

Research on Influence of Geometric Adjustment on Performance of Variable Cycle Engine

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Abstract. Based on conventional turbofan engine, this paper adding mode selection valve, the front variable area bypass injectors and the rear variable area bypass injectors to build a mathematical model of the variable cycle engine. Then the influence of adjustable components on engine performance is simulated by computation program. The simulation results show that in the same work mode, the front variable area bypass injectors and the rear variable area bypass injectors have the same effect on engine performance, but different from the mode selection valve; Both front variable area bypass injectors and rear variable area bypass injectors have different effects on engine performance in different modes.

1. Introduction

For conventional aero engines, it can only maintain a good working condition under certain conditions. The performance will also drop due to deviation from the specified conditions. The Variable Cycle Engine (VCE) can change the thermodynamic cycle by changing the geometric position, shape and size of some components. The engine has a turbofan cycle with low fuel consumption during subsonic flight and a high unit thrust turbojet cycle for supersonic flight [1]. This performance advantage makes the variable cycle engine become one of the main directions of aviation research.

Research work on variable cycle engines has been in progress since around 1960. In 1976, GE used the Rear Variable Area Bypass Injector (RVABI) structure on the YJ101 engine [2]. In 1978, GE conducted a test of a variable cycle engine with a Forward Variable Area Bypass Injector (FVABI) to verify its feasibility [3, 4].

In recent years, research work on variable cycle engines has focused on the structure and overall performance of components [5, 6]. However, there is a lack of research on the effects of geometric adjustments such as FVABI, RVABI and MSV on the performance of variable cycle engines.

In this paper, the mathematical model of the variable cycle engine is built and the simulation calculation program is programmed to analyze the influence of components such as MSV, FVABI and RVABI on the performance of the variable cycle engine, and provide theoretical support for the subsequent research on the key adjustment components of the variable cycle engine.

2. Research object

The research object of this paper is the double external culvert cycle engine. The basic structure is shown in Figure 1. The main adjustable components affecting engine performance include MSV, FVABI and RVABI. The channel where FVABI is located is called the first outer culvert, and the



channel regulated by MSV is called the second outer culvert. This engine has two modes and its working principle is as follows.

2.1. Single outer culvert mode

The engine operates in a small bypass ratio mode during high power conditions such as climb, acceleration and supersonic cruise (Figure 1 below). In this mode, the MSV is turned off, that is, the second outer culvert is closed. In order to allow more airflow into the core duct, the FVABI is turned down. Adjust the RVABI to the proper position to ensure the required bypass ratio and back pressure while achieving high thrust.

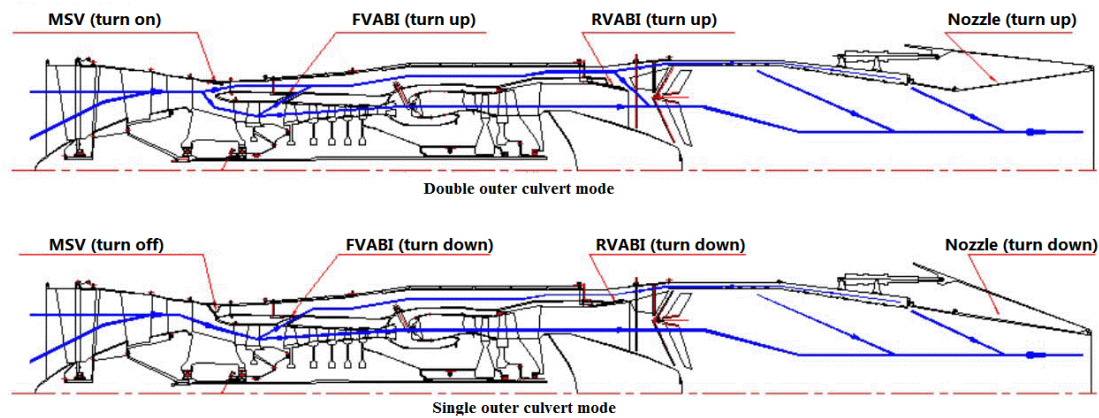


Figure 1. Variable cycle engine structure.

2.2. Double outer culvert mode

The engine operates in a large bypass ratio mode for take-off and subsonic cruise conditions (Figure 1 above). In this mode, the MSV is opened, and the first outer culvert and the second outer culvert are all open. By increasing the FVABI, the air flow into the core duct is reduced, and the air flow entering the outer duct is increased. The RVABI is increased, and the culvert airflow is injected into the exhaust gas, so that the engine thrust is further increased and the noise is reduced.

3. Research method

Compared to conventional turbofan engines, variable cycle engines add some adjustable components that bring new influences to the joint work. Therefore, in this calculation, the judgment parameters such as low-pressure rotor speed, high-pressure rotor speed, fan pressure ratio function, core drive stage fan pressure ratio function, compressor pressure ratio function, high-pressure turbine flow function, low-pressure turbine flow function, etc. are added. The following seven common working equations are selected based on engine airflow mass flow balance, pressure balance, physical speed equalization, and power balance relationship.

1. High pressure turbine flow balance

$$ERR(1) = (W_5 - W_{5g}) W_5^{-1} \quad (1)$$

ERR represents the residual, W_5 represents the high pressure turbine inlet converted flow, and W_{5g} represents the high pressure turbine inlet converted flow calculated from the high pressure turbine characteristic curve.

2. High pressure shaft power balance

$$ERR(2) = (N_C + N_D - N_{TH}) (N_C + N_D)^{-1} \quad (2)$$

N_C represents compressor power, N_D represents the core drive stage fan power, and N_{TH} represents high pressure turbine power.

3. Low pressure turbine flow balance

$$ERR(3) = (W_{55} - W_{55g}) W_{55}^{-1} \quad (3)$$

W_{55} represents the low pressure turbine inlet converted flow, and W_{55g} represents the low pressure turbine inlet converted flow calculated from the low pressure turbine characteristic curve.

4. Low pressure shaft power balance

$$ERR(4) = (N_F - N_{TL}) N_F^{-1} \quad (4)$$

N_F represents fan power, and N_{TL} represents low pressure turbine power.

5. Mixing chamber static pressure balance

$$ERR(5) = (PS_{55} - PS_{25}) PS_{55}^{-1} \quad (5)$$

PS_{55} represents the static pressure of the core duct outlet, PS_{25} represents the static pressure at the exit of the outer duct.

6. Nozzle mass balance

$$ERR(6) = (W_9 - W_7) W_9^{-1} \quad (6)$$

W_9 represents the conversion flow of the nozzle, and W_7 represents the converted flow rate of the afterburner outlet.

7. CDFS mass balance

$$ERR(7) = (W_2 - W_{21} - W_{13}) W_2^{-1} \quad (7)$$

W_2 represents the fan inlet conversion flow, W_{21} represents the core drive stage fan import conversion flow, and W_{13} represents the outer culvert conversion flow.

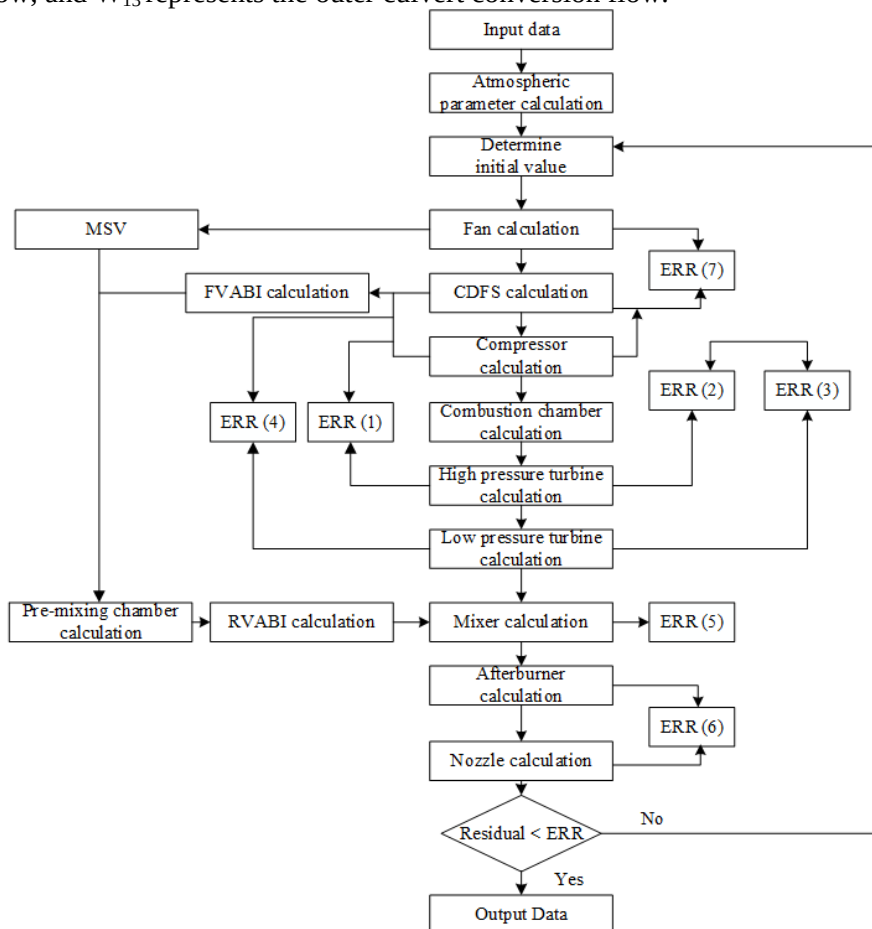


Figure 2. Calculation process

Thus, the mathematical model of the variable cycle engine is built and the simulation calculation program is written. The program calculation process is shown in Figure 2.

4. Research result

The design point parameters and control laws in the reference [7] are used for calculation. The simulation results of this paper are compared with the results in the reference, as shown in Table 1.

Table 1. Comparison of calculation results

H=0km, Ma=0.3	Reference [7]	This paper	Error
Fuel consumption rate	0.8315	0.8439	1.5%
Thrust	10597.25	10916.63	3.0%

The calculation results in this paper are basically consistent with the references [7-10]. The deviation of the calculation results is mainly due to the efficiency of the selected components and the Mach number of the design points of each section in this paper is inconsistent with the literature. Overall, the results illustrate the correctness of the simulation calculation program and can be used to further study the performance of the variable cycle engine.

The performance of the variable cycle engine is affected by adjusting the area of FVABI, RVABI, and MSV. The area of FVABI is represented by A22, the area of RVABI is represented by A25, and the area of MSV is represented by A13, in this paper, the change in area is expressed by the relative area, and the relative area is the actual area divided by the basic area. And the engine working state is H=0 km, Ma=0.3. In the single culvert mode, the control law is that the temperature before the turbine is equal to the constant, and the control law in the double culvert mode is that the relative physical speed of the low pressure rotor is equal to a constant.

4.1. Single outer culvert mode

In the single culvert mode, the MSV is off and the CDFS angle is 0°. In addition to the part to be studied can be changed, other parts are at the reference point.

4.1.1 FVABI geometry adjustment (A22)

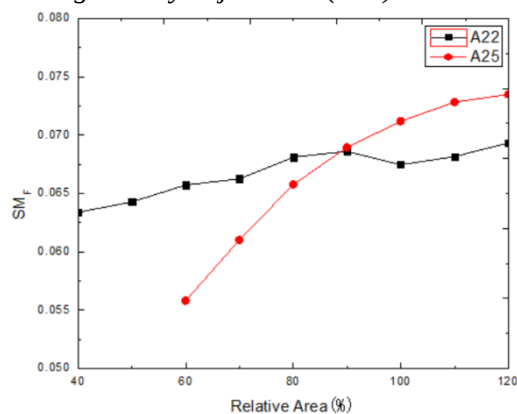


Figure 3. The fan surge margin

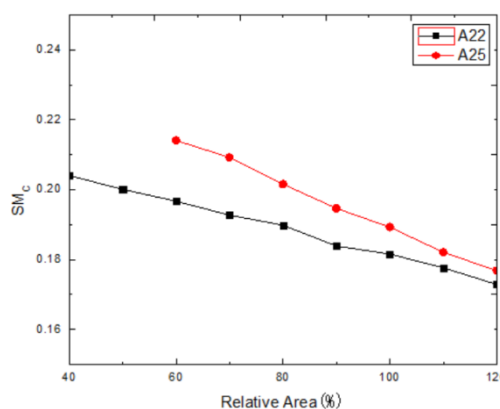


Figure 4. The compressor surge margin

It can be seen from Figure 3 and Figure 4 that if other geometric components are unchanged, decreasing A22 will result in a decrease in the surge margin of the fan, and the surge margin of the compressor is slightly increased. Similarly, Figures 5, 6 and 7 show that as A22 decreases, the thrust and fuel consumption rate will increase, but the bypass ratio will decrease.

In the process of reducing A22, the external culvert flow will be reduced and the total pressure loss will be further increased, causing the operating point of the fan to move up, resulting in a decrease in the surge margin. Conversely, the air entering the core channel will increase, resulting in a slight increase in the surge margin of the compressor. That is to say, in this process, the bypass ratio will

become smaller. This will result in an increase in unit thrust and fuel consumption, but the latter will vary greatly, so the total thrust and fuel consumption rate will increase.

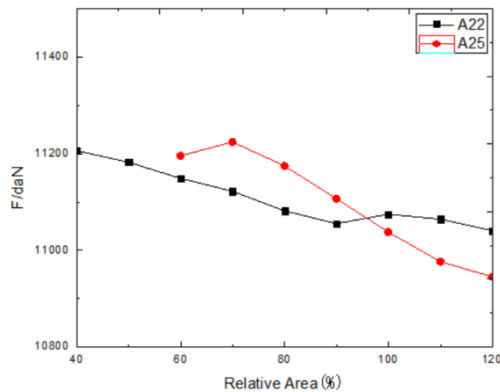


Figure 5. The engine thrust

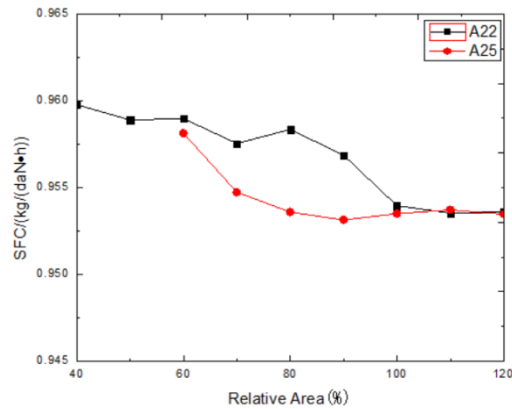


Figure 6. The fuel consumption rate

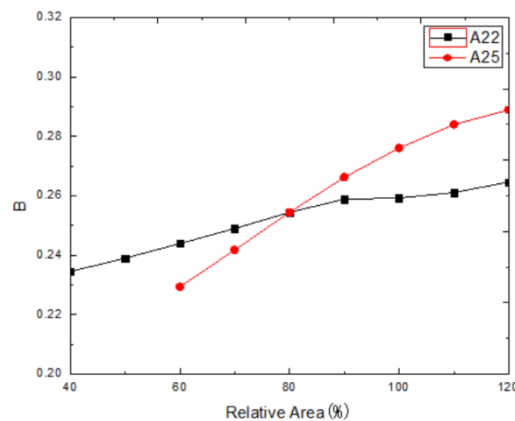


Figure 7. The bypass ratio

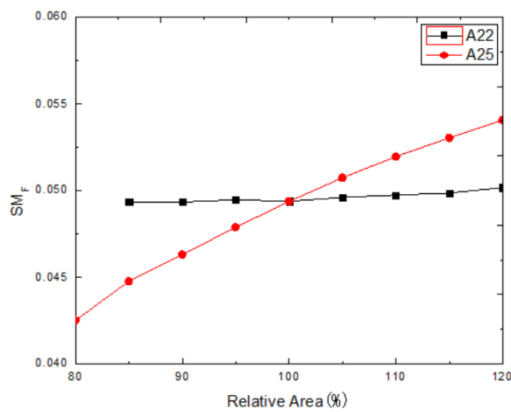
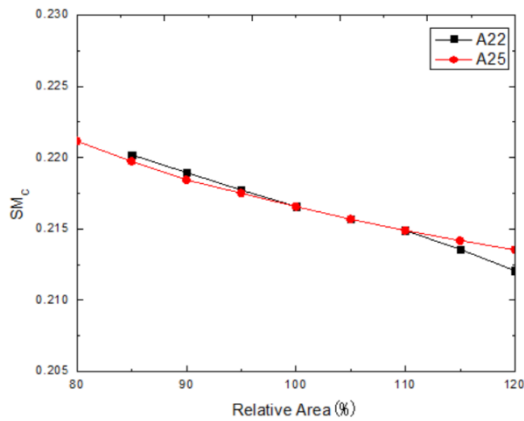
4.1.2 RVABI geometry adjustment (A25). As can be seen from the figures shown above, the variation trend of surge margin, bypass ratio, thrust and fuel consumption rate with A25 is consistent with that of A22. That is to say, the effect of the A25 on engine performance is similar to that of the A22.

When the A25 is reduced, the low pressure turbine drop ratio increases, but the high pressure turbine drop ratio does not change. Therefore, in order to ensure the regulation law, the low pressure turbine output power will increase, so that the low pressure rotor speed increases, causing the compressor surge margin to decrease. The decrease in A25 causes an increase in the air flowing into the core duct, causing the bypass ratio to decrease. As mentioned above, this will increase the thrust and fuel consumption rate.

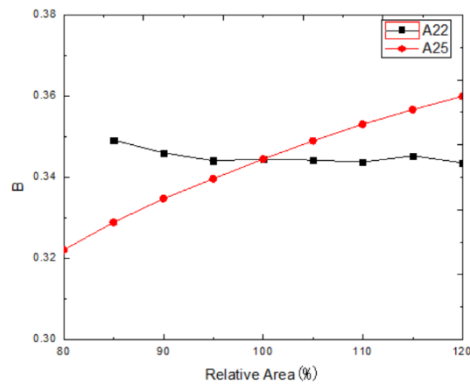
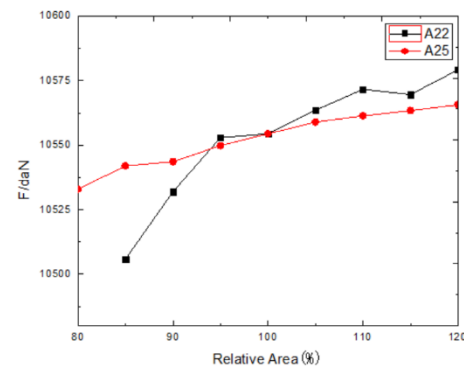
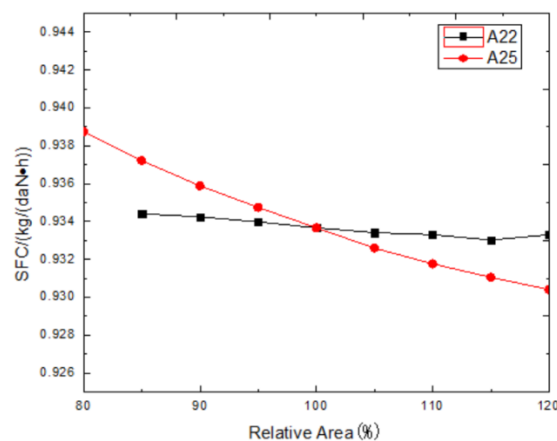
4.2. Double outer culvert mode

In the single culvert mode, the MSV is open and the CDFS angle is 15°. In addition to the part to be studied can be changed, other parts are at the reference point.

4.2.1 FVABI geometry adjustment (A22). Figure 8 to Figure 12 show the effect of A22 on engine performance in double outer culvert mode. With the increase of A22, the fan surge margin does not change much, showing an increasing trend, and the compressor surge margin is reduced, the engine thrust is increased, but the fuel consumption rate and the bypass ratio are reduced.

**Figure 8.** The fan surge margin**Figure 9.** The compressor surge margin

When A22 is increased, the static pressure of the airflow entering the outer culvert is reduced, so that the flow rate of the second outer culvert is decreased. Conversely, the flow rate entering the compressor is increased, so the bypass ratio is decreased and the thrust is increased. At the same time, the fan moves down under the influence of back pressure, so the fan surge margin increases. The control law causes the high-speed rotor speed to increase, which reduces the compressor surge margin.

**Figure 10.** The engine thrust**Figure 11.** The fuel consumption rate**Figure 12.** The bypass ratio

4.2.2 RVABI geometry adjustment (A25). As can be seen from the figures in the previous section, in the double outer culvert mode, when A25 is increased, the fan surge margin, thrust, and bypass ratio increase, but the compressor surge margin and fuel consumption rate decrease.

When A25 is increased, the low pressure turbine drop ratio is reduced, and the high speed rotor is increased in speed under the control of the regulation law, resulting in a decrease in the compressor surge margin. In addition, the working point of the fan moves down along the equal speed line, which means that the surge margin of the fan increases. At this time, the air flow of the outer duct increases, resulting in an increase in the duct ratio.

4.3. MSV geometry adjustment (A13)

The change process of MSV is also the switching process of the engine work modes. In this section, FVABI, RVABI and other components are at the reference point, and only the area change of MSV is studied.

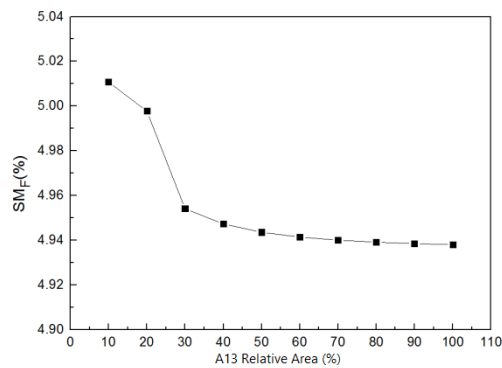


Figure 13. The fan surge margin

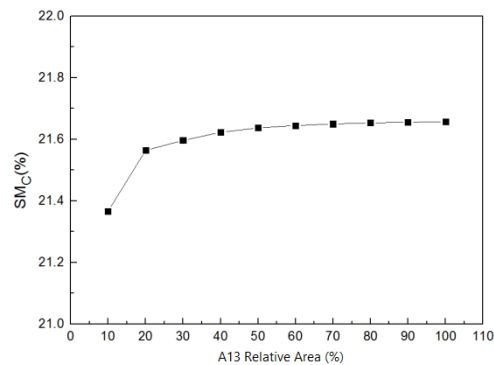


Figure 14. The compressor surge margin

As can be seen from Figure 13 to Figure 17, as the degree of closure increases, the flow area decreases, the fan surge margin and thrust increase, while the compressor surge margin, the fuel consumption ratio and the bypass ratio show a downward trend. When the area of MSV is gradually reduced to less than 30%, it can be seen that the fan surge margin and thrust rise rapidly, the compressor surge margin and the bypass ratio also decrease rapidly.

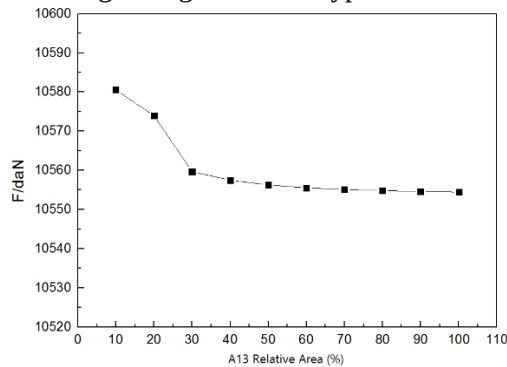


Figure 15. The engine thrust

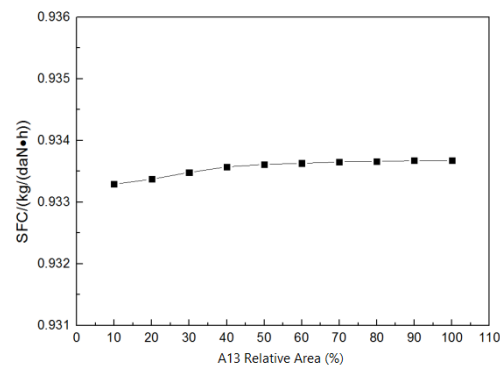


Figure 16. The fuel consumption rate

The process of reducing A13, that is, the engine is gradually approaching from the double culvert mode to the single culvert mode. At this time, the flow rate into the outer culvert is reduced, the flow rate into the CDFS is increased, and the high-speed rotor speed is increased, resulting in a decrease in the compressor surge margin. At the same time, due to the back pressure, the boost ratio of the fan decreases, and the operating point moves down, so the surge margin increases. The decrease in the flow rate of the outer culvert reduces the bypass ratio, and the magnitude of the increase in thrust becomes larger, resulting in a decrease in the fuel consumption rate.

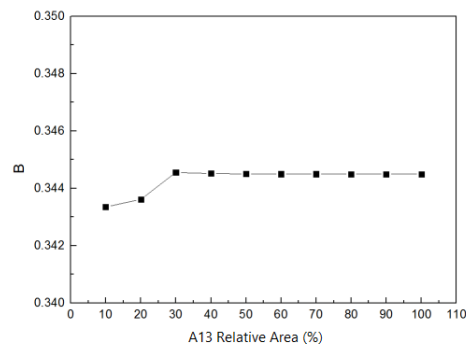


Figure 17. The bypass ratio

5. Conclusion

In this paper, the relationship between the adjustable components and the variable cycle engine performance is simulated. The following conclusions are obtained:

1. Based on the conventional turbofan engine, components such as MSV, CDFS, FVABI and RVABI are added to form a model of a double culvert variable cycle engine. The engine model and simulation calculation system are established, then the effectiveness of the model and method is verified by simulation of the reference point.
2. The effects of geometric adjustment components on engine performance under the two working modes are studied. The simulation results show that in the same work mode, the FVABI and the RVABI have the same effect on engine performance, but different from the MSV. Both FVABI and RVABI have different effects on engine performance in different modes.

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