LMECA2550 Aircraft propulsion systems: Olympus HP turbojet engine

30 novembre 2021

1 Laboratory

This laboratory aims at studying the complete cycle of a small turbojet engine and at developing a critical mind about usual assumptions taken in the theoretical courses.

It is important to closely read this document before starting the engine : it includes a brief description of the turbine, the steps of the laboratory and the instructions for the report.

1.1 Turbo jet description

The Olympus HP is intended for model airplanes and has all the characteristics of a real turbojet engine : it is composed of a radial compressor, an annular combustion chamber and a single stage axial turbine. It is powered by a safer variant of the usual kerosene used in the aviation, characterised by the chemical formula $C_{10}H_{22}$ and a LHV equal to 43.7 MJ/kg. Its maximal thrust is about 230 N.

This engine is equipped with additional sensors for an academic use : there are thermocouples, providing total temperatures, and pressure sensors, giving total or static pressures. These sensors are located at different points of the cycle (see Fig. 1) and provide :

— p_{s2}
— p_{s3}, p_{t3} et T_{t3}
— p_{t4} et T_{t4}
— p_{t5} et T_{t5}
— T_{t6}

The Olympus HP is mounted on a test bench, (see Fig. 2), with a thrust balance and a piezoelectrical sensor, allowing for an estimation of the produced thrust in N at any time of the test.

The engine is managed with two control settings : one switch button with 3 positions (running, autoshutdown, emergency stop) and one throttle, to control the produced thrust. All the settings

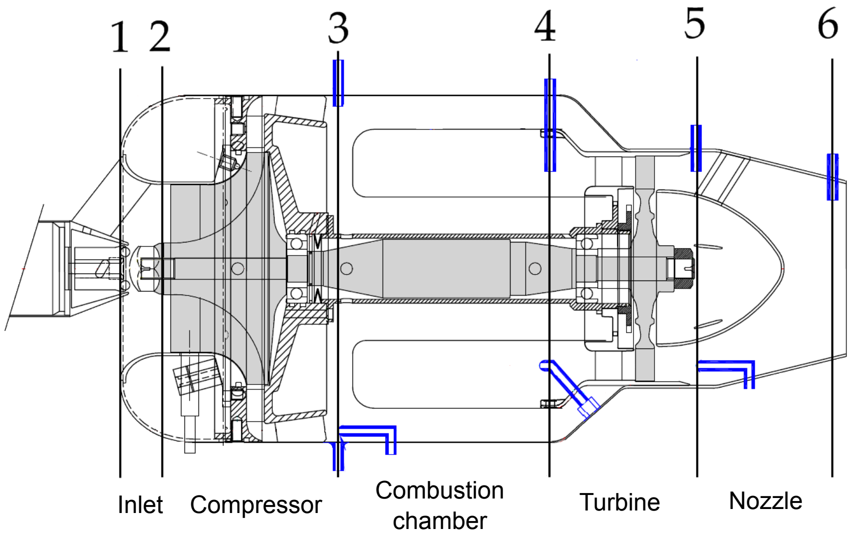

FIGURE 1 – Olympus HP Turbo jet engine with the different sections

FIGURE 2 – Test bench of the Olympus HP

go to a controller (Electronic Control Unit (ECU), see Fig. 3), that regulates the fuel quantity, and thus, the shaft speed and the thrust.

In addition to the “emergency stop” switch position, an emergency stop button (see Fig. 4) is also present, that instantly stops the power supply and thus the fuel arrival. In any case, an emergency shutdown procedure is harmful for the engine and should only be used in case of absolute necessity.

All the data sensors, as well as some values coming from the ECU (rotational speed, fuel pump tension that enables an estimation of the fuel mass flow rate, error messages, ...) are displayed in a graphic interface realised with Labview. They are recorded in a .txt file during all

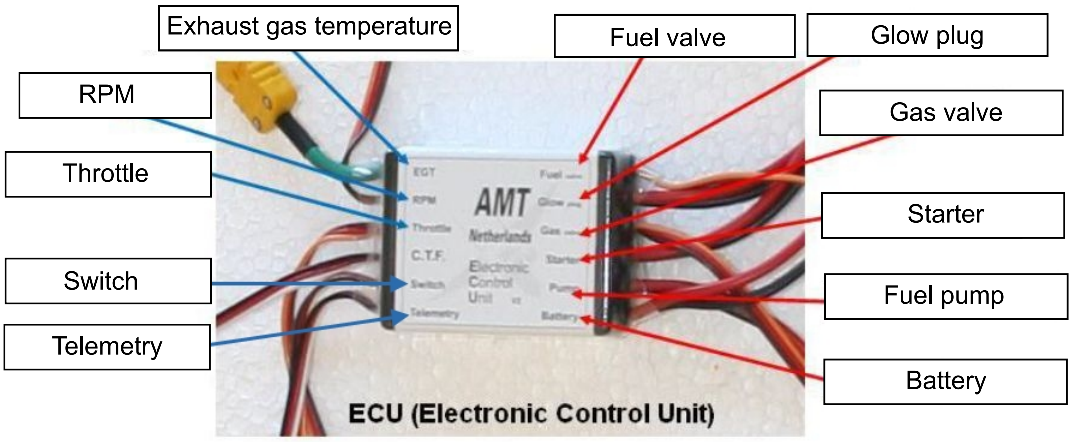

FIGURE 3 – ECU : « Electronic Control Unit »

FIGURE 4 – Emergency stop button

the test and it is also possible to save instantaneous data, by pushing a special record button (these values are then printed in another .txt file).

The Olympus HP starts with an electrical engine, located before the air diffuser. Once the shaft has a sufficient rotational speed, propane is injected during several seconds and the glow plug ignites the mixing air/propane. Once the combustion is initiated, the propane inlet valve is closed and the kerosene becomes the main fuel, the temperature now being sufficient for an ignition of the mixing air/kerosene. The engine increases its rotational speed up to 50,000 RPM, to calibrate the controller, and goes down to its idle regime, i.e. 36,000 RPM. When shutdown is required, the engine goes to 80 000 RPM (whatever the current regime) and stays at this speed during a few seconds, before stopping. After the shutdown of the engine, there is a cooling procedure, and the shaft turns thanks to the electrical engine so as to inject cooler air into the different components.

The different useful sections are : $A_1 = 5.168\ 10^{-3}\ m^2$, $A_2 = 2.818\ 10^{-3}\ m^2$,$A_3 = 4.112\ 10^{-3}\ m^2$, $A_4 = 6.323\ 10^{-3}\ m^2$, $A_5 = 3.519\ 10^{-3}\ m^2$ et $A_6 = 3.318\ 10^{-3}\ m^2$.

1.2 Starting and Shutdown procedure

Detailed starting and shutdown procedures will be given to you at the beginning of the laboratory.

1.3 Instructions

1. Before starting the engine, check the presence and the accessibility of the emergency stop button (Fig. 4).
2. Launch Labview. This software must display the pressure and temperature values of the ambiance. The recording automatically starts when the program is launched. Push the record button to keep the ambiance values, necessary for the computations required for the cycle analysis.
3. Verify that the casemate is powered on, that all its doors are closed and that nobody is inside.
4. Start the engine by following the starting procedure. Once the engine reaches its idle point (36,000 RPM), check that the Labview program does not provide any error messages and that all data are displayed on the interface. Pay particular attention to the value of the shaft speed, necessary for the following of the laboratory.
5. Stay at least one minute at idle, to be sure that the pressure and temperature data are no longer transient. Save the sensor values of this operating point by pushing the record button. Make more than one record to obtain mean values for the considered regime.
6. Slowly turn the throttle to reach a rotational speed of 50,000 RPM. Stay at this point until the temperature and pressure measurements stabilise, and push several times the record button to save the values.

   Re-iterate this operation for the following rotational speeds :

   — 60,000 RPM
   — 70,000 RPM
   — 80,000 RPM
   — 90,000 RPM
   — 100,000 RPM

   7 regimes will thus be studied.
7. Once the data are saved, stop the engine : you have to switch to the « auto-shutdown » position.
8. After the shutdown, keep the Labview program open to save the cooling procedure and the diminution of the temperatures inside the engine.
9. Stop the data acquisition by pushing « Stop acquisition » button. Take the two .txt files (one with the data saved during all the test, and one with the data saved when the « Record button » was pushed). These files are localised in the directory « turbine/enregistrement ». Check that these files are not empty and that the lab data has been correctly recorded.
10. Be sure that the shutdown procedure is fully finished (valves are closed,...).

1.4 Questions

1.4.1 Description

Describe the turbojet engine and its operation. How is the thrust obtained ?

1.4.2 Graphs

- Plot the evolution of the different recorded values as a function of time for the entire duration of the test. The meaning of the columns in the .txt files are the following :
  1. For the continuous data :
     hour minute second p_{s2} p_{s3} p_{t3} p_{t4} p_{t5} T_{t3} T_{t4} T_{t5} —— T_{t6} —— Thrust RPM —— —— —— $\dot{m}_f$
  2. For the instantaneous data (obtained with the record button) :
     hour minute second —— p_{s2} p_{s3} p_{t3} p_{t4} p_{t5} T_{t3} T_{t4} T_{t5} —— T_{t6} —— Thrust RPM —— —— —— $\dot{m}_f$
  3. Units :
     pressure : [bar]
     temperature : [°C]
     $\dot{m}_f$ = fuel mass flow rate : [g/s]
     Remark : —— means "do not use this value"
- Analyse these plots, as well as the behavior of the engine during the starting, shutdown and cooling procedures. What does happen when a regime change is required ? What does happen when the engine stops ? Why ?
- Plot the evolution of the pressures, temperatures, thrust, compression ratio π_c and fuel mass flow rate as a function of the shaft speed. Discuss.

1.4.3 Cycle analysis

- For each point of the cycle, and for each regime, compute the static and total pressures, temperatures, velocity and entropy (see Table 1). Detail the general approach and the computations. Compute the pressure and temperature ratios : π_d, π_b, π_t, π_n ; τ_d, τ_c, τ_b, τ_t, τ_n. What are τ_r and τ_λ ?

State 0	State 1	State 2	State 3	State 4	State 5	State 6
p_{s0}	p_{s1}	p_{s2}	p_{s3}	p_{s4}	p_{s5}	p_{s6}
p_{t0}	p_{t1}	p_{t2}	p_{t3}	p_{t4}	p_{t5}	p_{t6}
T_0	T_1	T_2	T_3	T_4	T_5	T_6
T_{t0}	T_{t1}	T_{t2}	T_{t3}	T_{t4}	T_{t5}	T_{t6}
u_0	u_1	u_2	u_3	u_4	u_5	u_6
s_0	s_1	s_2	s_3	s_4	s_5	s_6

TABLE 1 – Cycle analysis

Make the following assumptions :

— the transformation is isentropic from 0 to 2

— the combustion is complete and there is no unburnt fuel.

— the transformation is considered adiabatic in the compressor and in the turbine.

— the flow is isentropic in the outlet nozzle

— the constant R^* of air and gases are assumed equivalent.

Help :

1. The state 2 must be fully determined before the state 1. The state 1 can be computed from the state 2 and the state at sonic conditions (M=1 at the section A^*, cfr. MECA2322)
2. The state 4 can be determined by a system of several equations - unknowns. If you cannot find a solution, you can assume $p_{t4} = p_{t3}$, $p_{s4} = p_{s3}$.
3. The outlet nozzle is assumed isentropic. You can thus take the assumption $p_{t6} = p_{t5}$ (even if the sensors do not provide $T_{t6} = T_{t5}$).
4. Again, the state 6 must be fully determined before the state 5. The state 5 can be computed from the state 6 and the state at sonic conditions (under the assumption of an isentropic flow).
5. You can assume $\gamma = 1.4$ and constant or you can compute it at each state.

- From the computed values of Table 1, what do you think about the assumption of an isentropic flow in the inlet nozzle and the outlet nozzle ?
- Compute the air mass flow rate in the compressor. Plot the evolution of the mass flow rate as a function of the shaft speed. Discuss.
- Compute the primary power in the combustion chamber and the air excess with respect to the stoechiometric combustion. Again, plot the values as a function of the shaft speed. Discuss.
- Plot the (T,s) diagram for the regimes of 36,000 and 90,000 RPM. Analyse. Are the usual assumptions still valid ?
- For these two regimes, compute the power of the compressor and of the turbine. Are these values consistent ? Consider now a mechanical efficiency $\eta_{mec} = 0.96$ to obtain a new total temperature T_{t5} (still use T_{t2}, T_{t3} and T_{t4} as given by the sensors). How do you explain the difference between this new temperature value and the sensor measurement ?
- For each regime, compute the isentropic and polytropic efficiencies of the compressor and of the turbine. Study and discuss their evolution as a function of the regime.

Remark : Empirical formula can be used to obtain the specific heats of air and gases as a function of temperature. f is here the ratio between the fuel mass flow and the air mass flow.

For $200 < T \leq 800\ K$ **:**

$$c_{pa} = 1.0189 \times 10^3 - 0.13784T + 1.9843 \times 10^{-4}T^2 + 4.2399 \times 10^{-7}T^3 - 3.7632 \times 10^{-10}T^4$$

$$c_{pg} = c_{pa} + B_t \left(\frac{f}{f+1}\right)$$

$$B_t = -3.59494\times10^2+4.5164T+2.8116\times10^{-3}T^2-2.1709\times10^{-5}T^3+2.8689\times10^{-8}T^4-1.2263\times10^{-11}T^5$$

For $800 < T < 2200\ K$ **:**

$$c_{pa} = 7.9865 \times 10^2 + 0.5339T - 2.2882 \times 10^{-4}T^2 + 3.7421 \times 10^{-8}T^3$$

$$c_{pg} = c_{pa} + B_t\left(\frac{f}{f+1}\right)$$

$$B_t = 1.0888\times10^3-0.1416T+1.916\times10^{-3}T^2-1.2401\times10^{-6}T^3+3.0669\times10^{-10}T^4-2.6117\times10^{-14}T^5$$