Component Matching Based on Low Bypass Ratio Mixed Exhaust Turbofan Engine

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Abstract: In order to study component matching which exists in off-design situation at the initial design stage of turbine engine, by establishing performance analysis model of low bypass ratio mixed flow turbofan engine and components characteristic data, and by applying Newton-Raphson method to solve the nonlinear equations of off-design points in flying envelop, the factors which affect matching between engine components are studied. The results show that low pressure turbine (LPT) must not operate in a critical condition, and the partial derivative (slope) of pressure ratio to similitude mass flow ratio of working point in LPT characteristic map affects the stability of engine. The smaller the slope is, the more stable the engine is. In addition, the engine is more stable when the fan characteristic map is steep.

Key words: turbofan engine; low bypass ratio; off-design; component matching; OOP; performance analysis

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0 Introduction

Aero-engine is one of the most complex ones in aircraft systems, and its working condition directly affects the safety and reliability of aircraft[1]. With the development of modern electronic technology and the improvement of combat weapons, the combat mode has undergone major changes. The missions of fighter become more and more stringent, such as supersonic penetration, over-speed maneuver combat and so on. Higher requirements are also put forward to the aircraft propulsion system[2]. Therefore, in the engine design, we can not only consider the design of the engine alone, but also the interaction between various components, as well as components matching. At the same time, military fighters continue to develop, causing the components matching more and more prominent. Components matching throughout the mission envelope face greater difficulties in the initial stage of the engine[3]. In the field of aero-engine design, matching problem between various components is important. Therefore, the study of aircraft engine components matching not only need to develop and improve the theoretical basis, but also need to develop computing and analysis platform related to components matching

In order to ensure the stability of the engine, components matching technology attracts more and more attention of domestic and foreign scholars. However, there is little research on components matching of turbofan engines throughout the whole mission envelope. Based on the literatures of engine components matching, we establish an engine model of the low bypass ratio mixed exhaust turbofan, study the components matching of the engine throughout the whole mission envelope, and analyze the factors affect components matching.

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1 Components Matching for Full Flight Envelope

Engine design should be based on the mission requirements of the fighter[4], and the engine must be able to complete all possible missions within the envelope. During the initial design stage of the engine, the selection of the design point and off-design points have a variety of options, and for the design point, the important fighter flight mission should be selected as the design point. The selected design point and component characteristics should ensure that the engine can match well within the entire envelope, and ensure a certain surge margin. According to the fighter suitability requirements, we need to select typical missions as an analysis of the situation[5]. Here we select 13 typical missions of the low bypass mixed exhaust turbofan engine. Fig. 1 shows engine mission envelope and the position of typical mission in the envelope. Table 1 shows the parameters of the selected missions.

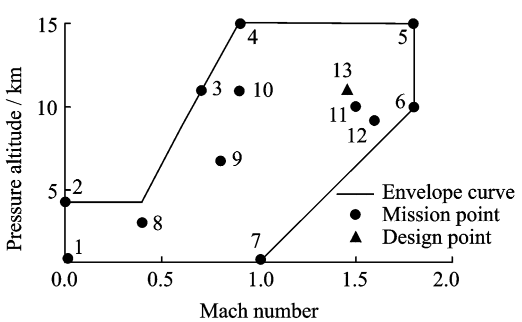


Fig. 1 Engine envelope curve and typical mission points

Table 1 Parameters of fighter typical mission

Number	Mission	Mach number	Flight height/m
1	Sea level takeoff	0	609. 6
2	Highland takeoff	0	4 250
3	Subsonic cruise1	0. 79	11 000
4	Max height/Min speed flight	0. 9	15 000
5	Max speed flight	1. 8	15 000
6	Min height/Max height flight	1. 8	10 000
7	Max speed in land	1. 0	609. 6
8	Climb acceleration	0. 4	3 048
9	Horizontal acceleration	0. 8	6 704
10	Subsonic cruise2	0. 9	11 000
11	Escape	1. 5	10 000
12	Supersonic penetration	1. 6	9 144
13	Design point	1. 45	9 144

2 Calculation Model and Method

During the initial design stage of the overall performance of the turbine engine, there is no real components and performance data. In this period, it is necessary to use the hypothesis performance data according to the design team's ability. It should be noticed that fully simulation will promote post-research and development . The off-design points calculation will not converge because of the unreasonable data, and non-convergence means that the component data does not match.

In order to reduce the complexity of the computational program and to find out the factors of the mismatch problem more easily, an object-oriented programming method (OOP) is used to compile the engine overall performance calculation program.

2.1 Calculation Model

In this paper, the object is a low bypass mixed exhaust turbofan engine, Fig. 2 shows the typical cross-section and calculate the flow pattern. The model is a zero-dimensional model, which can be used for engine component matching analysis, overall performance calculation and control law research. Each rectangle in Fig. 2 is a computer memory corresponding to an OOP in the computer.

2.2 Calculation Method

At present, there are many types of engines derived from turbo engine. In general, the more components, the more difficult to match. For the future high-performance fighter, structure of variable cycle engine and TBCC engine[6-7] are more complex, components matching problem is more obvious. According to the existing experience, during the design of the low bypass mixed exhaust turbofan engine, due to the existence of the mixer, the component matching is more difficult.

To simplify the complexity of performance calculation problems, one feature of OOP is abstraction. No matter what type of turbine engine,

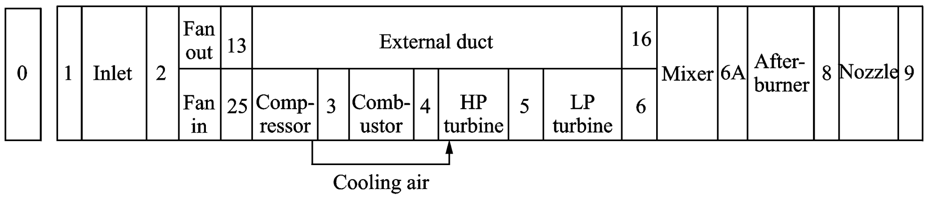


Fig. 2 Engine section and flow path

its components are nothing more than two: Rotating components and pipe components. Each component is equivalent to a black box. The black box on both sides are defined as the inlet cross-section and the outlet cross-section, and the performance of internal components is determined by performance data or a certain physical relationship between the components calculated by the inlet and outlet cross-section of a series gas parameters, such as flow, total pressure, total temperature, oil/gas ratio, Mach number. Other parameters can be calculated from the above parameters. The overall performance calculation of the engine mainly refers to the total pressure and total temperature through the transmission of component characteristics. So it can be summarized as follows, so as to avoid a lot of cumbersome formula.

The total pressure and total temperature of the fan, and high pressure compressor are calculated by the following formula

$$p_{\mathrm{t,out}} = \pi_C^* p_{\mathrm{t,in}} \tag{1}$$

$$\eta_C = \frac{h_{\mathrm{t,out},i} - h_{\mathrm{t,in}}}{h_{\mathrm{t,out}} - h_{\mathrm{t,in}}} \tag{2}$$

The total pressure and total temperature of the turbine is calculated as follows

$$p_{\mathrm{t,out}} = p_{\mathrm{t,in}} / \pi_{\mathrm{T}} \tag{3}$$

$$\eta_{\mathrm{T}} = \frac{h_{\mathrm{t,in}} - h_{\mathrm{t,out}}}{h_{\mathrm{t,in}} - h_{\mathrm{t,out,i}}} \tag{4}$$

The total pressure of the pipe is transmitted through the total pressure recovery coefficient σ, and the total pressure of the mixer is determined by the momentum conservation. The total temperature is mainly transmitted by energy conservation, in which the total temperature of the combustion chamber is calculated by the following formula

$$\eta_{\mathrm{b}} = \frac{(W_{\mathrm{in}} + W_{\mathrm{f}}) h_{\mathrm{t,out}} - W_{\mathrm{in}} h_{\mathrm{t,in}}}{W_{\mathrm{f}} \mathrm{LHV}} \tag{5}$$

where the subscript in and out denote the inlet and outlet sections; i, t, f represent the isentropic ideal state, the total parameter, and fuel, respectively; T, b represent the turbine, combustion chamber, respectively; p, h represent pressure and enthalpy, respectively; π, η and W represent the pressure ratio, efficiency, and mass flow, respectively; LHV is the fuel low calorific value. In addition, h_{t} is a single-valued function of total temperature.

Both the design point and off-design points are calculated through the cross-section parameters of the above mentioned components. From the above equation we can see that the basis of the physical equation is simple, regardless of the type of engine, if the data is accurate, the calculation can be a good simulation of the real engine.

The off-design points calculation is different from the design point calculation, and it is necessary to consider the equilibrium equations of multi-group components working together. This is a mathematical problem of solving a group of nonlinear equations. These equilibrium equations are calculated based on the characteristic data between the components of the engine, under the condition of continuous flow, energy conservation, shaft power balance and control law. Point-calculation design and parameters transmission process is generally simple, and there will not be a large cycle iteration, but off-design points calculation requires a certain group of initial guess values, and a check to the residual errors of balance conditions until converge. In the off-design points calculation of this paper, the selected equilibrium equation is as follows:

(1) Balance between high-pressure compressor inlet flow and the flow on high-pressure com-

pressor performance map

$$W_{\text{HPC}} - W'_{\text{HPC}} = \varepsilon_1 \tag{6}$$

(2) Balance between low-pressure turbine inlet flow and the flow on low-pressure turbine performance map

$$W_{\text{LPT}} - W'_{\text{LPT}} = \varepsilon_2 \tag{7}$$

(3) Balance between high-pressure turbine inlet flow and the flow on high-pressure turbine performance map

$$W_{\text{HPT}} - W'_{\text{HPT}} = \varepsilon_3 \tag{8}$$

(4) Balance between mixer internal and external static pressure

$$p_{16} - p_6 = \varepsilon_4 \tag{9}$$

The parameter ε represents the residual error of the equation, as long as one of them does not meet the accuracy requirements. It must re-guess the initial value of the calculation.

At the same time, the combustion chamber outlet temperature T_{t4} inspection, high-pressure turbine power P_{HPT} balance and low-pressure turbine power P_{LPT} balance using local iteration to complete, so there are only four large cycle iteration guess, reducing the difficulty of guessing and iterating. In order to compute the nonlinear equations, the same number of matching guess values are indispensable. All the initial guess values constitute the initial vector corresponding to the nonlinear equations. In this paper, all of the balance equation and the initial guess values are as shown in Table 2.

Table 2 Equilibrium equation and initial guess values

Equilibrium equation	Initial guess value	Solving method
HP compressor flow continuity	LP rotor speed	Newton Raphson iteration
LP compressor flow continuity	Fan pressure ratio	
HP turbine flow continuity	LP compressor pressure ratio	
Mixer static pressure balance	HP compressor pressure ratio	
Combustor exit temperature balance	Fuel	Local iteration
HP turbine power balance	HP turbine expansion ration	
LP turbine power balance	LP turbine expansion ration	

The Newton-Raphson method is the most commonly used method in solution of non-linear equations. When the relative deviations of all the equations are less than the required precision (1e−5), the group of guess values are assumed to be an equation solution. In the calculation of the iterative process, if the components do not match, it is necessary to constantly adjust the characteristic map of the rotating components such as fan and turbine map and the position of the design point in the performance map so that the equations converge in all the missions. The calculation procedure of the matching of the low bypass mixed exhaust turbofan engine is shown in Fig. 3.

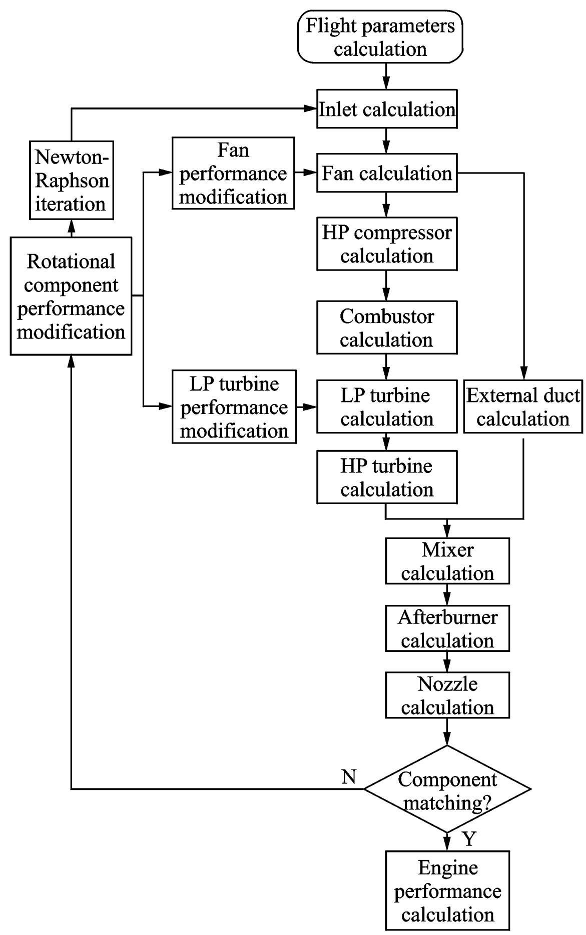


Fig. 3 Flow chart of component matching calculation

3 Analysis of Calculation Results

3.1 Stability analysis of off-design point calculation method

First, consider the effect of variation of the low-pressure turbine characteristic map slope on component matching in the case of high-pressure compressor, high-pressure turbine and fan parameters and characteristics are constant, and the slope of the fan characteristic chart is large. As shown in Fig. 4, the fan characteristics map is steeper, and the design point is selected as a calculation point, then three cases of engine components matching under low-pressure turbine performance speed line partial derivation is $\frac{\partial \pi_T}{\partial W}=0.18$, $\frac{\partial \pi_T}{\partial W}=1.8$ and $\frac{\partial \pi_T}{\partial W}=8.6$, as shown in Fig. 5.

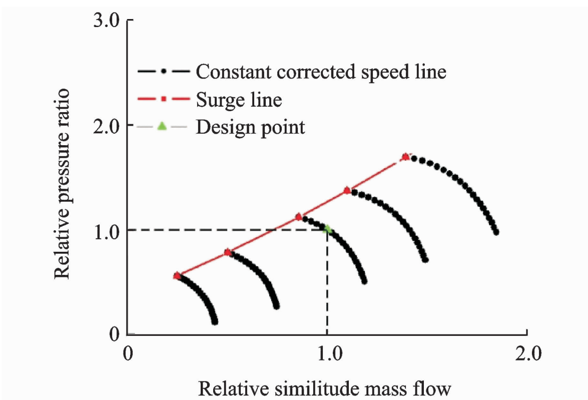


Fig. 4 Fan characteristic map and location of design point

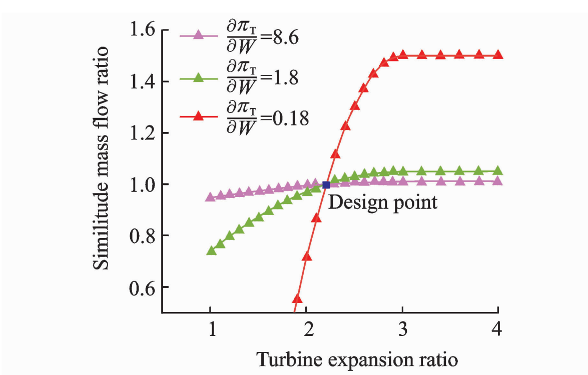


Fig. 5 Three low pressure turbine characteristic map

The above example is an off-design point algorithm to calculate the design point. If the initial guess values is given exactly, all the errors to be checked in the off-design point algorithm will satisfy the convergence requirement, the program will not enter the iteration, and the engine is in the stable or critical steady state. However, if the initial guess values are slightly biased, the program enter iteration. And if it is convergence, the system is stable; if not, it is critical stable state. In the project, the critical stability is unstable.

Fig. 6 shows the history of residual errors of the calculation results. It can be seen from the Fig. 6 that when the low pressure turbine characteristic partial derivative is small about $\frac{\partial \pi_T}{\partial W}=0.18$. The equilibrium equation is easy to converge and the number of iterations is fewer. With the low pressure turbine characteristic line partial derivative $\frac{\partial \pi_T}{\partial W}$ gets larger, the engine is more difficult to converge, that is, components get more difficult to match. In particular, when the slope approaches infinity (turbine critical), the calculation can not converge when the guess values are deviated, which means that the turbine cannot match the engine.

In addition, as shown in Fig. 7, change the slope of the fan characteristic line smaller, and

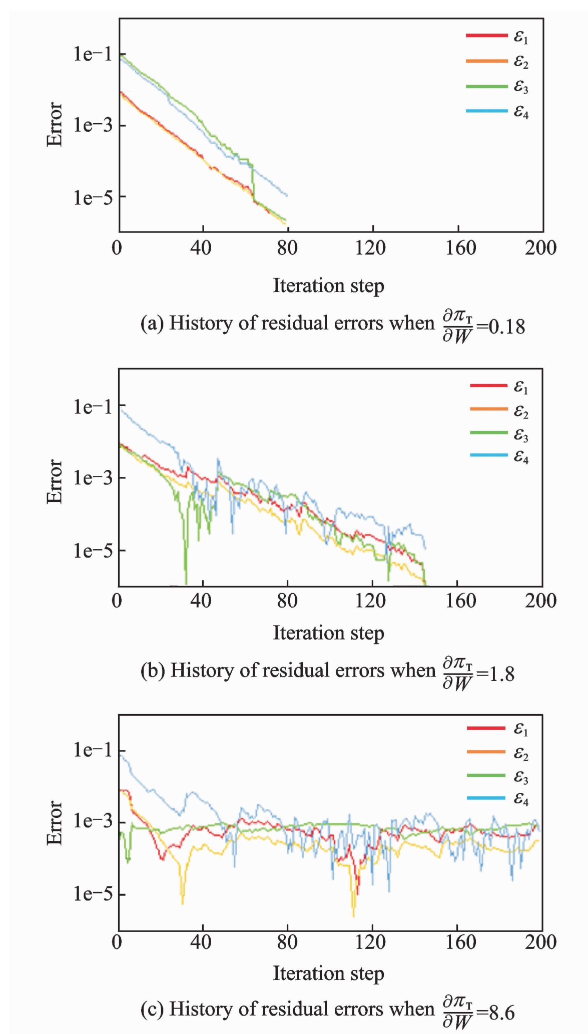


Fig. 6 History of residual errors

the design is also selected at the same position to study the influence of the fan characteristic line slope on the engine component matching. The result is shown in Fig. 8.

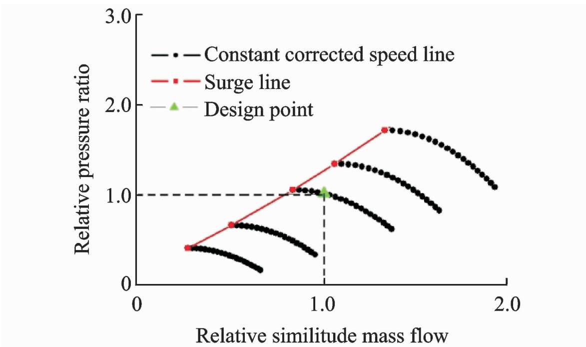
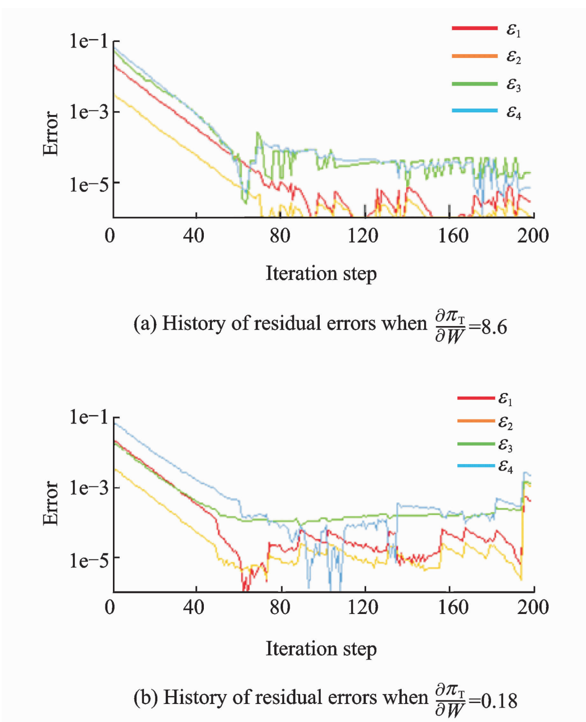


Fig. 7 Modified fan characteristic map



(a) History of residual errors when $\frac{\partial \pi_T}{\partial W}=8.6$

(b) History of residual errors when $\frac{\partial \pi_T}{\partial W}=0.18$

Fig. 8 History of residual errors after modifying characteristic map

After the slope of the fan characteristic line becomes smaller, under the condition of the slope of the low-pressure turbine characteristic is $\frac{\partial \pi_T}{\partial W}=0.18$ and $\frac{\partial \pi_T}{\partial W}=8.6$, the system is not easy to converge and the residual cannot meet the requirement of precision. Compared with the above results, it can be seen that in the case of the slope of the low-pressure turbine characteristic line is constant, The smaller the slope of the line, the less likely it is to converge.

3.2 Components matching examples

In order to match the engine components throughout the mission envelope, it is necessary to select the characteristics of the fan and the low pressure turbine, and the position of the design point in the characteristic map reasonably. In this paper, during the typical missions calculation, select the fan characteristic map (Fig. 4) and low pressure turbine slope $\frac{\partial \pi_T}{\partial W}=0.18$. The control law of the engine are: The high-pressure rotor speed is constant, and ensure the engine has a certain surge margin. With the above characteristics and control rule, the typical missions of the engine shown in Table 1 are calculated and the working lines of the engine components are shown in Figs. 9—12. It can be seen that the selected fan and low pressure turbine characteristics enable the engine components well matched during executing the missions.

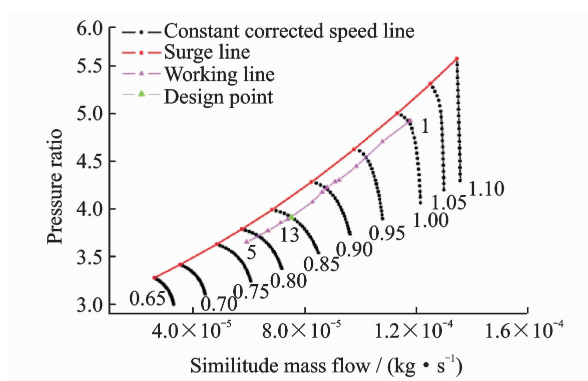


Fig. 9 Working line of fan

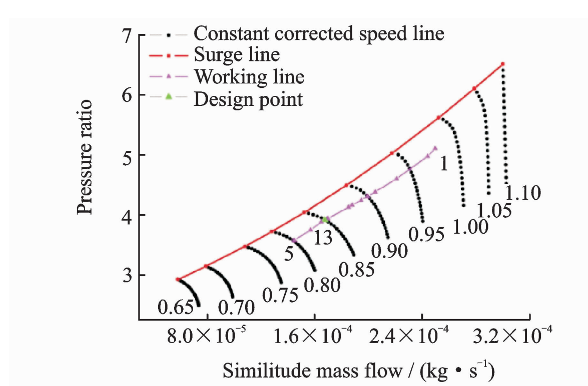


Fig. 10 Working line of low pressure compressor

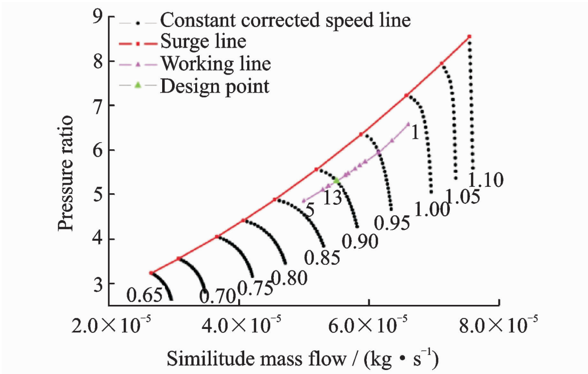


Fig. 11 Working line of high pressure compressor

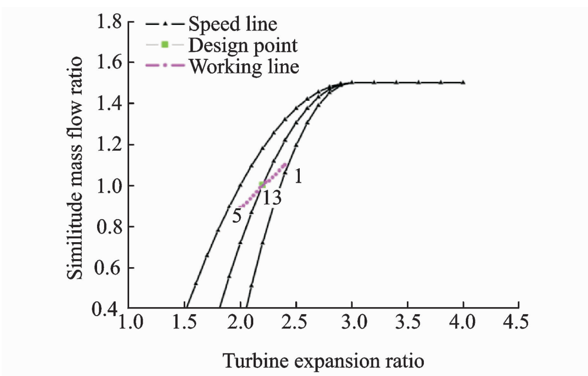


Fig. 12 Working line of low pressure turbine

4 Conclusions

The mathematical model and analysis software of components matching analysis of the low bypass ratio mixed exhaust turbofan engine are developed. The influence of the slope of the fan and the low pressure turbine on the components matching is analyzed, and the reasonable parameters are selected for a certain type of fighter. Components matching calculation is performed for typical missions in flight envelope. Calculations proves that:

(1) For low bypass ratio mixed exhaust turbofan engine, LPT must not operate in the critical condition;

(2) In the case where the fan performance remains constant, the partial derivative (slope) of pressure ratio to similitude mass flow ratio of working point in LPT performance map affects the stability of engine;

(3) In a certain range, the lower the partial derivation of the performance map line of the low pressure turbine is , the better components matching of the engine is.

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