Assignment 5:

Flat Rating limits of turbofan CFM56-3

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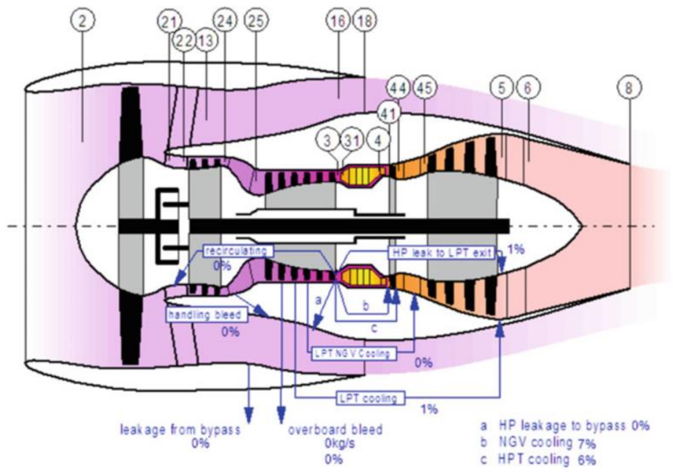
Introduction:

The goal is to develop and calibrate an off-design model to simulate the CFM56-3 turbofan engine and deduct the thrust limits guaranteeing the engine safe operation at low ambient conditions as a function of ambient temperature at both maximum continuous thrust and maximum take-off thrust.

Notation:

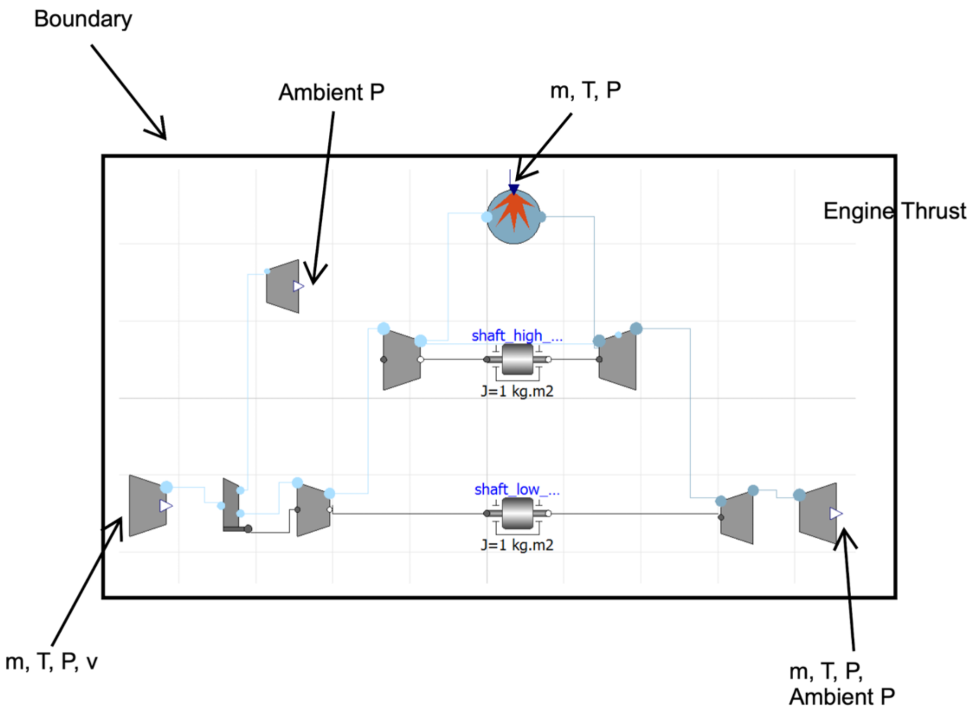


9 steps method:

<u>Purpose:</u>

- Create a calibrated model of the turbofan CFM56-3 engine capable of simulating the engine steady state response in off-design conditions to imposed thrust and EGT limits and use it to determine the Flat Rated curve of different parameters (see "Output relevant for the study") at maximum continuous thrust and maximum take-off conditions at sea level. The curves will then be used by the control system to keep the engine in the safe operating zone.
- Type:
    - Dynamic model (used as steady state)
    - 0D.
    - Open-loop to calibrate the model and for the basic off-design model, closed loop with a PI controller on the fuel to compute the flat rated curves.
    - Modular.
- Output relevant for the study: Thrust, EGT, Shaft rotational speeds N1 and N2 and Pressure in the combustion chamber for given ambient temperatures under constant Thrust or EGT imposed.

System Borders and variables:



m = mass flow
P = pressure
T = temperature
v = flow velocity

Relevant phenomena:

- Variation of the inlet air in terms of temperature (enthalpy).
- Losses of total pressure in inlet and ram compression and increase in static temperature in the inlet.
- Increase in pressure of the fluid (fan transmits energy and momentum to the fluid). Compression and increase in T in the fan. As well as separation of the flow between bypass and core.
- Bypass:
  - Losses of total pressure, reduction of pressure and increase of velocity in the bypass exhaust (expansion) and reduction of static T to produce thrust.
- Core:
  - Increase in pressure of the fluid (LPC and HPC transmit energy and momentum to the fluid). Compression and increase in T in the compressors.
  - Injection of the fuel in combustion chamber and combustion with air (Lean combustion) with formation of the combustion products (flue gasses). Energy is introduced in the flow as heat, thus there is an increase in T and enthalpy of the flow as well of the mass flow (mass of the fuel is added) meanwhile the pressure decreases slightly due to losses (otherwise will stay constant)
  - Expansion of the flue gasses, reduction in pressure and transfer of momentum and power to the turbines (HPT and LPT), reduction in T of the flow in the turbines.
  - Losses of total pressure, reduction of pressure and increase of velocity in the core exhaust (expansion) and reduction of static T to produce thrust.
- Pressure losses in ducts (can be neglected).
- Transfer of mechanical energy from the HPT to the HPC and from the LPT to the LPC and Fan through the 2 separate shafts.

- Accumulation of angular momentum in the two shafts (negligible since we are working in steady state conditions).

Hypothesis and assumptions:

Assumption:

- The inertia of the shafts is negligible since we are in steady state conditions, thus a very low (arbitrary) value is considered to avoid problems with the solvers.
- A Fixed Cooling type is used for the HPT turbine. This means that a fixed cooling fraction of the HPC flow is assigned in each stator and rotor row. Film cooling and convection are the heat transfer methods used to cool the stator and rotor of the HPT.
- For further assumptions about each single module the BasicAeroEngines library documentation has to be consulted.

Sub models:

- Intake
- Fan
- Bypass exhaust
- LPC
- HPC
- Combustion chamber
- Low speed shaft
- High speed shaft
- HPT
- LPT
- Core exhaust

Conservation laws and relations:

Components from the BasicAeroEngines library are used, thus for the equations and simplifications of each module the corresponding documentation has to be consulted.

Simplifications:

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Implementation:

The equations of each module are implemented in the Modelica language.

Components from the BasicAeroEngines library are used, thus for the implementation of each module the corresponding documentation has to be consulted.

The components are then connected as shown in the schema above (blue connection indicate the flow and black connection the mechanical connections of the shafts). A connection from the HPC to the cooling port of the HPT is implemented as well. This is such that the exhaust gas from the HPC is used to cool the HPT.

The map for the Fan, compressors and turbines are added as well as the ambient conditions.

A Fixed Cooling type is used for the HPT turbine. This means that a fixed cooling fraction is assigned in each stator and rotor row. Film cooling and convection are the heat transfer methods used to cool the stator and rotor of the HPT. Only one bleed is used to supply cooling air to the turbine.

Expressions to compute the net thrust and the EGT are added to the model (see “Calculations”).

Parameters from “Kurtzke & Halliwell, Propulsion and Power” are used.

A simulation using the on-design option (Environment module) is run to obtain the reference cycle's (max continuous thrust at ISA conditions) parameters of the Turbofan. These data are then used as parameters in the turbomachinery maps for the calibrated version of the engine.
To simulate the Flat Rated curves the two additional versions of the model are created, both add a SISO PI controller module to the fuel flow: one using as input the desired thrust and the other using as input the desired EGT.

<u>Simulation, Validation and Application:</u>
The model is validated by steady state simulation at the cycle of reference (maximum continuous thrust at ISA conditions) and by comparing the data obtained to the values available on the "Kurtzke & Halliwell, Propulsion and Power" which is the reference for this project.

Running of the model:
4 variations of the model are available.

- CFM56_3 is used to compute the cycle reference parameters and to validate the model.
- CFM56_calibrated is the basic open loop off-design calibrated model.
- CFM56_calibrated_PI is the closed loop model used to obtain the data for the flat rated curves when constant thrust is imposed (by the user), i.e., is used to compute the first part of the flat rated curves (from 0°C to 30°C). This is the point up until the engine reaches its EGT limit.
- CFM56_calibrated_PI_const_EGT is the closed loop model used to obtain the data for the flat rated curves when constant EGT is imposed (by the user), i.e., is used to compute the second part of the flat rated curves.

Calculations:
An equation must be imposed in the model by the user to find the net thrust of the engine, while simulating the operating conditions. The equation used is provided below, where the different components of the thrust are taken from the outputs of their respective sub models:

$$Thrust = Thrust_{Core} + Thrust_{Bypass} - Drag_{Air\ Intake}$$

Similarly, the EGT calculation must also be imposed in the model such that it can be plotted as an output after the simulation is ran. The equation for this (taken from the book of Kurtzke & Halliwell)

$$EGT = T_{45} - 0.3(T_{45} - T_5)\left(\frac{1141}{T_{45}}\right)^{0.4}$$

Methodology:
<u>Reference cycle:</u>
To obtain the reference cycle and thus verify that the model is working as expected, the model is constructed in Modelica as specified in Figure 1. The model is then run for a steady-state simulation at the corresponding atmospheric conditions.
Once the model has been verified against the reference cycle values and the differences are acceptable, the resultant values for the parameters of the turbomachines are recorded and implemented in the turbomachinery maps for the off-design model.
The EGT limit, max continuous thrust and max take-off thrust are known from the book of Kurtzke & Halliwell. It is also known from the book that the EGT limit occurs at one of the latter operating conditions.
A SISO PID controller is then implemented to simulate the flat part of the flat-rating curve (the PID controller keeps the thrust constant at the desired value) up to 30 degrees Celsius and to find the EGT limit of both maximum continuous thrust and max take-off thrust.

After 30 degrees the limit is not more imposed by the thrust but instead by the EGT, so another SISO PID controller is implemented to obtain the second part of the flat-rating curve (this time the EGT is kept constant). Therefore the thrust, EGT, shaft rotational speeds N1 and N2 and pressure in the combustion chamber for increasing ambient temperatures are then computed and plotted for constant thrust up to an ambient temperature of 30 degrees Celsius and a constant EGT above this ambient temperature.

Results:

The values of the steady-state reference cycle parameters have been compared to the values reported by Kurtzke & Halliwell. The percentage difference for each parameter is reported for ease of comparison. Upon inspection of the table below, it can be seen that the differences between the data of the steady-state model simulation and the book's reported values are negligible, the highest being a percentage difference of 5.6% for the mass flow at station 31. Given this result, it is concluded that the model has been validated and can therefore be used for further development to simulate the flat-rating of the turbofan.

Station	W [kg/s]			T [K]			P [kPa]		
2	313.798	313.798	0%	288.15	288.15	0%	101.325	101.325	0%
13	260.946	260.946	0%	338.15	338.082	$2.01\cdot 10^{-2}$%	167.686	167.686	0%
21	52.852	52.8518	0%	288.24	288.241	0%	101.426	101.426	0%
22	52.852	52.8518	0%	288.24	288.241	0%	101.426	101.426	0%
24	52.852	52.8518	0%	369.92	369.758	$4.38\cdot 10^{-2}$%	221.130	221.130	0%
25	52.852	52.8518	0%	369.92	369.758	$4.38\cdot 10^{-2}$%	221.130	221.130	0%
3	52.852	52.8518	0%	770.82	771.473	$8.47\cdot 10^{-2}$%	2447.654	2447.65	0%
31	45.400	47.9476	5.6%	770.82	771.473	$8.47\cdot 10^{-2}$%	2447.654	2447.65	0%
4	46.495	49.0427	5.5%	1577.55	1535.65	2.66%	2325.268	2325.2675	0%
41	50.195	49.0427	2.3%	1522.91	1535.65	$8.37\cdot 10^{-1}$%	2325.268	2325.27	0%
43	50.195	49.0427	2.3%	1162.74	1131.85	2.65%	541.359	529.866	2.1%
44	53.366	53.947	1.1%	1140.92	1134.04	$6.03\ 10^{-1}$%	541.359	529.866	2.1%
45	53.366	53.947	1.1%	1140.92	1134.04	$6.03\ 10^{-1}$%	541.359	529.866	2.1%
49	53.366	53.947	1.1%	862.58	859.586	$3.47\ 10^{-1}$%	148.131	146.737	$9.4\ 10^{-1}$%
5	53.366	53.947	1.1%	862.58	859.586	$3.47\ 10^{-1}$%	148.131	146.737	$9.4\ 10^{-1}$%
8	53.947	53.947	0%	861.63	859.586	$2.37\ 10^{-1}$%	146.649	146.737	$6\ 10^{-2}$%
18	260.946	260.946	0%	338.15	338.082	0%	164.108	167.686	2.2%
Bleed	0	0	0%	770.82	771.473	$8.47\cdot 10^{-2}$%	2447.654	2447.65	0%

Isentropic Efficiency	Kurzke Value	Simulated Value	Error
Outer LPC	0.8901	0.8901	0%
Inner LPC	0.9001	0.9001	0%
IP Compressor	0.8777	0.8777	0%
HP Compressor	0.8677	0.8677	0%
Burner	0.9995	0.9995	0%
HP Turbine	0.8250	0.825	0%
LP Turbine	0.9000	0.9000	0%

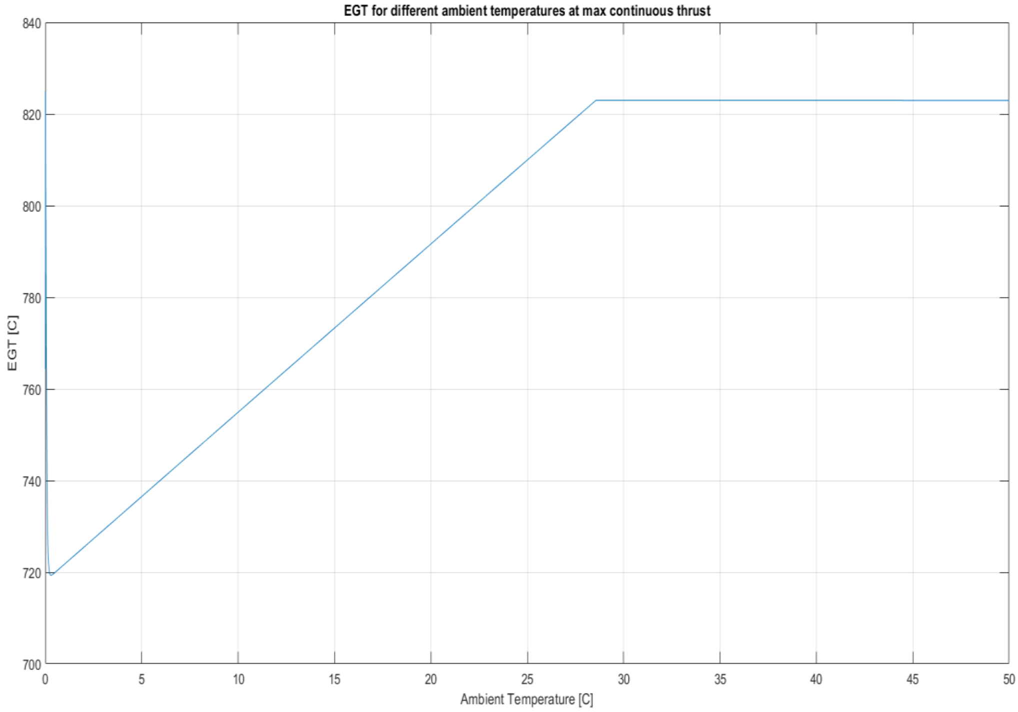
Spool Speed [rpm]	Kurzke Value	Simulated Value	Error
HP Spool	14324	14324.040	0%
LP Spool	4835	4834.9998	0%

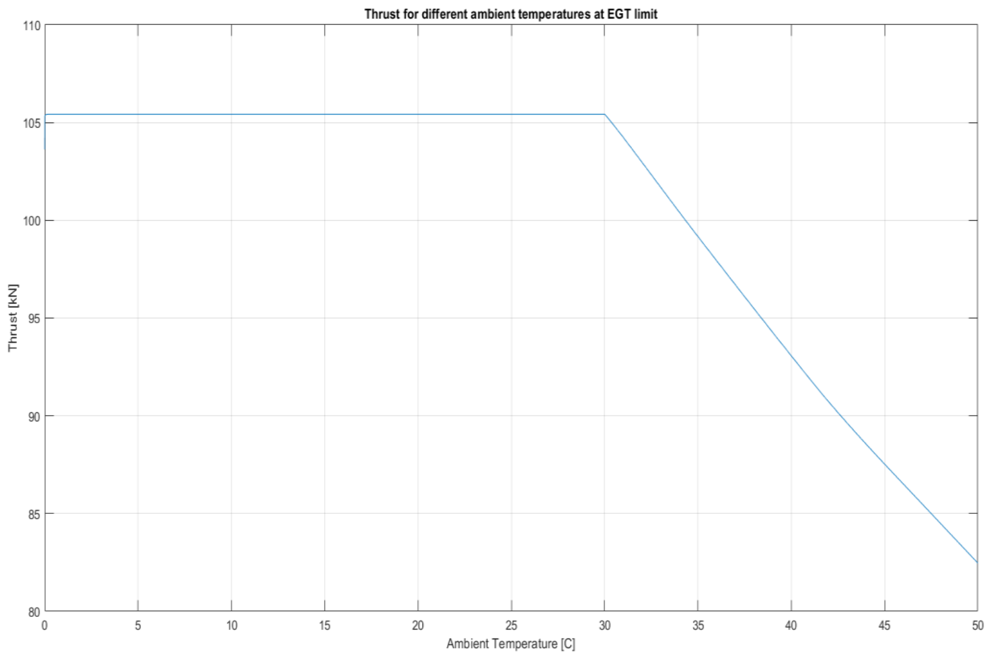
	Kurzke Value	Simulated Value	Error
FN [kN]	99.43	101.499	2.08%
TSFC [g/kN s]	11.0146	10.7901	2.04%
BPR	4.9373	4.9373	0%
A8 [m^2]	0.29325	0.287061	2.11%
A18 [m^2]	0.74236	0.718918	3.16%

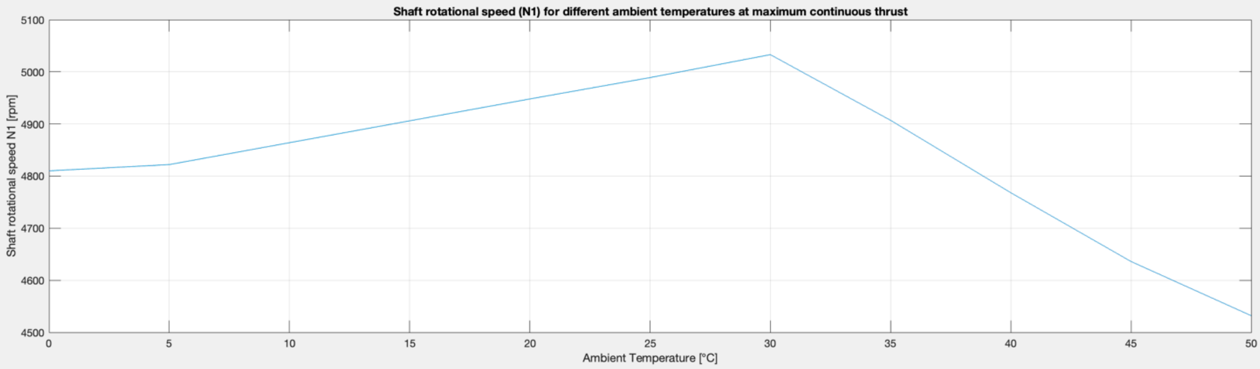
Legend: in black are the Kurtzke values and in blue the simulated values.

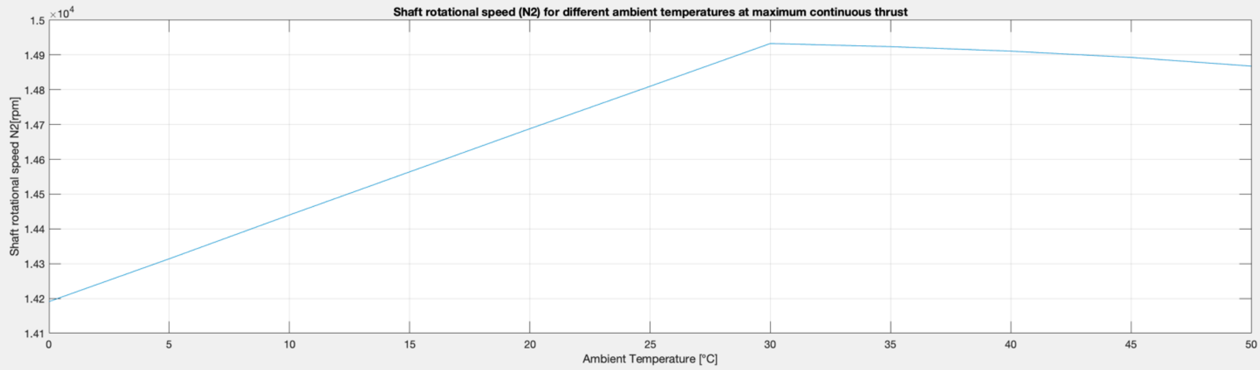
The results for both the flat rating curves at maximum take-off thrust and maximum continuous thrust have been presented below. A discussion on the results for both conditions is presented after the figures.

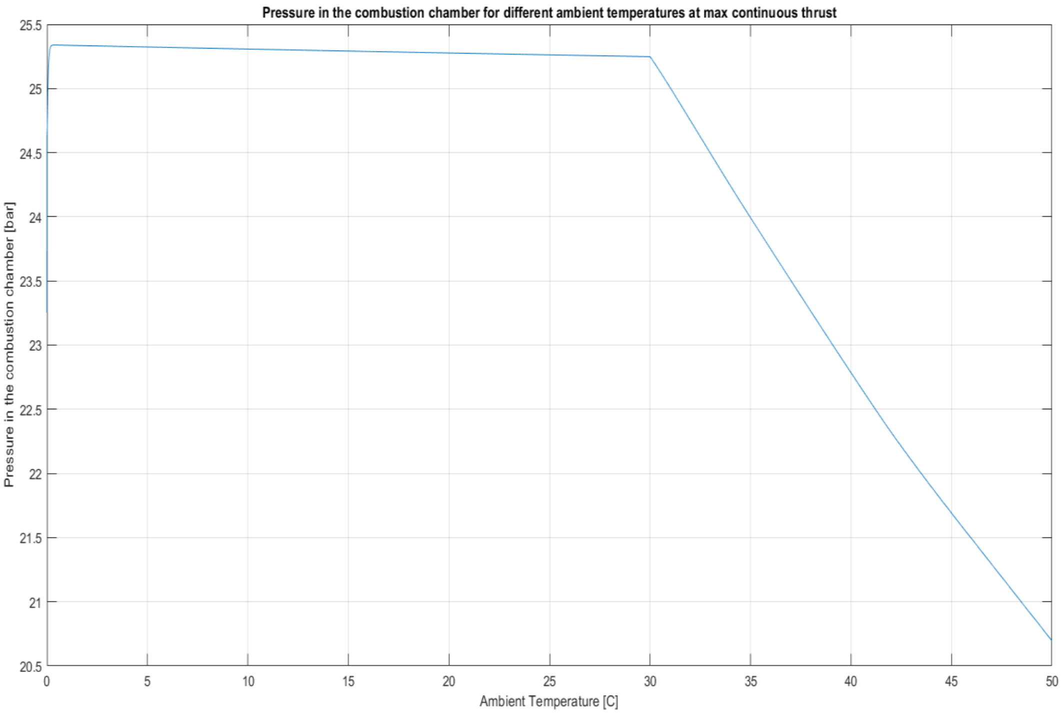
Flat Rating maximum continuous thrust:



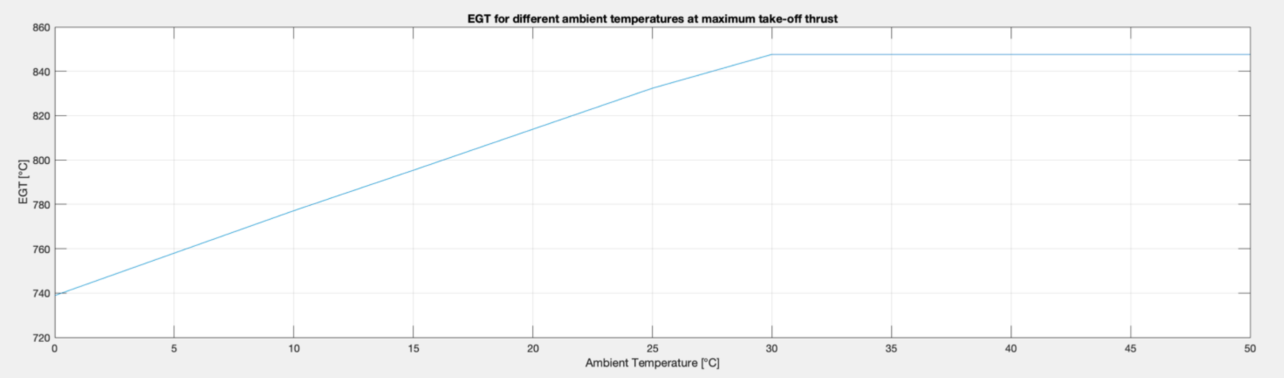


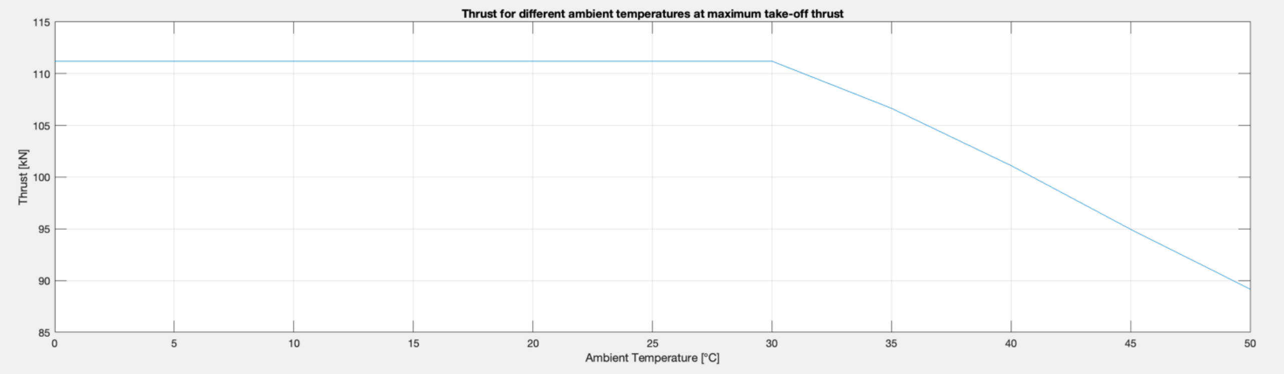

Shaft rotational speed (N1) for different ambient temperatures at maximum continuous thrust
Shaft rotational speed N1 [rpm]
5100
5000
4900
4800
4700
4600
4500
0
5
10
15
20
25
30
35
40
45
50
Ambient Temperature [°C]

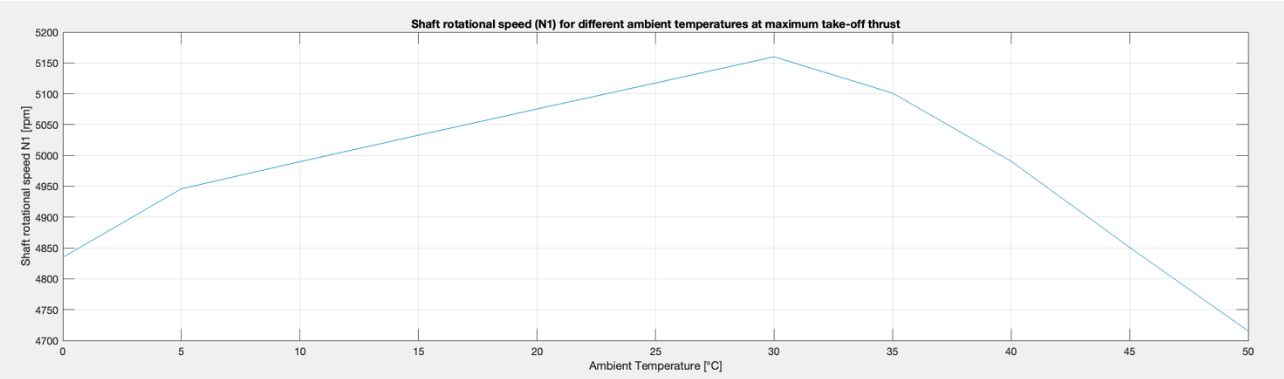

Shaft rotational speed (N2) for different ambient temperatures at maximum continuous thrust
$\times 10^4$
Shaft rotational speed N2[rpm]
1.5
1.49
1.48
1.47
1.46
1.45
1.44
1.43
1.42
1.41
0
5
10
15
20
25
30
35
40
45
50
Ambient Temperature [°C]

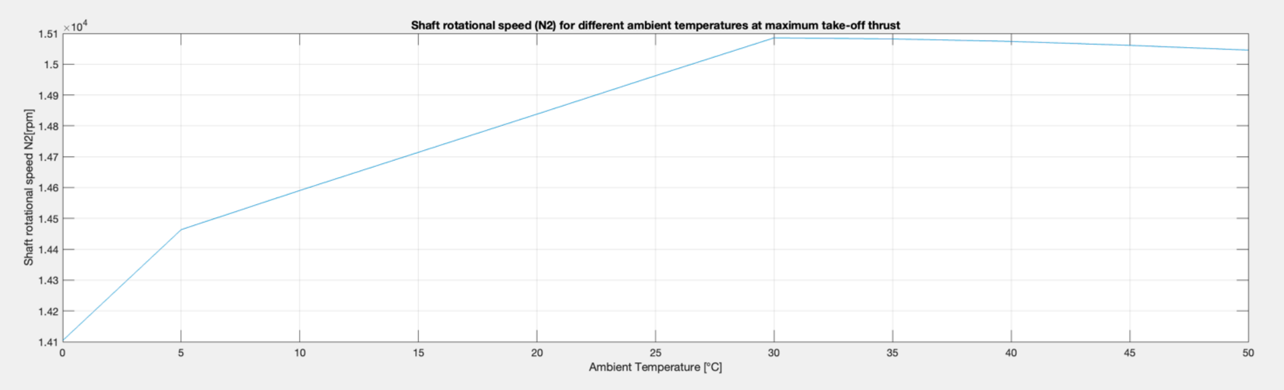

Pressure in the combustion chamber for different ambient temperatures at max continuous thrust
Pressure in the combustion chamber [bar]
25.5
25
24.5
24
23.5
23
22.5
22
21.5
21
20.5
0
5
10
15
20
25
30
35
40
45
50
Ambient Temperature [C]

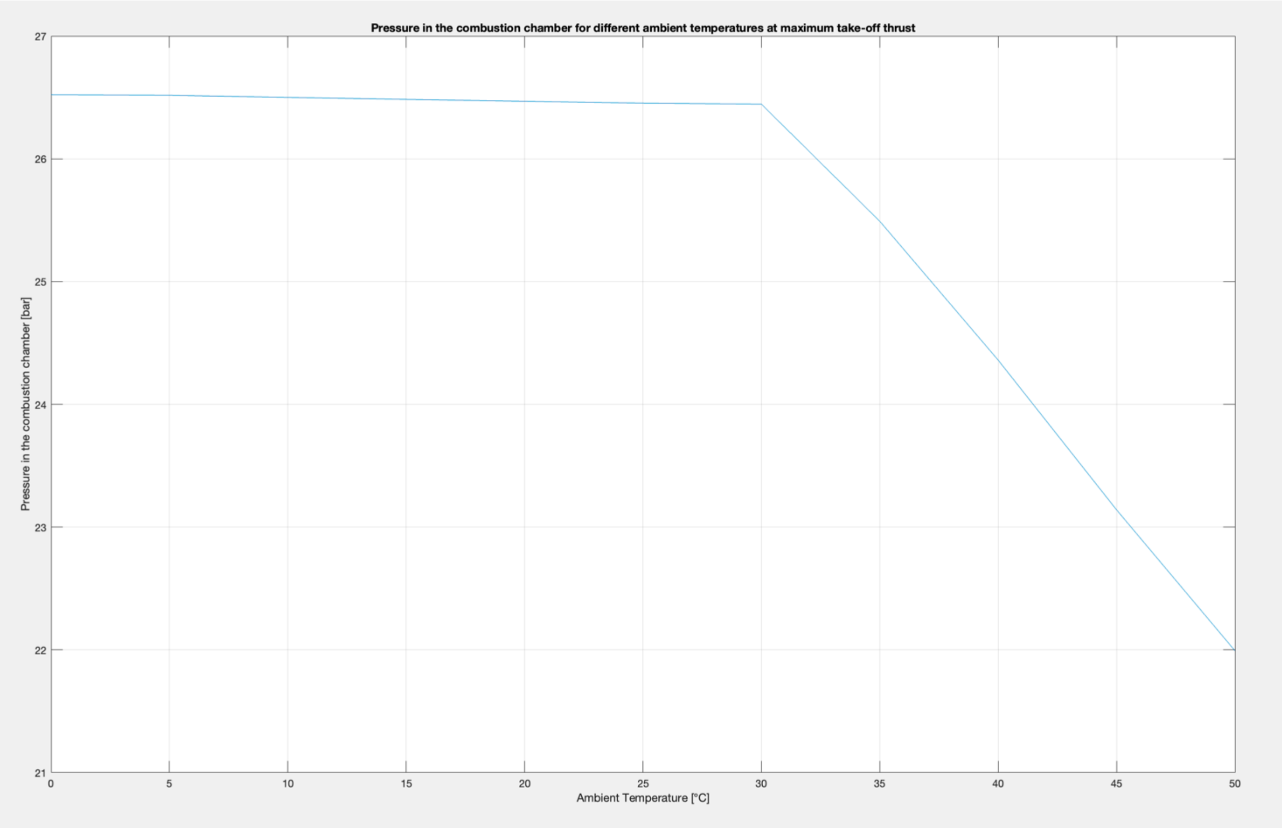
Flat Rating maximum take-off thrust:











The flat rating is better visualized in the first figure. As the EGT limit of the turbofan is reached at an ambient temperature of 30 degrees Celsius, it can be seen that the EGT increases until this limit is reached, at which point the EGT is kept constant by the controller. The effects this has on the turbofan can be seen in the plots that follow it.
The thrust that the engine produces starts to decrease once the engine reaches its EGT limit. This is because, the controller will limit the fuel flow rate to the engine when the EGT limit is reached. This is because burning fuel generates heat and therefore increase the EGT. When the fuel flow rate is limited/ decreases to match the EGT limit, the power output of the engine decreases and therefore the thrust of the engine will also decrease. Furthermore, the decrease in thrust imply a decrease in pressure and could also be linked to the increase in ambient temperature. As the ambient temperature increases, the density of the air decreases. This leads to a lower mass flow rate of air through the engine and therefore also a decrease in thrust produced.

The changes in shaft rotational speed can be explained similarly. First, up to the EGT limit point (30 degrees Celsius), the rotational speed for both the high speed and low speed shaft increases. For both the maximum continuous thrust setting and max take-off thrust setting, the shaft will rotate at a high-speed setting. When the ambient temperature decreases, the density of the air and therefore mass flowrate through the engine will decrease. This means that, to maintain the thrust setting, the controller will have a higher mass flow rate, burning more fuel and causing the shaft to rotate at a higher speed.
At 30 degrees Celsius, the EGT limit is reached, and the controller will try to maintain this limit. The fuel flow rate will decrease, resulting in less heat being produced and the thrust and shaft rotational speed decreasing.
The trend observed for the pressure in the combustion chamber is the same as that of the thrust produced by the engine. When the fuel flow is limited to keep the EGT constant, less combustion occurs and the pressure in the combustion chamber therefore decreases.

Conclusions:

The goal of this report was to develop an off-design model of the CFM56-3 engine and determine the limits guaranteeing the engine safe operation at low ambient conditions. The model was first validated by simulating the reference cycle, from which it was found that the discrepancies between the data were negligible. After this, an off-design model was calibrated using provided default turbomachinery maps. Simulations for both maximum thrust and maximum continuous thrust conditions were executed, and the data reconciled. The data acquired was reconciled as it followed the trends as expected. Therefore, it can be concluded that the objective of this assignment was met.

Furthermore, from the results of the exercise, it is evident that while flat rating is important for the reliability and durability of the engine, it comes at the cost of reduced thrust output. Therefore, it is important for engine manufacturers to simulate the performance of engines under such operating conditions to understand the limits of the engine. By gaining such insight into the behavior of the engine, the manufacturer can optimize engine performance by changing other parameters. Therefore, a recommendation for this assignment would be to investigate the performance of the engine at max thrust settings when parameters such as the