MAE 112 Design Project
Preliminary Design of a Turbofan Engine

Nov. 7, 2021

Due 11:00pm, Fri. Nov. 26, 2021

No extension, start right now.

This design project constitutes 15% of the final grade. No standard solution is available since each one of you may do things differently. The design report will be judged upon based on: 1) Clear presentation of your analysis, design procedure, final design parameters, and performance assessment; 2) Correctness and completeness of the analysis, design criteria, and performance assessment.

1 Mission Requirement

Boom Technologies (https://boomsupersonic.com) is developing a new supersonic business jet called Overture. Presently, Boom intends to select Rolls-Royce to be a partner in developing the engine for Overture.

UCI-Supersonic 2021, however, plans to offer a better turbofan engine for Boom's Overture than Rolls-Royce. Boom projects the following design conditions/requirements for the plane:

1. Total number of passangers including crew: 65
2. Maximum Take-off Weight (MTOW): 77,000 kg
3. Cruise Mach number: $M = 1.7$
4. Cruise Altitude: 60,000 feet
5. Range: 8000 km
6. Three non-afterburner turbo-fan engines, each with no less than 80 KN thrust at cruise condition

UCI-Supersonic 2021 must guarantee

1. a minimum thrust of 80 kN at the cruise Mach number and altitude.
2. a minimum take-off thrust of 100 kN.
3. competitive TSFC
4. an inlet diameter of no more than 2 m.
5. A turbine inlet stagnation temperature of no more than 1800 K due to material limit and reliabilty considerations.

2 On-Design Parameters

Sketch your basic engine configuration and show on the $h-s$ diagram of your engine cycle. For preliminary design we need to choose the following design parameters

1. turbine inlet temperature: T_{04};
2. compressor pressure ratio: π_c;
3. bypass ratio: β;
4. bypass pressure ratio: π_f;
5. afterburner maximum temperature if an afterburner is used;
6. size of the engine (inlet diameter);

Component efficiencies depend on the performance of each individual component. Some typical values, however, are listed below

Component	Efficiency	Average Specific heat ratio
Inlet/Diffuser	$\eta_d = 0.95$	1.4
Compressor Polytropic efficiency	$\eta_{pc} = 0.90$	1.37
Fan Adiabatic Efficiency	$\eta_{c'} = 0.92$	1.4
Burner efficiency	$\eta_b = 0.97$	1.35
Burner Pressure Recovery	$\pi_b = 0.95$	1.35
Turbine Polytropic Efficiency	$\eta_{pt} = 0.92$	1.33
Primary Nozzle	$\eta_n = 0.98$	1.36
Fan Nozzle	$\eta_{n'} = 0.99$	1.4

The maximum mass flow rate per unit area of the inlet may be estimated as

$$\frac{\dot{m}}{A} = 231.8\frac{\delta_0}{\sqrt{\theta_0}} \quad (\mathrm{kg/s})/\mathrm{m}^2$$

where

$$\delta_0 = p_{02}/p_{a,st}$$

$$\theta_0 = T_{02}/T_{a,st}$$

$p_{a,st}$ and $T_{a,st}$ are the standard sea level pressure and temperature.

The design objective is to determine a design that satisfies the mission requirement and strikes the best trade-off between fuel efficiency and engine size for the given mission and design constraints. Practical design involves a lot of complex factors. You may want to discuss such factors in your report. Discuss such factors in your choice of parameters for your final design.

3 Suggested Design Procedure

Use the computer program you have developed in your homework assignments to calculate TSFC, ST and any other performance paraters of your interest for different design parameters listed in the above section.

1. You will find that for given T_{04} and π_c, a higher bypass ratio will yield higher propulsion efficiency, and thus lower $TSFC$. This $TSFC$ is called the uninstalled or bare thrust specific fuel consumption rate: $TSFC_{bare}$. However, increasing bypass ratio increases the engine size, which in turn increases the external drag of the engine nacelle once installed on the airplane. This drag effectively decreases the net thrust $\mathcal{T}$ and thus increases the effective $TSFC$, which we call the installed thrust and specific fuel consumption rate. The effective installed thrust may be estimated to depend on the bypass ratio through the following equation for supersonic flight

$$\mathcal{T} = \frac{\mathcal{T}_{bare}}{1.04 + 0.01\beta^{1.2}}$$

2. For the purpose of this design project, it is convenient to define the Specific Thrust based on the total mass flow rate $\dot{m} = \dot{m}_a(1+\beta)$, ie.,

$$ST = \frac{\mathcal{T}}{\dot{m}_a(1+\beta)}$$

   where $\dot{m}_a$ is the mass flow rate through the core engine.

3. For the outer most loop. Loop through the turbine inlet temperature T_{04}, say in the range of 1400K to 1800K, with 50K intervals;

4. Within the given T_{04} in the outer loop, creat an inner loop of the compressor pressure ratio π_c, say from 16 to 40 with an interval of 2.

5. Once you have chosen the T_{04} and π_c, you will notice that the fuel air ratio $f = \dot{m}_f/\dot{m}_a$, p_{05} and T_{05} are determined. In other words, the core engine (gas generator) is determined. Now the job is to optimize the by-pass ratio β and fan pressure ratio π_f to make the best use of the high-temperature high-pressure gas generated by the core engine. Create countour plots for $TSFC$ and ST in the (β, π_f) plane. Use these plots to determine your choice of β and π_f. You may favor $TSFC$ over ST or strike a balance between the two based on your judgement and preference. Record your choice of the β and π_f and the corresponding $(TSFC, ST)$ pair for the chosen T_{04} and π_c.

6. Once you complete the above loops, you will then have completed tables of $TSFC$, ST, or any other performance parameters of your interest vs. T_{04}, π_c, say with T_{04} as the row variable and p_c as the column variable.

   Each $(TSFC, Thurst)$ pair marks one point in the $(TSFC, ST)$ plane. Use the rows and columns in this table to produce a carpet plot for the cruise condition similar to the figure shown below.

   Create also countour plots of $TSFC$, ST (constant lines of $TSFC$ and ST in the (π_c-T_{04} plane. Create contour plots of η_t, η_p, η_0, and any other performance parameters of your interst in the (π_c-T_{04}) plane.

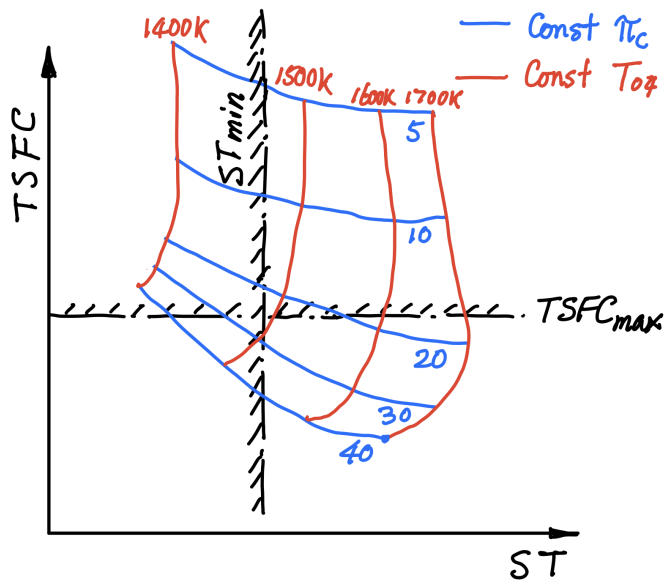

Figure 1: Carppet Plot of $TSFC$ and ST vs. T_{04} and π_c

7. Draw a dashed horizontal line on the carpet plot corresponding to the maximum allowable TSFC for the cruise condition. Draw a dashed vertical line for the minimum ST with the inlet diameter limit. Now you can use the above plots or contours to help you choose the design π_c-T_{04} and without violating the constraints. You may also use the contour plots for the same purposes.

Notice in the above process, you may find that your computer program may fail for some choices of high β and π_f values. That is most likely because your core engine does not have enough power to support such high bypass ratio and fan pressure ratio. That is ok, you can leave them blank in your table and leave them out in your graph.

4 Project Report

The report should be typed (equations may be handwritten) and in the following format

- Title, name, date
- Abstract (less than one page)
- Introduction
- Design Method, the basic equations.
- Calculation Results and Analysis. Present all your results in neat graphs, discuss the results and justify your choice of design parameters.
- Discuss any potential social and econmical impact your design might have.
- Summary. Conclude by summarizing in a one paragraph your design methodology and whether you have achieved your design objective. List your final design and the performance data of your engine.
- Appendix. Attach your computer program at the end of the report.