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Optimum Line of High Bypass Twin Spool Separated Flow Turbofan Engine

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Abstract

Today's modern aircraft is based on air-breathing jet propulsion systems, which use moving fluids as substances to transform energy carried by the fluids into power. Throughout aero-vehicle evolution, improvements have been made to the engine performances and pollutants reduction. These goals were achieved by changing of the bypass ratio (B), fan pressure ratio (P_f), overall pressure ratio (OPR), turbine inlet temperature (TIT) as well as using new materials, production and cooling techniques for both turbines and combustion chamber. Such modifications led to improvements in thermal, propulsive and overall efficiencies, decreases in thrust specific fuel consumption (TSFC) and increase the specific thrust. This paper describes an optimization of a twin spool, separated flow, high bypass turbofan engine and focuses on maximum specific thrust (F_s) with optimum specific fuel consumption (SFC). The two variables, fan pressure ratio (P_f) and bypass ratio (B), were selected as ranges of 1.2-1.9 and 5-8. After that optimum line was investigated that connects the points of maximum F_s and optimum SFC in these ranges that shows optimum engine performance.

Keywords:Turbofan; high bypass ratio; performance; optimum;

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Nomenclature	
P	pressure
T	temperature
M	Mach number
π_c	pressure ratio
P_f	fan pressure ratio
η	isentropic efficiency
ΔP_b	pressure loss
f	fuel air ratio
B	bypass ratio
h_{PR}	fuel low heating value
c	velocity
F_s	specific thrust
SFC	specific fuel consumption

1. Introduction

Air travel is continuing to experience the fastest growth among all modes of transport, averaging 5 to 6% per year [1], [2]. Current estimates show that global air traffic volume is growing so fast that total aviation fuel consumption and subsequent aviation emissions' impacts on climate change will continue to grow despite future improvements in engine and airframe technologies and aircraft operations [2], [4]. With a constant increase of air passengers, and the demands for technological innovation to reduce harmful emissions and noise, the impact of commercial propulsion systems becomes even more pronounced. In aviation, engine fuel consumption and aircraft impacts on the environment are two important areas of research. From an environmental perspective, using energy with high efficiency reduces pollutant emissions and harm to ecological systems. For a given output, less fuel is needed when efficiency increases and less waste is released. These benefits lead to increased life times for energy resources and greater sustainability. [1], [3].

In Europe the H2020 ULTIMATE (Ultra Low emission Technology Innovations for Mid-century Aircraft Turbine Engines) project [5] is exploring synergistic combinations of radical technologies to target reductions in all three major loss sources in a state-of-the-art 2015 aero-engine [6]: i) combustor irreversibility; ii) core exhaust heat rejection; and iii) excess of kinetic energy in the propulsive jets.

New commercial aero engines for 2050 are expected to have lower specific thrusts for reduced noise and improved propulsive efficiency, but meeting the ACARE Flight path 2050 fuel burn and emissions targets will also need radical design changes to improve core thermal efficiency [7]. Throughout aero-vehicle evolution, scientists and engineers have attempted to improve engine efficiency, to make it smaller, lighter, require less fuel consumption, and yet more powerful [8].

Aircraft emissions depend on engine characteristics, particularly on the fuel flow rate and the thrust [9]. Aircraft noise is an issue of enormous environmental, financial, and technological impact. There are two main sources of noise in today's commercial aircraft engines: fan/compressor noise and jet noise. The increase in bypass ratio over the last three decades has resulted in a dramatic suppression in the jet noise of turbofan engines [10].

1.1. Turbofan Engines

The turbofan engine had many developments in the past 60 years and becomes the common power plant employed in both civil airliners and military aircrafts. It combines the advantages of both of turboprop engines (high propulsive efficiency and thrust) and turbojet engines (high flight speed and altitude) [11].

Turbofan engines are commonly used on commercial transports due to their advantages for higher performance and lower noise. The noise reduction comes from combinations of changes to the engine cycle parameters and low-noise design features. Engine noise sources principally come from the fan (including the stator), the exhaust (also referred to as the jet), the compressor, the combustor, and the turbine [12].

Over the years gas turbine engines have improved significantly from pure turbojets to the current high bypass turbofan engines. Engine development motivation was done to make them more powerful, lighter and lower fuel consumed. Today aero engines are still developed, but the requirements for new engines introduced to the market growth of new mainly environmental criteria [13].

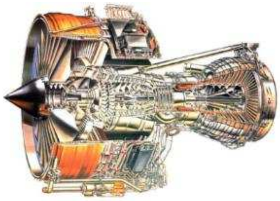

Fig. 1. Turbofan engine (Rolls-Royce Trent 800) [14]

1.2. Classification

Turbofan engines may be classified based on fan location as either forward or aft fan. Based on a number of spools, it may be classified as single, double, and three (triple) spools. Based on a bypass ratio, it may be categorized as either low- or high bypass ratio. The fan may be geared or ungeared to its driving low-pressure turbine. Moreover, mixed types (low-bypass types) may be fitted with afterburner or not. Cross matching between different categories is identified in Fig. 2 [15].

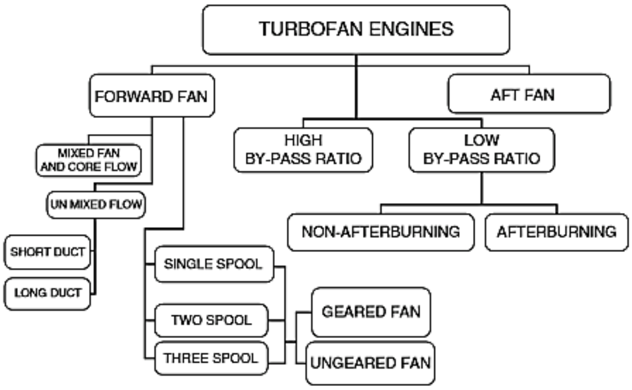

Fig. 2. Classification of turbofan engines [15]

2. Methodology

2.1. Cycle Analysis

Cycle analysis studies the thermodynamic changes of the working fluid (air and products of combustion in most cases) as it flows through the engine. It is divided into two types of analysis: parametric cycle analysis (also called design- point or on-design) and engine performance analysis (also called off-design) [16].

2.2. Twin-spool Separated Flow Turbofan Cycle Modelling

In this section is performed a model overview throughout each component of a two-spool turbofan engine with separated exhaust flows. The model includes:

- Inlet
- Fan
- Compressor
- Combustor
- Turbine (High Pressure Turbine and Low Pressure Turbine)
- Nozzles (Bypass Nozzle and Core or Exhaust Nozzle)
- Thrust and Thrust Specific Fuel Consumption

The following figure will be used throughout the thesis as a reference of the stage numbering within the turbofan.

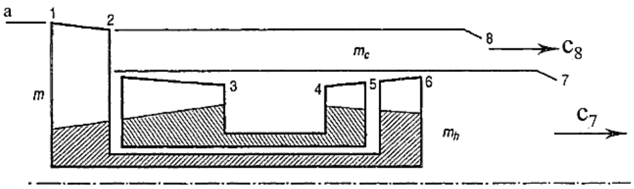

Fig. 3. States numbering for twin-spool turbofan engine [17]

2.3. Baseline Model

1) Inputs and Assumptions:

- Properties of working fluids: γ_a=1.4, c_{pa}=1004 J/kg K, γ_g=1.33, c_{pg} =1148 J/kg K

Table 1. Inputs and assumptions

Inputs and Assumptions	Symbols	Values
Inlet Mach number	M_1	0.9
Inlet static pressure (Pa)	P_a	22700
Inlet static temperature (K)	T_a	216.78
Compressor pressure ratio	π_c	30
Fan pressure ratio	P_f	1.5
Bypass ratio	B	6
Turbine Inlet Temperature (K)	T_{04}	1800
Intake efficiency	η_i	0.98
Fan efficiency	η_f	0.98

Fan nozzle efficiency	η_{fn}	0.99
Compressor efficiency	η_c	0.85
Combustor efficiency	η_b	0.99
High pressure turbine efficiency	η_{HPT}	0.89
Low pressure turbine efficiency	η_{LPT}	0.89
Mechanical efficiency	η_m	0.98
Core nozzle efficiency	η_j	0.99
Combustor pressure loss	ΔP_b	0.04
Fuel low heating value (MJ/kg K)	h_{PR}	42.8

2) Useful Equations:

- Intake

$$P_{01} = P_a \left[1+\eta_i \frac{\gamma_a-1}{2} M_1^2\right]^{\gamma_a/\gamma_a-1}$$

$$T_{01} = T_a \left(1+\frac{\gamma_a-1}{2} M_1^2\right)$$

- Fan

$$P_{02} = P_{01} P_f$$

$$T_{02} = T_{01} \left[1+\frac{1}{\eta_f} \left(\pi_f^{\gamma_a/\gamma_a-1}-1\right)\right]$$

- Compressor

$$P_{03} = P_{02} \pi_c$$

$$T_{03} = T_{02} \left[1+\frac{1}{\eta_c} \left(\pi_c^{\gamma_a/\gamma_a-1}-1\right)\right]$$

- Combustor

$$P_{04} = P_{03} (1- \Delta P_b)$$

$$f = \frac{c_{pg} T_{04}-c_{pa} T_{03}}{\eta_b h_{PR}-c_{pa} T_{04}}$$

- High Pressure Turbine

$$P_{05} = P_{04} \left(1-\frac{T_{04}-T_{05}}{\eta_{HPT} T_{04}}\right)^{\gamma_g/\gamma_g-1}$$

$$T_{05} = T_{04} - \frac{c_{pa} (T_{03}-T_{02})}{c_{pg} \eta_m (1+f)}$$

- Low Pressure Turbine

$$P_{06} = P_{05} \left(1-\frac{T_{05}-T_{06}}{\eta_{LPT} T_{05}}\right)^{\gamma_g/\gamma_g-1}$$

$$T_{06} = T_{05} - \frac{(B+1)c_{pa} (T_{02}-T_{01})}{(1+f)c_{pg}}$$

- Fan Nozzle

$$P_{fc} = P_{02}\left[1-\left(\frac{\gamma_a-1}{\eta_{fn}(\gamma_a+1)}\right)^{\gamma_a/\gamma_a-1}\right]$$

if $P_{fc} < P_a$ (Unchoked)

$$P_8 = P_a$$

$$T_8 = T_{02}\left\{1-\eta_{fn}\left[1-\left(\frac{P_8}{P_{02}}\right)^{\gamma_a/\gamma_a-1}\right]\right\}$$

$$c_8 = \sqrt{2\, c_{pa}\,(T_{02}-T_8)}$$

if $P_{fc} > P_a$ (Choked)

$$P_8 = P_{fc}$$

$$T_8 = T_{02}\left(\frac{2}{\gamma_a-1}\right)$$

$$\rho_8 = \frac{P_8}{R_a\, T_8}$$

$$c_8 = \sqrt{\gamma_a\, R_a\, T_8}$$

- Jet Nozzle

$$P_{jc} = P_{06}\left[1-\left(\frac{\gamma_g-1}{\eta_j(\gamma_g+1)}\right)^{\gamma_g/\gamma_g-1}\right]$$

if $P_{jc} < P_a$

$P_7 = P_a$ (Unchoked)

$$T_7 = T_{06}\left\{1-\eta_j\left[1-\left(\frac{P_7}{P_{06}}\right)^{\gamma_g/\gamma_g-1}\right]\right\}$$

$$c_8 = \sqrt{2\, c_{pg}\,(T_{06}-T_7)}$$

if $P_{jc} > P_1$ (Choked)

$$P_7 = P_{jc}$$

$$T_7 = T_{06}\left(\frac{2}{\gamma_g-1}\right)$$

$$\rho 7 = \frac{P_7}{R_g\, T_7}$$

$$c_7 = \sqrt{\gamma_g\, R_g\, T_7}$$

- Specific Thrust and Specific Fuel Consumption

$$F_s = \frac{1}{B+1}(c_7-c_a)+\frac{B}{B+1}(c_8-c_a)+\frac{P_8-P_a}{\rho_8\, c_8}+\frac{P_7-P_a}{\rho_7\, c_7}$$

$$SFC = \frac{f}{(1+B)F_s}\times 3600\times 1000$$

3) Outputs: The outputs of baseline model are shown in Table 2.

Table 2. Outputs for baseline model

Outputs	Values	Units
P_{01}	0.3839	bar
P_{02}	0.5759	bar
P_{03}	17.277	bar
P_{04}	16.586	bar
P_{05}	4.0214	bar
P_{06}	2.2114	bar
P_7	1.1869	bar
P_8	0.3021	bar
T_{01}	251.898	K
T_{02}	283.469	K
T_{03}	831.271	K
T_{05}	1325.1	K
T_{06}	1162.5	K
T_7	997.8659	K
T_8	236.2242	K
c_7	614.8427	m/s
c_8	308.1592	m/s
F_s	519.8740	N/(kg/s)
SFC	0.0305	kg/(N.hr)

4) Parametric Studies

Parametric cycle analysis is also called design point analysis or on-design analysis because each plotted engine is operating at its so-called design point. The main objective of parametric cycle analysis is to relate the engine performance parameters (primarily thrust F and thrust specific fuel consumption S) to design choices (compressor pressure ratio, fan pressure ratio, bypass ratio, etc.), to design limitations (burner exit temperature, compressor exit pressure, etc.), and to flight environment (Mach number, ambient temperature, etc.). From parametric cycle analysis, we can easily determine which engine type (e.g., turbofan) and component design characteristics (range of design choices) best satisfy a particular need [16].

3. Results and discussions

3.1. Fixed bypass ratio

Two important parameters, fan pressure ratio and bypass ratio, are selected ranges of 1.2-1.9 and 5-8 (high bypass). Consider the effects of P_f and B on specific thrust and SFC. Firstly, bypass ratio fixed and fan pressure ratio were changed from 1.2 to 1.9 as shown in Fig. 4 and Fig. 5.

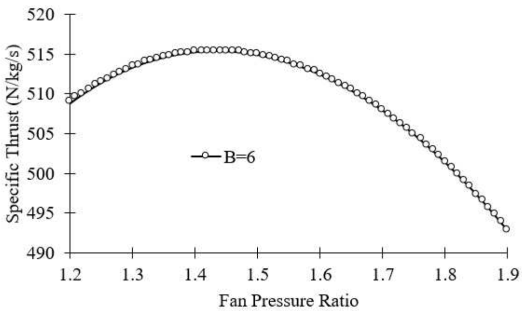

Fig. 4. Variation of F_s with P_f (fixed B)

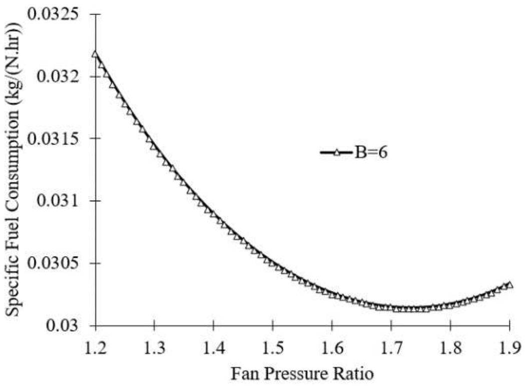

Fig. 5.Variation of SFC with P_f (fixed B)

The specific thrust increases with fan pressure ratio until P_f is 1.43. After this point, F_s decreases when P_f increases.

Also, the specific fuel consumption decreases with fan pressure ratio before P_f=1.73. From these graphs, we could determine the points that are maximum F_s and minimum SFC for B=6.

3.2. Fixed Fan Pressure Ratio

After that, fan pressure is fixed and bypass ratio is changed from 5 to 8 for high bypass turbofan engine. Fig. 6 and Fig. 7 show the variation of F_s and SFC with bypass ratio.

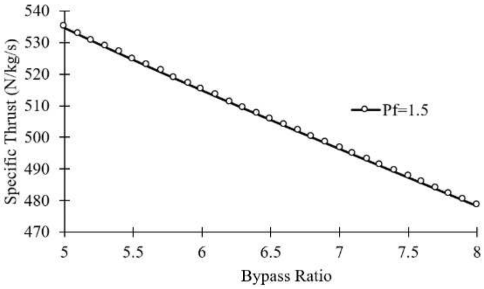

Fig. 6. Variation of Fs with B (fixed P_f)

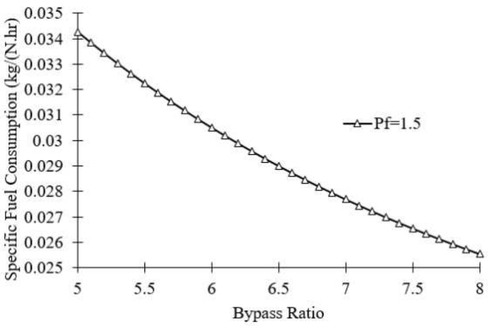

Fig. 7. Variation of SFC with B (fixed P_f)

These figures could be summarized as increasing bypass ratio decreases both F_s and SFC.

3.3. Consideration on effects of 10% changing parameters

In this section we analyse which parameter is more influence on performances. Therefore, two parameters are decreased 10% from the baseline model.

Table 3. Percentage changes of parameters

	Baseline	10% decrease in B	10% decrease in Pf
P_f	1.5	-----	-10%
B	6	-10%	-----
F_s (N/kg/s)	514.8740	+2.26%	+0.58%
SFC (kg/N.hr)	0.0305	+6.88%	+1.97%

As can be seen in Table 3, bypass ratio is more influence on engine performances at this condition. And then, SFC is optimized to get maximum specific thrust when changing parameters.

3.4. Optimization of SFC for maximum specific thrust

In this section the analysis of optimum line for higher performance is described. As shown in Fig. 8 and Table. 4, the optimum point is the point of maximum specific thrust and optimum SFC for specific bypass ratio and related fan pressure ratio.

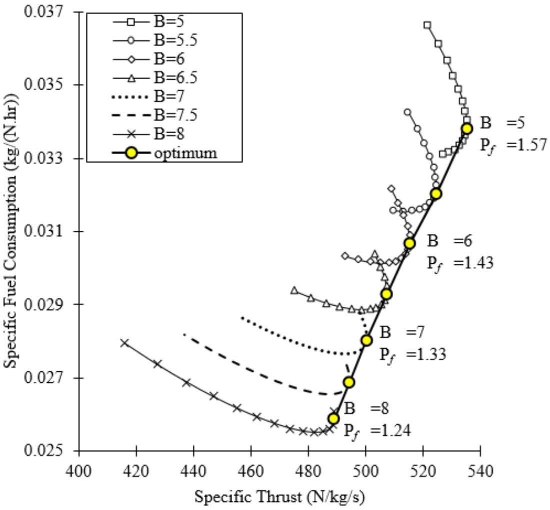

Fig. 8. Optimum line for high bypass turbofan engine

Table 2. Optimum line for maximum thrust

B	P_f	Max F_s (N/kg/s)	Opt SFC (g/N.hr)
5	1.57	535.1471	0.0339
5.5	1.5	524.5556	0.0322
6	1.43	515.3582	0.0308
6.5	1.38	507.3562	0.0294
7	1.33	500.3851	0.0281
7.5	1.28	494.3111	0.0270
8	1.24	489.0149	0.0259

4. Conclusions

Firstly, bypass ratio fixed and fan pressure ratio were changed from 1.2 to 1.9.The specific thrust increases with fan pressure ratio until P_f is 1.43. After this point, F_s decreases when P_f increases. Also, the specific fuel consumption decreases with fan pressure ratio before P_f=1.73.

After that, fan pressure was fixed and bypass ratio is changed from 5 to 8 for high bypass turbofan engine. When the bypass ratio increases, both F_s and SFC decreases.

And then, optimum line for higher performance turbofan engine was designed. This line is very compatible for consideration of maximum thrust with optimum specific fuel consumption.

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