y. Liu, "Switching control for aero-engines based on switched equilibrium manifold expansion model," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3156–3165, Apr. 2017.

[9] X. Zhao, Y. Yin, B. Niu, and X. Zheng, "Stabilization for a class of switched nonlinear systems with novel average dwell time switching by T–S fuzzy modeling," *IEEE Trans. Cybern.*, vol. 46, no. 8, pp. 1952–1957, Aug. 2016.

[10] B. Niu, H. Li, T. Qin, and H. R. Karimi, "Adaptive NN dynamic surface controller design for nonlinear pure-feedback switched systems with time-delays and quantized input," *IEEE Trans. Syst., Man, Cybern., Syst.*, to be published.

[11] H. Qiao and A. Xia, "Study on adjustment of starting fuel supply for a certain type of aero engine at high altitude," *J. Aeronaut. Dyn.*, vol. 18, no. 4, pp. 534–537, 2003.

[12] Y. Jiang, Z. Zhou, and Z. Sang, "A preliminary study on ground start experiment of engine on the plateau," *J. Propuls. Technol.*, vol. 24, no. 6, pp. 547–549, 2003.

[13] H. Miao, W. Yan, and X. Zhang, "Analysis of influence of plateau condition on launch performance of aviation turbofan engine," *Eng. Test.*, vol. 56, no. 1, pp. 57–60, 2016.

[14] F. Li, J. Li, and Y. Jiang, "Experimental study on improving ground start performance of engine on the plateau," *J. Air Force Eng. Univ. (Natural Sci. Ed.)*, vol. 13, no. 5, pp. 25–29, 2012.

[15] F. Ommi and M. Azimi, "Main fan noise mitigation technologies in turbofan engines," *Aviation*, vol. 18, no. 3, pp. 141–146, 2014.

[16] M. Gorji-Bandpy and M. Azimi, "Technologies for jet noise reduction in turbofan engines," *Aviation*, vol. 16, no. 1, pp. 25–32, 2012.

[17] M. Gorji-Bandpy and M. Azimi, "Airframe noise sources and reduction technologies in aircraft," *Noise Vib. Worldwide*, vol. 43, no. 9, pp. 29–36, 2012.

[18] M. Azimi, F. Ommi, and N. J. Alashti, "Using acoustic liner for fan noise reduction in modern turbofan engines," *Int. J. Aeronaut. Space Sci.*, vol. 15, no. 1, pp. 97–101, 2014.
[19] M. A. Chappell and P. W. McLaughlin, "Approach of modeling continuous turbine engine operation from startup to shutdown," *J. Propuls. Power*, vol. 9, no. 3, p. 2865, 1993.
[20] A. K. Owen, A. Daugherty, D. Garrard, H. C. Reynolds, and R. D. Wright, "A parametric starting study of an axial-centrifugal gas turbine engine using a one-dimensional dynamic engine model and comparisons to experimental results: Part 2—Simulation calibration and trade-off study," *J. Eng. Gas Turbines Power*, vol. 121, no. 3, pp. 384–393, 1999.
[21] R. K. Agrawal and M. Yunis, "A generalized mathematical model to estimate gas turbine starting characteristics," *J. Eng. Power*, vol. 104, no. 1, pp. 194–201, 1982.
[22] J. L. Simonetti and J. H. McMurry, "Start fuel schedule enhancements for the ETF40B gas turbine engine," in *Proc. ASME Turbo Expo*, 2009, pp. 1001–1007.
[23] L.-C. Hsu, W.-C. Ho, and C.-C. Hsueh, "Design of a gas turbine based air start unit for larger aircraft engine," in *Proc. ASME Turbo Expo*, vol. 4, 2004, pp. 723–729.
[24] G. Pucher and W. D. Allan, "Turbine fuel ignition and combustion facility for extremely low temperature conditions," in *Proc. ASME Turbo Expo*, vol. 1, 2004, pp. 385–392.
[25] A. Peretz, S. Khosid, and A. H. Gross, "Improvement of a turbine engine start by an external oxygen-rich gas generator," *Int. J. Energetic Mater. Chem. Propuls.*, vol. 9, no. 1, pp. 43–54, 2010.
[26] P.-Y. Duan, J.-Q. Li, Y. Wang, H.-Y. Sang, and B.-X. Jia, "Solving chiller loading optimization problems using an improved teaching-learning-based optimization algorithm," *Optim. Control Appl. Methods*, vol. 39, no. 1, pp. 65–77, 2018.
[27] J.-Q. Li, H.-Y. Sang, Y.-Y. Han, C.-G. Wang, and K.-Z. Gao, "Efficient multi-objective optimization algorithm for hybrid flow shop scheduling problems with setup energy consumptions," *J. Cleaner Prod.*, vol. 181, pp. 584–598, Apr. 2018.

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