ME 140
Advanced Thermal Systems

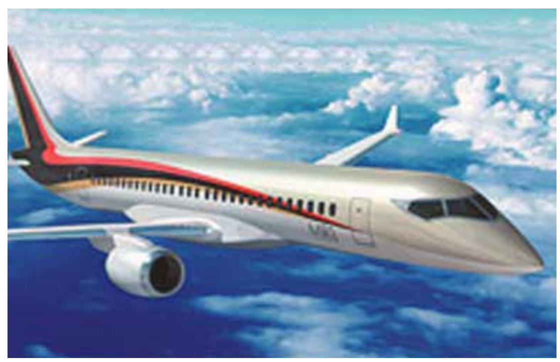
Project #1
Pratt-Whitney 1000G High-Bypass Geared Turbofan Engine
(Due Wednesday, April 11, 2018)

Background

Aircraft engine manufacturers are developing new engines for the next-generation of commercial aircraft that will provide increased engine efficiency and deliver significantly lower fuel consumption, emissions and noise. One such engine is the Pratt & Whitney PW1000G turbofan engine that utilizes a state-of-the-art gear system allowing the engine's fan to operate at a slower, optimum speed while freeing the low-pressure compressor and turbine to operate at their optimized higher speed. The geared turbofan concept is combined with a two-shaft design that is inherently simpler than the three-shaft design employed by Rolls Royce to accomplish the same objective of optimum speeds of fan, compressors and turbines.

The PW1000G provides maximum thrust in the range of 14,000 – 23,000 lb_f (62 – 102 kN), and is intended for use on the next-generation of regional jets, including the Bombardier C-series and the Mitsubishi MRJ, shown below in artist conceptions.

Bombardier C-Series Aircraft



Mitsubishi Regional Jet

A photograph of a PW1000G engine is shown in Fig. 1 and an engine cutaway is shown in Fig. 2.

Fig. 1 Photograph of the PW1000G geared turbofan engine

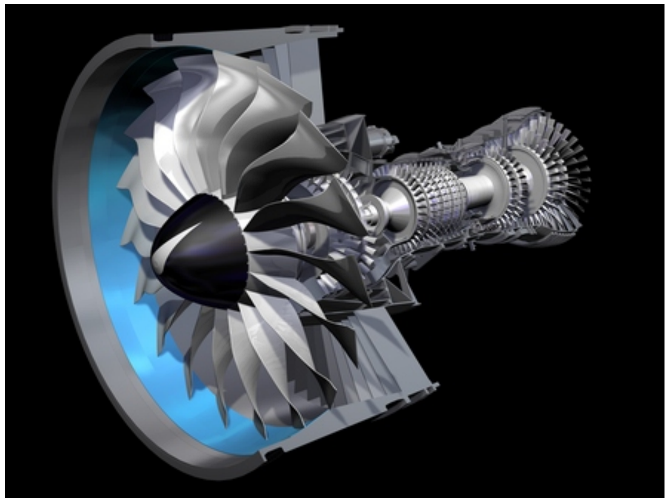


Fig. 2 Cutaway of the PW1000G geared turbofan engine

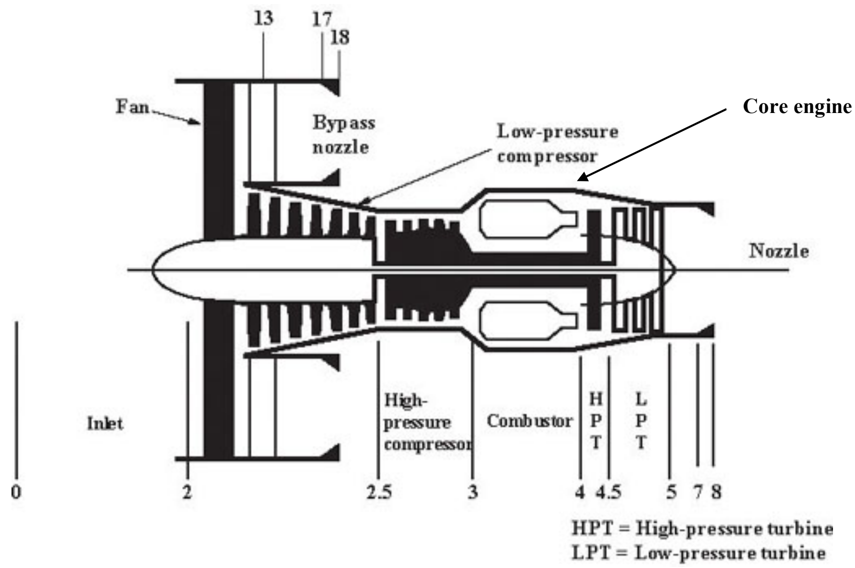


Fig. 3 Schematic diagram of a conventional two-spool turbofan engine

The PW1000G is a two-spool turbofan engine of the type shown in Fig. 3, which means that there are two independent compressors and turbines. In the geared turbofan design, the single-stage fan is driven by a gear box connected to the shaft that couples the axial flow low-pressure (LP) compressor to the axial flow low-pressure (LP) turbine. The high-pressure (HP) compressor is driven by a separate shaft connected to the high-pressure (HP) turbine. Note that all of the air passes through the fan, but only a fraction of this air flows through the core engine. An important design parameter for turbofan engines is the bypass ratio, which is the ratio of the air mass flow rate that "bypasses" the core engine to the air mass flow rate through the core engine. The PW1000G series engines have bypass ratios in the range of 10-12, which means that most of the thrust is generated by the fan.

The Assignment

The objective of this assignment is to perform a cycle analysis of the PW1000G to determine the engine performance at the sea-level static (SLS), or take-off condition, and at the design cruise condition (35 kft). The parameters to be determined include, thrust (kN), specific thrust ($kN/kg_{air}/s$), and thrust specific fuel consumption ($kg_{fuel}/s/kN$). Important flight and engine parameters at cruise and SLS are given in Table 1. Engine component data are given in Table 2.

1. 10 points: Prepare a computer-generated component diagram of the overall engine showing the relationships between the various components using the state designations from the engine schematic (That is, translate the schematic diagram of Fig. 3 into a thermodynamic component diagram).

2. 30 points: Develop an ideal-fluid/real-process model for the engine. Here, ideal fluid means that the working fluid is treated as engineering (dry) air with constant specific heats (use k = 1.4, C_p = 1.005 kJ/kgK). See Chapter 9 in Çengel and Boles (6th edition) for a refresher on analysis of open Brayton cycles. Real process means that the component performance parameters in Table 2 should be incorporated in your analysis. Use this model to compute the parameters listed above at both the SLS and design cruise conditions. Compare your SLS thrust value with the maximum certified value of 17,000 lb_f (75.6 kN) for the PW1217G that will be used on the initial versions of the MRJ90 aircraft. This will be a test of the accuracy of your model/calculations. It might be useful to initially do these calculations "by hand" before writing the Matlab script.

3. 40 points: Repeat the calculation of (2) using a real-fluid/real-process model for the engine. Here, real fluid means engineering air with variable specific heat. Use the polynomial expression for air C_P, given in Appendix 1, Table A-2 of Çengel and Boles. Matlab should be used for these calculations.

Table 1. Parameters for Cruise and SLS

Parameter	Cruise	SLS
Altitude (km)	10.67 (35kft)	0
Static T at station 0 - $T_{0static}$ (K)	218.8	288.15
Static P at station 0 - $P_{0static}$ (bar)	0.239	1.014
Mach number	0.78	0
Overall pressure ratio, P_{03}/P_{02} (Fan & Comp)	32	28
Fan pressure ratio, P_{013}/P_{02}	1.55	1.52
T_{04} (K) –TIT (Turbine Inlet Temperature)	1450	1650
Total air mass flow rate (kg/s)	110	265
Bypass ratio	10	10

Table 2. Engine Component Data

Component	Parameter	Value
Engine inlet	Pressure recovery factor (P_{02}/P_{00})	1.00^{*}, 0.998^{+}
Fan	Adiabatic (total-to-total)** efficiency	0.95
Compressor	Adiabatic (total-to-total) efficiency	0.89
Turbine	Adiabatic (total-to-total) efficiency	0.90
Core/Bypass Nozzle	Adiabatic (total-to-static) efficiency	0.95
Combustor	Pressure loss ratio (P_{04}/P_{03})	0.95

* SLS, + Cruise

**(total-to-total) means the efficiency is defined for stagnation rather than static values

4. <u>10 points:</u> Using Matlab, plot T-s diagrams for both the SLS and design cruise conditions, for part (3). Show separate plots for the fan and the overall engine. Carefully label the state points using static states at the inlet and exit and stagnation states at internal stations, using the standard state notation of the engine schematic. Since the exact path connecting the states is not known, connect the state points by a dashed line.

5. The Report (one report per group) <u>10 points</u>: A formal write-up is not required for this assignment. Please provide the requested component diagram and performance parameters (in a neat, formatted table) plus a set of neat, professional figures. Your analysis will be evaluated both for accuracy and presentation quality.

   <u>Discussion:</u> The purpose of a turbofan engine is to provide thrust. Key design parameters are the overall pressure ratio, the turbine inlet temperature and the bypass ratio. Vary each of these parameters in your model (one at a time) to determine for each parameter whether it should be increased or decreased to improve engine performance. Also provide a brief discussion of the impact of including variable specific heats on the results.

6. In addition to your plots, please include a brief statement BY EACH MEMBER OF THE TEAM about how much time was spent on each part of the analysis and what you thought were the most and least useful aspects of the assignment. Also comment on what is still unclear to you, if anything. (We will ask for this each week.)

<u>Summary of the Deliverables</u>

(1) A computer-generated component diagram that includes state labels consistent with the engine schematic

(2) A table that includes performance parameters (thrust, specific thrust, and thrust specific fuel consumption) for an *ideal-fluid/real process* at both SLS and design cruise conditions

(3) A table that includes the performance parameters *for a real-fluid/real-process* at both SLS and design cruise conditions

(4) Four T-s diagrams

a diagram for the core flow and one for the bypass flow at SLS

a diagram for the core flow and one for the bypass flow at design cruise conditions

(5) Brief discussions addressing

- how engine thrust varies with variations in pressure ratio, turbine inlet temperature and bypass ratio
- the impact of employing variable specific heats instead of using constant specific heats

(6) Brief reflections about the project by each member of team (time spent, useful aspects, still unclear issues)

(7) Any Matlab codes that were developed during the project

Definitions

Bypass ratio, BPR $\equiv \dfrac{\text{bypass air mass flow rate}}{\text{core engine air mass flow rate}}$

Thrust, F = the ***net*** forward force provided by the engine.

Specific thrust, ST $\equiv \dfrac{\text{F}}{\text{air mass flow rate}}$ = thrust per unit of total air flow through the engine, a measure of how efficiently the engine uses it cross-sectional area. This is important for fan engines with large cross-section since cross-sectional area is related to drag and engine weight.

Thrust-specific fuel consumption, TSFC $\equiv \dfrac{\text{fuel mass flow rate}}{\text{F}}$ = fuel used to produce unit thrust.

Thrust-specific fuel consumption is an inverse measure of engine efficiency. This parameter is viewed as being very important by the airlines (low values are good) since fuel costs are one of the major operating expenses. For the idealized cycles you are analyzing, where there is no fuel addition, only heat addition, the equivalent fuel flow rate may be approximated using $\dot{Q} = \dot{m}_{fuel} \cdot \text{LHV}$, where LHV = fuel lower heating value = 42.8 MJ/kg for jet fuel. The result is only approximate as the added fuel mass in the core engine exhaust (which contributes to core engine thrust) is neglected. Fortunately, since the fan is the major contributor to thrust and the air/fuel ratio in the core engine is very large, neglecting fuel flow rate introduces very small errors in the thrust calculation.

Adiabatic (total-to-static) efficiency, η = the adiabatic efficiency as defined in class for stagnation enthalpies rather than static enthalpies. The use of stagnation values allows the calculation of thermodynamic states without knowing the velocity at each station.