BRUFACE

MECAH402
Turbomachinery

Lab 3: Assembly/disassembly of a high-pressure line of a modern aero-engine

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1 Introduction

The jet engine explored during the laboratory case study is the DGEN 380. The DGEN engine family represents the world's smallest turbofan. It is used in a 4 to 5 seat twin engine plane, flying under 7260 meters and Mach 0.35.

As main characteristics, easy maintainability, low fuel consumption and low noise level. The engine control unit and the oil fuel injection equipment is fully integrated around the engine, all controlled by the Full-Authority Digital Engine Control (FADEC).

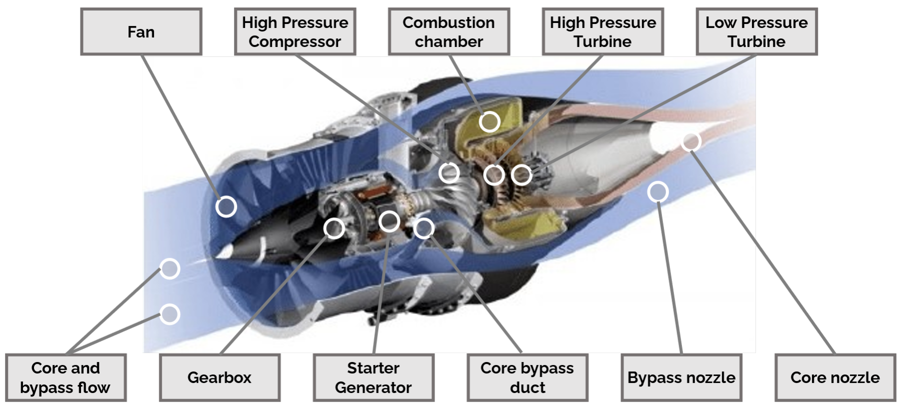

Figure 1: DGEN 380 engine

This report will deep dive into two elements of the high pressure body of the DGEN 380, the centrifugal compressor and the axial turbine, as well as in other fundamental components such as bearings and the lubrication system. Further reasoning with regards to energy transfer, temperature evolution, entropy and degree of reaction will be issued. Finally, the material selection for the compressor and turbine will explored.

2 Overall operation and energy transfer to the wheel for a centrifugal compressor

In order to initiate the operation of the jet engine, the starter generator, induce by an electric motor and electric drive, will initiate the rotation of the front fan and the compressor.

Air towards the compressor is driven by a centrifugal force. The wheel of the compressor accelerates the gas passing through its rotor blades. The compressor will bring energy into the gas, by increment of pressure. 2 transforms mechanical energy available on their shaft at its entrance, into pressure energy and kinetic energy of the gas.

Figure 2: High pressure compressor

The blades of the turbine will receive the pressurize gas. The turbine will extract the kinetic energy of the gas by expansion of the gases. The kinetic energy is used as mechanical power for the rotation of the shaft. Turbine and shaft are welded. The rotation of the turbine will be transfer back to the compressor's wheel through the shaft, driving the compressor. To calculate the specific work of the compressor:

$$W_c = h_3 - h_1 = c_p \cdot (T_3 - T_1) \tag{1}$$

where h_i[J] and T_i[K] are respectively the enthalpy and the temperature at the i^{th} stage. c_p[J/K] is the specific heat capacity at constant pressure.

3 T-s diagram

The figure 3 corresponds to the Brayton thermodynamic cycle with temperature in function of entropy.

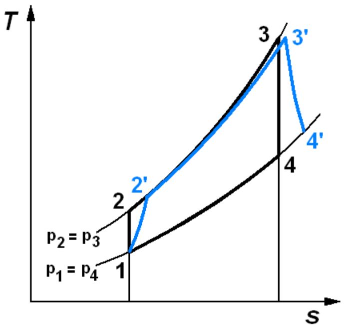

Figure 3: T-s diagram

At station 1, the **compression** phase is initiated. This phase takes place in the compressor. There are two outcomes for the compression, station 2 and station 2i.

Station 2' corresponds to the real case, where there is a pressure increment defining a new isobar, as well as variation in entropy. Station 2 or isentropic, assumes no heat exchange or heat transfer.

The following phase is the **combustion** phase that ends in station 3 isentropic, with constant pressure with respect to station 2 and with a temperature and entropy increment. In reality, 3' should have a lightly different pressure than 2 and slightly greater entropy.

The transition from 3 to 4 or 4' corresponds to the **expansion** process that takes place in the turbine. Similarly to station 2' and 3', station 4' represents the real case considering some heat transfer. 4 represents represent the ideal case or isentropic, without heat transfer. In this case, the pressure decreases to become equal to the station 1, being both stations represented in the same isobar.

To complete the Brayton thermodynamic cycle, the transfer from station 4 or 4i to station 1 describes the **exhaust** or **admission**, restarting the cycle. The area under the T-s diagram is proportional to the useful work and thrust generated by the engine.

4 Degree of Reaction

In the case of this study, the axial turbine of the DGEN is a reaction turbine. One can identify this by the shape of the blades of the turbine. The are no symmetrical, and they have a different height between the inlet and the outlet section. A brief summary of major difference between impulse and reaction turbines follows:

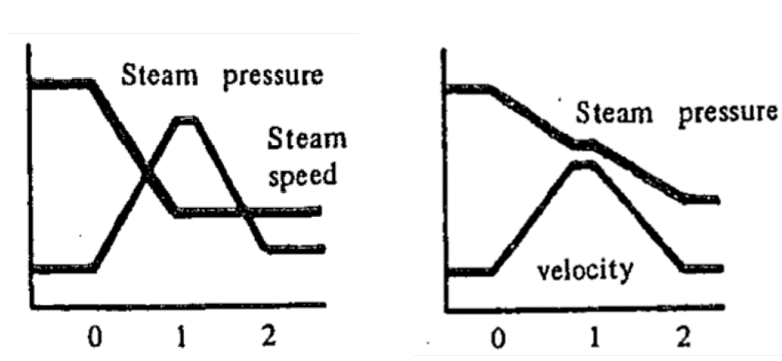

Figure 4: Impulse and reaction turbines: velocity and pressure evolution

Axial turbines	
Impulse turbine	**Reaction turbine**
Stator: It creates channels for the convergence of the gas. This translates pressure into kinetic energy, meaning speed on the gas.	**Stator:** It creates channels for the convergence of the gas. This translates pressure into kinetic energy, meaning speed on the gas. The gas already experiences a pressure drop along the stator. The pressure drop is shared between the rotor and the stator.
Rotor: There is no pressure transformation. Entrance section equal to exit section, with a symmetrical shape.	**Rotor:** Due to its shape, the gas converges, causing a pressure drop between the rotor blades or reaction. The amount of pressure drop shared between the rotor and the stator is given by the **degree of reaction**.
Stator (0 − 1): Increase of velocity in the gas, with its maximum at the exit of the stator. All pressure drop takes place in the stator. **Rotor (1 − 2):** Kinetic energy transfer to mechanical work as rotation of the shaft.	**Stator (0 − 1):** Increase of velocity in the gas, with its maximum at the exit of the stator. Pressure drop shared with the rotor. **Rotor (1 − 2):** Further pressure drop due to the convergence induce by the shape of the rotor blades. Kinetic energy transfer to mechanical work as rotation of the shaft.
Lower efficiency compared to reaction turbine due to higher friction losses.	Higher efficiency that impulse turbines due to a lower sum of the losses in the stator and the rotor.

The degree of reaction can be described in several ways:

- Ratio between the enthalpy drop in the moving blades (rotor) and the enthalpy drop in the stage (stator + rotor).
- Ratio between the static pressure drop in the rotor and the static pressure drop in the stage (stator + rotor).
- Ratio between the power of the gas on the wheel in reactive working, over the total power given by the gas to the rotor.
- Ratio of energy transfer by the change in static head to the total energy transfer in the rotor.

$$R = \frac{(P_R)_{react}}{P_R} = \frac{\frac{w_2^2 - w_1^2}{2}}{\frac{v_1^2 - v_2^2}{2} + \frac{w_2^2 - w_1^2}{2}} = \frac{\int_{p_2}^{p_1} \nu \, dp - w_f^{"}}{\frac{v_1^2 - v_2^2}{2} + \int_{p_2}^{p_1} \nu \, dp - w_f^{"}} \approx 0$$

Figure 5: Degree of reaction - Reaction Turbine

The formula Degree of Reaction shown in figure 5 introduces the ratio between the power of the fluid in a reactive working $(P_R)react$ and the total power deliver to the rotor P_R, given by the Euler-Rateau equation. In the case of impulse turbines, the degree of reaction is almost zero. If friction losses would be taken into account, the degree of reaction could it be considered negative. In the case of reaction turbines, and due to the already described pressure drop in the rotor blades, the degree or reaction could be higher than 1.

To estimate the Degree of Reaction of the turbine investigated in this report, the evolution of the pressure in stator and rotor is considered. In designs where the pressure drop is equally shared by the stator and rotor, it can be considered a degree of reaction of 50%.

- Degree of reaction equal to zero: as described before, this is the typical case of impulse turbines. The entire pressure drop occurs in the stator.
- Degree of reaction lower than 50%: the pressure drop in the rotor is less than the pressure drop in the stator of the turbine.
- Degree of reaction greater than 50%: the pressure drop in the rotor is greater than the pressure drop in the stator of the turbine.

Due to the characteristic shape of the blade of the reaction turbine of the jet engine, its Degree of Reaction is estimated to be closer to the 100%.

5 Working principles of the rotating bearings

Rotating bearings are elements to reduce the friction between two objects that are in linear or radial circular motion against each other. These bearings can support extremely heavy loads at different speeds. As mentioned, they allow the transmission of both axial and radial forces. Based on the type of load, thrust and roller bearings are identified and further explored:

- Thrust bearing: This type of bearing permits the rotation between parts similarly to other rotatory bearing. Their specific design support predominately axial loads, parallel to the rotation axis. Since the A380 engine combines compressor and turbine, used to increase the energy of the fluid or extract energy from it respectively, the pressure at both sides of the rotor shaft is considerably different. Therefore, an axial force is transmitted and thrust bearings are optimal for this purpose.

- Roller bearing: This type of bearing is selected when a high accuracy and defined purposed is identified. With a more cylindrical shape, they are designed to accommodate combined loads. The shape of the roller will contribute to support a more radial, axial or angular contact. The thrust bearing of the A380 engine can take radial forces, perpendicular to the rotation axis, as well as a small part of axial force. Their function is to provide accurate radial and axial positioning and to properly support rotor loads.

The difference between these bearing is given by the kind of load that they can take. As a summary, the thrust bearing support axial load, the roller bearing radial force with small axial load.

Lifetime and performance are greatly affected by the lubrication of its moving parts. Ineffective or inadequate lubrication of moving parts can lead to equipment failure or wasted energy. Lubrication is essential to improve their performance. Bearings are lubricated within the area enclosed by the seals. By lubrication, performance of mechanical elements is endured. It protects surfaces against oxidation and corrosion. The seal, apart from isolation the lubricant from the rest of the system, keep the system clean of impurities as well as avoiding leakages. In this engine they are lubricated by a oil close loop circulation. The seals used in the A380 are composed of a main body in steel and a seal made of carbon.

6 Material selection

Under this section, further reasoning regarding the material selection of the different parts of the jet engines and more precisely DGEN 380 A7 engine will be issued. By continuing with the breakdown introduce in the laboratory notes for the high-pressure elements of the jet engine such us centrifugal compressor, reverse combustion chamber and axial turbine, 6 shows the evolution of pressure and temperature distribution along those elements.

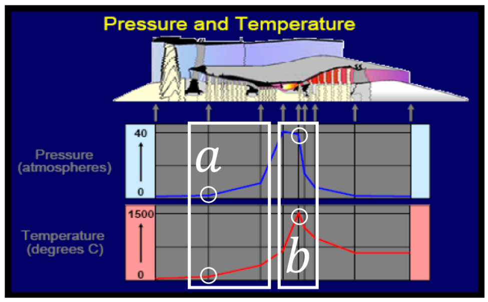

Figure 6: Pressure and temperature distribution

Section a, where the compression phase occurs, one can see that pressure and temperature are relatively lower compared to the other areas of the jet engine. In this section, the air or fluid entering the jet engine is distributed towards the compressors. Despite relatively low pressure and temperature, this section is confronted with high centrifugal forces and pressure difference. Under section b, where the turbine is located, one can identify an almost maximum pressure point, as well as the highest temperature point in the jet engine. This corresponds to the transition between the combustion and expansion phases described under figure 00. The optimal design of the jet engine requires a material selection considering the conditions described above. The material selection of centrifugal compressor and axial turbine will be further elaborated.

- Centrifugal compressor It is composed of lightweight metallic blades attached to the impeller. Fluid accessing in the compressor axially, enters in contact with two rows of blades, that maximize the contact surface of the fluid with the blades. These blades have a twisted shape from root to tip that change the angle of the fluid flow. They are exposed to centrifugal forces, with an increasement of pressure towards the tip of the blade, in the direction of the flow.

By comparing the specific strength of different materials and alloys in function of temperature, one can see that at lower temperatures, titanium alloys are

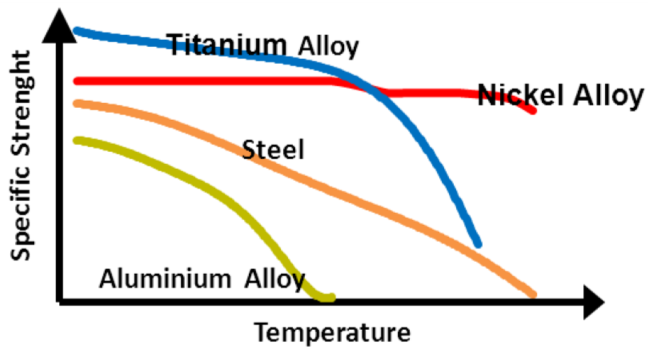

Figure 7: Specific strength in function of temperature

the right material selection. For higher temperatures, nickel alloys seemed to maintain a stable specific strength compared to the other materials and elements plotted under the figure. Considering the subject of our analysis, DGEN 380 A7 engine, titanium is an optimal choice for the compressor due to it high specific strength at the operational temperature of the compressor and the resistance to high load.

- Axial turbine Based of the distribution of temperatures shown in 6, the hottest areas are located at the combustion chamber, where turbine blades are positioned. As an order of magnitude, figure 00 shows a temperature of 1500°C. Considering the temperature as the major boundary condition, nickel superalloy is the optimal material for the blades of the turbine. Superalloys are metallic materials with optimal mechanical strength, with resistance at high temperatures and against oxidation and corrosion. These alloys materials can be found in shaft, compressor, combustion chamber, turbine, and exhaust nozzle. Depending on their composition, these alloys can operate in a temperature range between 500 and 1100°C.

7 Conclusion

This part of the lab allowed the students to visualize the internal composition of the High Pressure Unit of the jet engine DGEN 380. The working principle and degree of reaction of the centrifugal compressor and axial turbine were discussed. Further reasoning out of the equation of the degree of reaction was elaborated. The roles of the two types of bearings as well as the influence of the material selection were reviewed.

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