Proceedings of the 2nd International Conference on Computing Innovation and Applied Physics (CONF-CIAP 2023)
DOI: 10.54254/2753-8818/5/20230384

Analysis of variable cycle engines performance in cruising using GasTurb11

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Abstract. Variable cycle engines (VCE) have always been a hot topic in aircraft engine research. Because of its variable thermal cycle characteristics, it has a wide range of optimum operating conditions (altitude, flight Mach number). In this paper, a typical double bypass variable cycle engine is used as the object of study, and the Gasturb11 software is used to simulate the engine in two main modes at different altitudes and Mach numbers, to observe the engine operation performance, as well as the relationship between the range and endurance from the derivation of cruise equation. The results show that VCE has a best thermal cycling pattern for a given altitude and Mach number, and for a range of lift-to-drag ratios, resulting in the longest range or endurance of the aircraft. This paper investigates the relationship between range, endurance and thrust of a variable cycle engine and altitude and Mach number to help make the VCE better suited to the needs of an aircraft with multiple missions, long range and high endurance.

Keywords: Variable Cycle Engine (VCE), Double bypass engine, maximum cruise range (endurance), Gasturb, Thrust Specific Fuel Consumption (TSFC).

1. Introduction

The variable cycle engine concept has been proposed and designed in the 20th century [1, 2]. A variable cycle engine (VCE) is an engine that can control the variation of thermal cycle characteristics. The subject of this paper is a typical double bypass variable cycle engine, whose main control factor is the bypass ratio, and there are two main modes: supersonic single bypass mode (approximate to turbojet) and subsonic double bypass [3], so this engine can be considered as a turbofan engine that can control the variation of bypass ratio. Therefore, the variable cycle engine can solve the contradiction that low unit fuel consumption and high thrust-to-weight ratio of aircraft engines cannot be achieved at the same time, which greatly meets the needs of military engines for multi-mission and long range or high endurance [4].

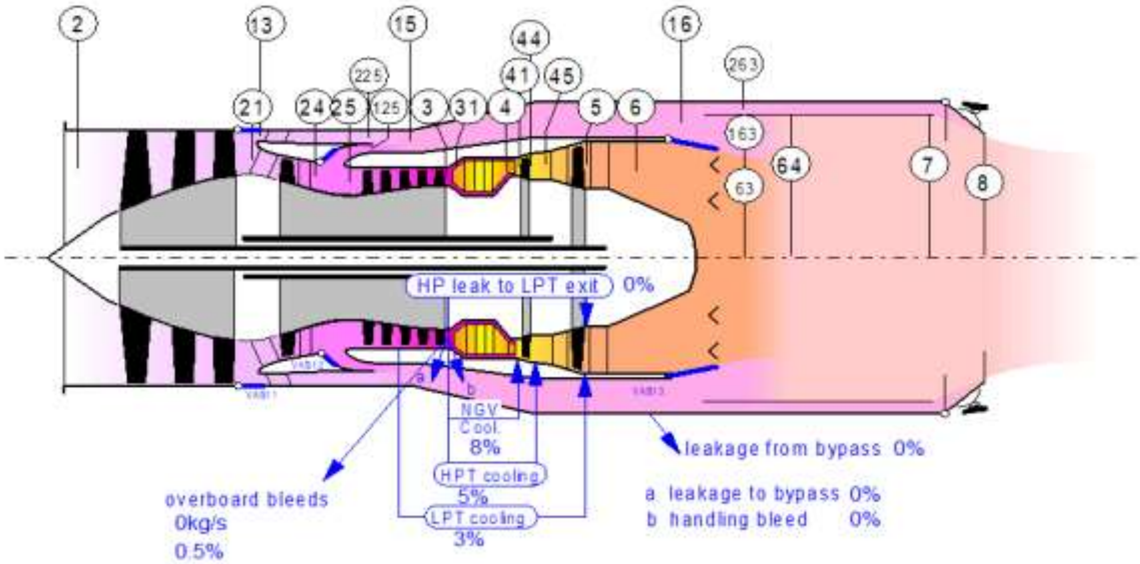

Figure 1. Typical double bypass variable cycle engine architecture (screenshot from Gasturb11) [5].

The double bypass variable cycle engine shown in Figure 1 is similar in construction to the low bypass ratio twin shaft turbofan engine above, with the main differences being the branch between the intermediate pressure compressor (IPC) and high pressure compressor (HPC) leading to the outer bypass, and the presence of three Variable-Area Bypass Injectors (VABI) including the mode selector valve (i.e. VABI1), the front adjustable pilot injector (FVABI) (i.e. VABI2), and the rear adjustable injectors (i.e. VABI3).

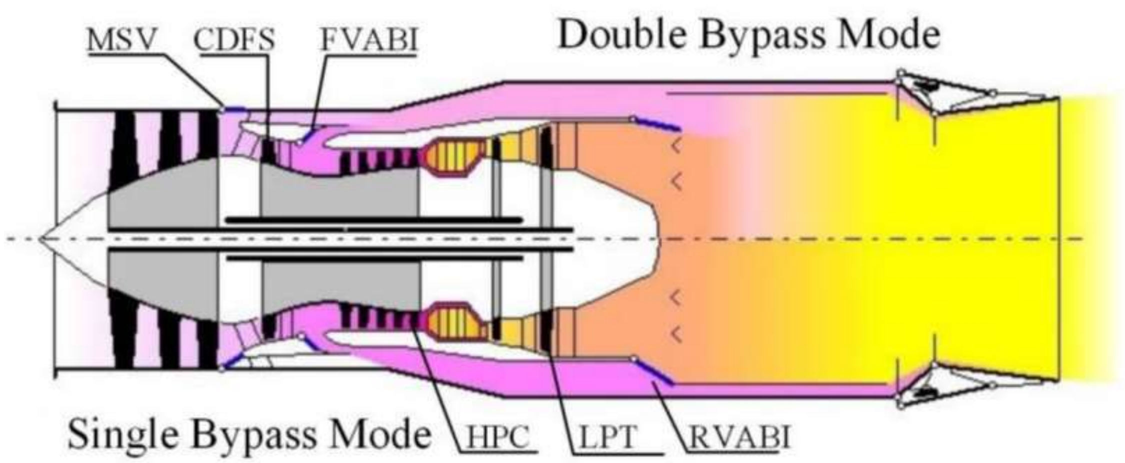

Figure 2. Double and Single Bypass Modes for VCE [6].

When the engine is operating in the large bypass ratio mode, the mode selector valve (MSV) and the forward variable area bypass injector (FVABI) is opened, and the outer bypass area of the rear adjustable injector is opened to match the static pressures of the inner and outer bypasses. As shown in the upper part of Figure 2, this mode is also known as double bypass mode (DBM) or low fuel consumption mode.

When working in the small bypass ratio mode, the MSV is closed, the FVABI is closed a little, so that a less amount of airflow is separated to the outer bypass, and the outer bypass area of the rear

DOI: 10.54254/2753-8818/5/20230384

adjustable injector is closed to a certain extent to match pressures. As shown in the lower part of Figure 2, this mode is also called single bypass mode (SBM) or the large thrust mode.

This paper focuses on analyzing the simulation data of VCE operating at different Mach number and altitudes by adjusting the bypass ratio controlled by FVABI in both modes in Gasturb11, an engine simulation software (where the thermodynamic data of the main components of the engine including pressure, temperature, mass flow, etc. are obtained from the GasTurb11 program).

The resulting data and graphs, combined with the aircraft performance cruise equation, provide the optimum thermal cycling pattern for a defined altitude and Mach number for a high-endurance or long-range cruise under ideal conditions.

This paper can be used as a reference for a preliminary estimate of the appropriate altitude and Mach number for a typical double bypass VCE, and relatively for the preliminary design of the bypass ratio range for VCE. Enabling aircraft with this type of engine to better meet the needs of multiple missions, long-range and high-endurance abilities.

2. Analysis of cruise performance of VCE using Gasturb11

2.1. Cruising range and endurance calculations

Refer to Aerodynamics and Aircraft Performance, 3rd edition, Chapter 6. Range and Endurance written by J. F. Marchman [8], the following equation can be obtained.

$$R = -\int_{W_1}^{W_2} \frac{1}{\gamma_T}\left(\frac{2}{\rho s}\right)^{\frac{1}{2}} \frac{C_L^{\frac{1}{2}}}{C_D} \frac{dW}{W^{\frac{1}{2}}} \tag{1}$$

$$E = -\int_{W_1}^{W_2} \frac{1}{\gamma_T} \frac{C_L}{C_D} \frac{dW}{W} \tag{2}$$

$$Where\ \gamma_T = gC_T \tag{3}$$

When the aircraft is in level flight (level flight), the air density (ρ) is constant, the angle of attack is constant, and therefore C_L and C_D does not change, then here comes the following.

$$R = \frac{2}{\gamma_T}\left(\frac{2}{\rho s}\right)^{\frac{1}{2}} \frac{C_L^{\frac{1}{2}}}{C_D}(W_1 - W_2) \tag{4}$$

$$E = \frac{1}{\gamma_T} \frac{C_L}{C_D} ln\left(\frac{W_1}{W_2}\right) \tag{5}$$

Based on the level flight formula (4), if setting a longer range as target, in addition to better aerodynamic design aerodynamics (i.e. larger $\frac{C_L^{\frac{1}{2}}}{C_D \cdot s^{\frac{1}{2}}}$) and carrying more fuel (i.e. larger $W_1 - W_2$), on the engine side, weight to fuel consumption (γ_T) should be lower, which also means lower thrust to fuel consumption (TSFC) (C_T), and air density (ρ) should be reduced, which is altitude dependent, and since the required altitude change is considered, the dependent variable studied here is $\rho^{\frac{1}{2}}C_T$, i.e. $\frac{1}{\rho^{\frac{1}{2}}\gamma_T}$in equation; and the endurance equation (5) indicates that if greater endurance (E) is desired, in addition to a better aerodynamic design (i.e. a larger$\frac{C_L}{C_D}$) and carrying more fuel (i.e. larger$\frac{W_1}{W_2}$), the engine has to be more fuel efficient (i.e. larger $\frac{1}{\gamma_T}$).

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In summary, with the cycle altitude and Mach number determined, to get the longest cruising range, make $\frac{1}{\rho^{\frac{1}{2}}\gamma_T}$ largest; and to get the highest endurance, make $\frac{1}{\gamma_T}$ largest.

2.2. Gasturb11 simulation

The simulations are carried out here using the variable cycle engine and associated data that comes with Gasturb 11. In order to visualize the variation in range and endurance, the dependent variable for the final image was set to $\frac{1}{\rho^{\frac{1}{2}}\gamma_T}$ and $\frac{1}{\gamma_T}$. Some data of VCE from the Gasturb11 is shown in Table1.

Table 1. Some data of VCE.

Name	Unit	Value
Intake Pressure Ratio		-0.99
Apply to Bypass only (0/1)		1
Inner Fan Pressure Ratio		3.2
Outer Fan Pressure Ratio		3.5
IP Compressor Pressure Ratio		1.3
Compr. Interduct Press. Ratio		0.99
HP Compressor Pressure Ratio		6
Inlet Corr. Flow W2Rstd	kg/s	50
Burner Exit Temperature	K	1850
Burner Design Efficiency		0.995
Burner Partload Constant		1.6
Fuel Heating Value	MJ/kg	43.124
Overboard Bleed	kg/s	0
Nozzle Cooling Air Wcl/W16		0.3
Power Offtake	kW	50
HP Spool Mechanical Efficiency		1
LP Spool Mechanical Efficiency		1
Bypass 1 Press Ratio P225/P13		0.98
Bypass 2 Press Ratio P125/P24		0.98
Bypass Press Ratio P16/P15		0.98
Design Bypass Mixer Mach Number		0.4
Design Bypass Mixer Area	m^2	0
Burner Pressure Ratio		0.95
Turb. Interd. Ref. Press. Ratio		0.98
Turbine Exit Duct Press Ratio		0.985
Hot Stream Press Ratio		0.99
Cold Stream Press Ratio		0.99
Mixed Stream Pressure Ratio		1
Mixer Efficiency		0.5
Design Mixer Mach Number		0.2944
Design Mixer Area	m^2	0

The following graphs are simulations of $\frac{1}{\rho^{\frac{1}{2}}\gamma_T}$ and $\frac{1}{\gamma_T}$ graphs in Gasturb11 for variable cycle engines in double and single bypass mode, respectively, at Mach numbers of 0.6 and 1.4, at altitudes from 12,000m to 34,000m with changes in FVABI bypass ratio, which also contain net thrust value in colorful contours.

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2.2.1. Double bypass mode DBM (W13:W21=0.3). In Figure 3, the Mach number is determined to be 0.6, and at a certain altitude, at 22,000m for example, the higher the value of FVABI bypass ratio when it is within the range of the above graph, the $\frac{1}{\rho^{\frac{1}{2}}C_T}$ the greater, the greater the maximum range, but as can be seen from the graph, the greater the bypass ratio, the less significant the increase in range. In fact when the bypass ratio reaches a value, $\frac{1}{\rho^{\frac{1}{2}}C_T}$ reaches its highest point and then decreases, for example for a curve of 32,000m, when the bypass ratio is about 0.9, $\frac{1}{\rho^{\frac{1}{2}}C_T}$ has a maximum point of about 0.29, that the range is largest; from 12,000m to 23,000m, the $\frac{1}{\rho^{\frac{1}{2}}C_T}$ at the highest point, the corresponding bypass ratio should be greater than 2.45, but which is not plotted in Figure 3. The Mach number remains constant and the bypass ratio for the longest range at a given altitude continues to increase as the altitude decreases.

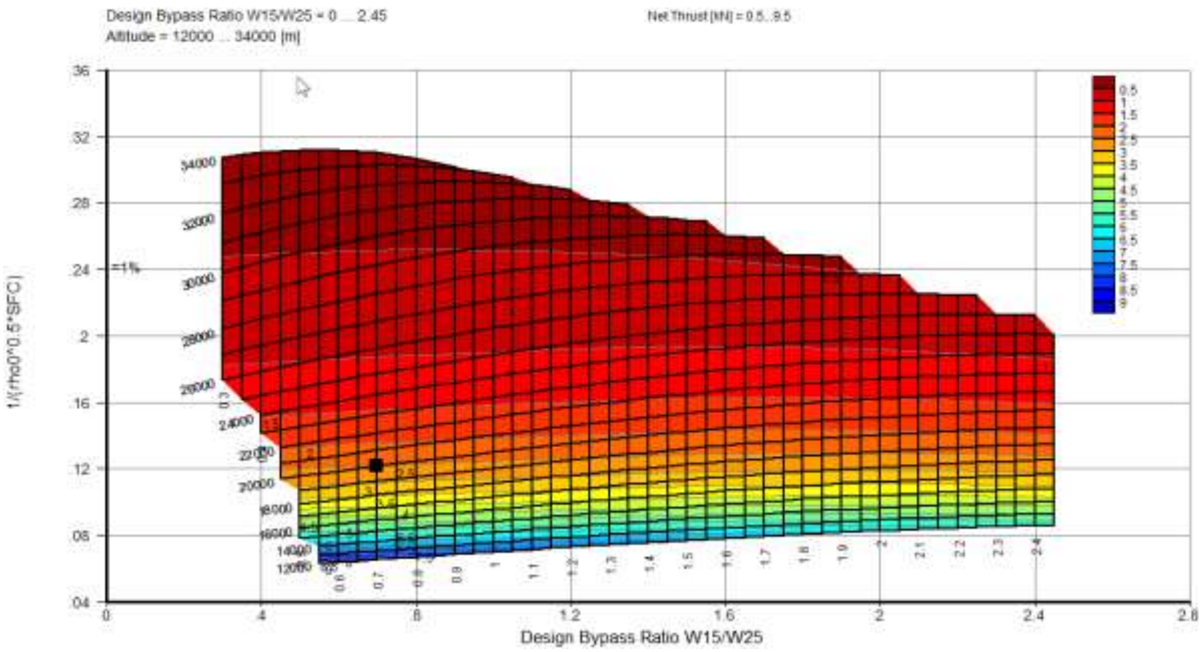

Figure 3. Bypass ratio of W15/W25 vs 1/(rho0^0.5*SFC) ($i.e.$ $\frac{1}{\rho^{\frac{1}{2}}c_T}$) (Ma= 0.6).

Note: original by the author (screenshot from Gasturb11).

In order to pursue a long range, when the cruising Mach number is determined, the cruising altitude range is determined, the bypass ratio design range can refer to in this type of diagram.

The range in Figure 3, where Mach number is determined, and the higher the bypass ratio, the lower the thrust at a given altitude, suggesting that the VCE can reduce the bypass ratio to increase thrust at a constant altitude in flight, but possibly at the cost of reduced range.

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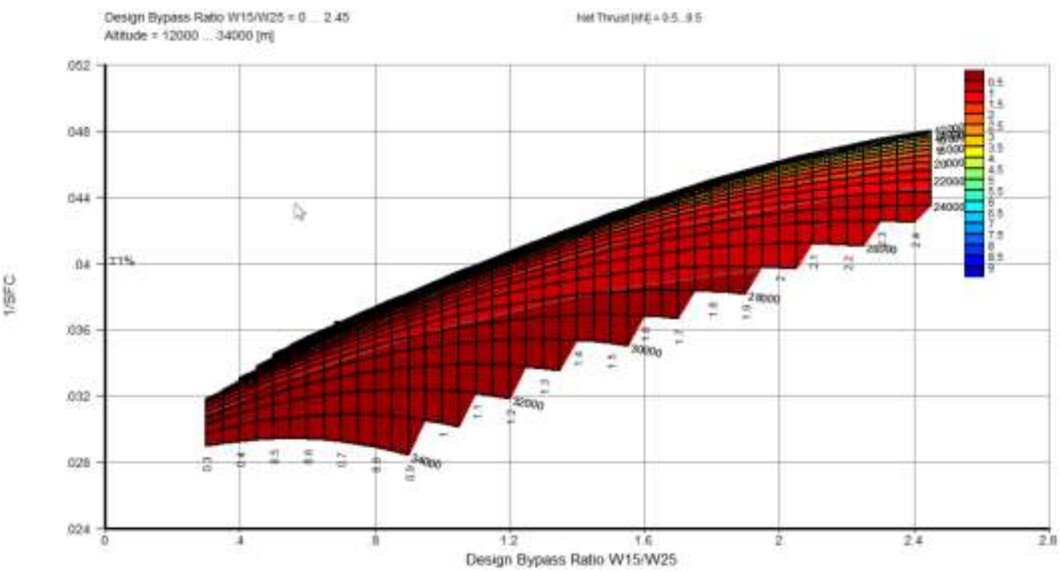

Figure 4. Bypass ratio of W15/W25 vs 1/SFC ($\frac{1}{C_T}$) (Ma=0.6).

Note: original by the author (screenshot from Gasturb11).

In Figure 4, the Mach number is also set at 0.6 and the altitude is determined for a range of 34,000m to 25,000m, and the corresponding bypass ratio making $\frac{1}{\mathrm{C_T}}$ maximum, i.e. the longest sailing time can be found in the range within the figure; it is same for an altitude range of 24,000m to 12,000m, but is outside the range of the plotting. The by-pass ratio for the highest endurance at a given altitude continues to increase as the altitude decreases, and the by-pass ratio for the highest endurance at the same altitude is the same for the largest range (due to the consistent air density at the same altitude).

The main difference with Figure 3 is that in the altitude range of 12,000m to 34,000m, the range and flight time tend to increase and decrease respectively with altitude if the bypass ratio remains constant.

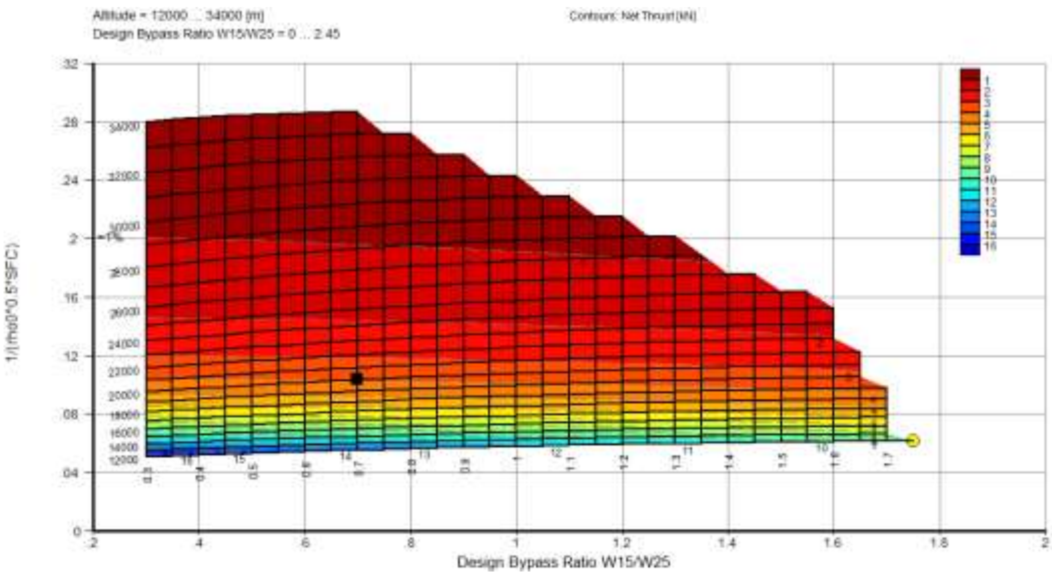

Figure 5. Bypass ratio of W15/W25 vs 1/(rho0^0.5*SFC) ($i.e.$ $\frac{1}{\rho^{\frac{1}{2}} C_T}$) (Ma=1.4).

Note: original by the author (screenshot from Gasturb11).

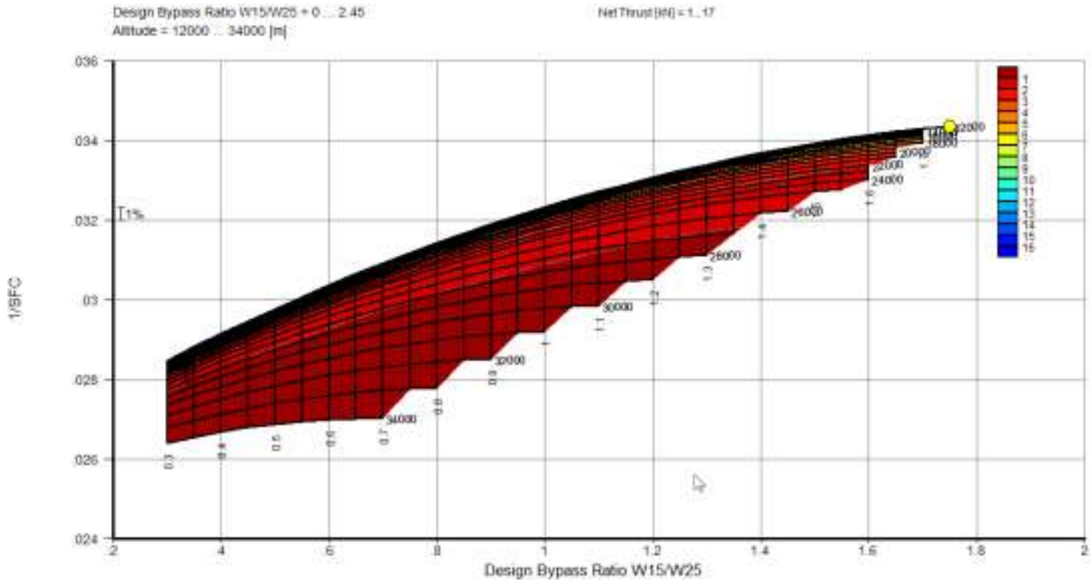

Figure 6. Bypass ratio of W15/W25 vs 1/SFC $(i.e.\ \frac{1}{C_T})$ (Ma=1.4).

Note: original by the author (screenshot from Gasturb11).

Mach numbers of Figure 5 and Figure 3 are 1.4 and 0.6 respectively, and other conditions are same, the magnitude of maximum range at each altitude decreases when Mach number increases in Figure 5. Comparing Figure 6 with Figure 4, the endurance also decreases, since the SFC (thrust specific fuel consumption) increases at each point (which may correlated with an increase in Mach number and an increase in intake flow). The FVABI bypass ratio for both the largest range and endurance tends to increase as Mach number increases.

2.2.2. Single bypass mode SBM (W13:W21=0)

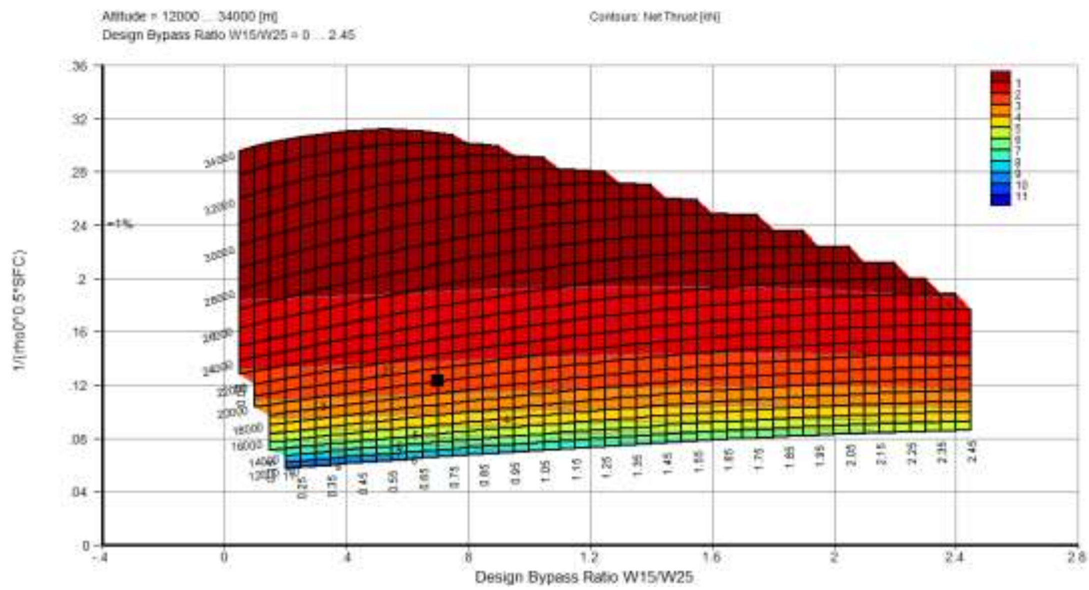

Figure 7. Bypass ratio of W15/W25 vs 1/(rho0^0.5*SFC) $(i.e.\ \frac{1}{\rho^{\frac{1}{2}} c_T})$ (Ma=0.6).

Note: original by the author (screenshot from Gasturb11).

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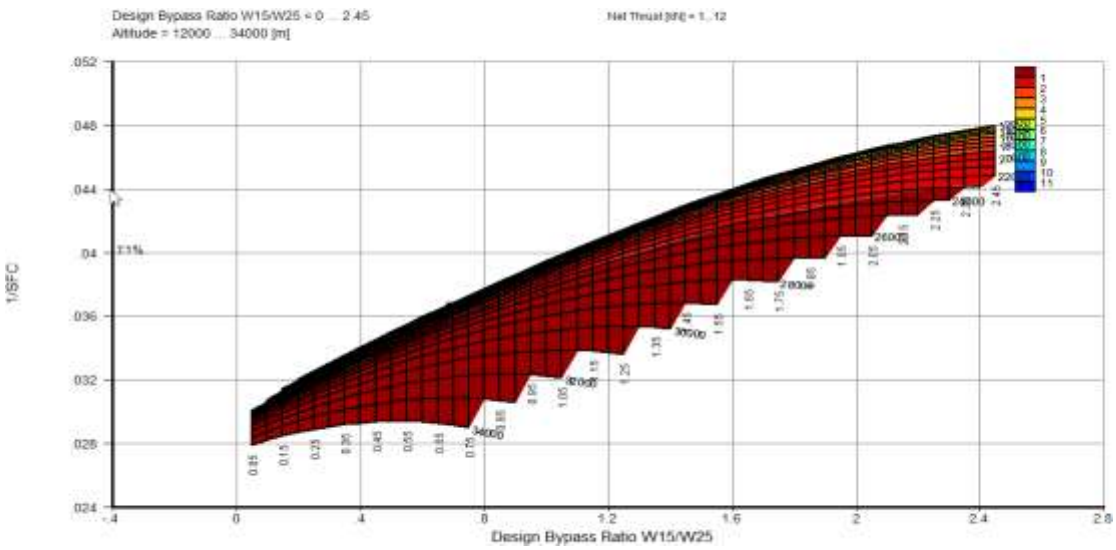

Figure 8. Bypass ratio of W15/W25 vs 1/SFC ($i.e.\ \frac{1}{C_T}$) (Ma=0.6).
Note: original by the author (screenshot from Gasturb11).

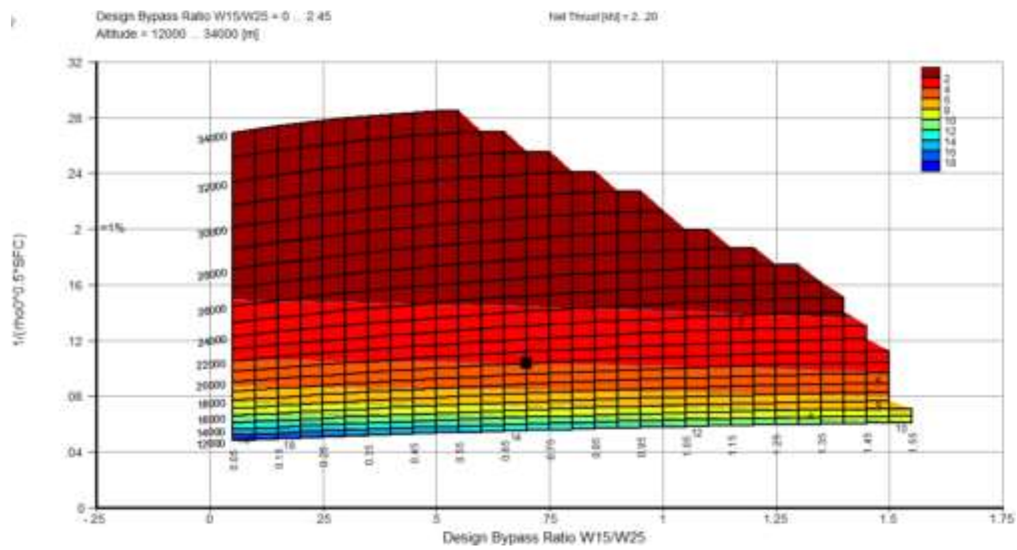

Figure 9. Bypass ratio of W15/W25 vs (rho0)^0.5*SFC ($i.e.\ \frac{1}{\rho^{\frac{1}{2}} c_T}$) (Ma=1.4).
Note: original by the author (screenshot from Gasturb11).

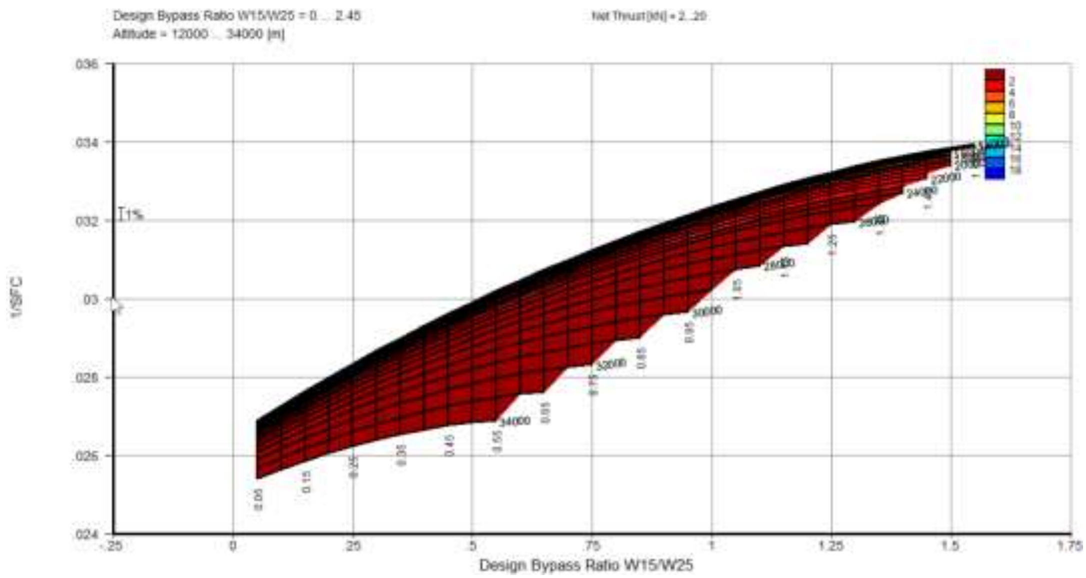

Figure 10. Bypass ratio of W15/W25 vs SFC $(i.e.\ \frac{1}{C_T})$ (Ma=1.4)

Note: original by the author (screenshot from Gasturb11).

Figures 7, 8, 9, and Figure 10 are for single bypass mode (SBM) compared to Figures 3, 4, 5, and Figure 6 for double bypass mode (DBM). The variation of range and endurance with bypass ratio is similar in SBM compared to DBM. There is insignificant variation in the bypass ratio for maximum flight time and range. There is an increase in thrust (higher performance) for the same altitude, Mach number and bypass ratio, which is more pronounced at lower altitudes. Besides, the increase in TSFC leads to a reduction in flight time and range.

3. Conclusion

This paper can be broadly divided into two parts: part 2.1 uses the jet engine cruise equation to find the relevant variables for range and flight time to be studied; part 2.2 uses Gasturb11 to investigate how the relevant variables change when the independent variables, altitude and bypass ratio, are varied for two selected Mach numbers (0.6 and 1.4) in both modes. The results show that for a given Mach number and altitude, there is a corresponding bypass ratio that gives the longest engine flight time and range, and that for a given altitude range, if the bypass ratio remains constant, the range and flight time tend to increase and decrease respectively with increasing altitude. Other things being equal, the single bypass mode gives more thrust than the dual bypass mode, but also increases fuel consumption.

This paper analyses how changes in altitude, bypass ratio and Mach number affect range, endurance and net thrust, enabling aircraft of this engine type to better meet the needs of multi-mission, long range or endurance aircraft.

For limitations, firstly, the paper does not discuss the changes in lift coefficient and drag for a change in altitude and speed (or Mach number) with constant lift (assuming constant aircraft weight). As the relationship between drag coefficient and lift coefficient is unknown in this paper, there is no drag related discussion. Considering that the thrust may not be able to overcome the drag of the Mach number at a certain altitude, the horizontal flight limit is exceeded, and the altitude has to be lowered, or the values of lift coefficient and drag coefficient have to adjust, and more thrust is obtained to overcome the drag. Secondly, here lacks consideration to the actual situation where there is an air adjustable intake in front of the engine and the air intake flow is adapted to the actual speed and altitude (air density and temperature) change according to Mach number and air condition conditions. Third, the value or range of data is set arbitrarily or in a wide range, so the graph directly shot from Gasturb11 lacking precise details.

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