Introduction to the mechanical design of aircraft engines

Reference:
AERO0015-1 - MECHANICAL DESIGN OF TURBOMACHINERY - 5 ECTS - J.-C. GOLINVAL
Principles of jet propulsion

Comparison between the working cycle of a turbo-jet engine and a piston engine
Development process of the structural design

- Request For Proposal
- Preliminary Design Review
- Program Launch
- Detailed Design
- Industrialization
- Testing Program
- Certification

Definition of the thermodynamic cycle consistent with the specification and of the best structural architecture of the engine

Today, the duration of this process is about 3 years (against ~ 6 years in the 90s)
Evolution of turbojet engines to the technology level of today

In conclusion,

- new concepts or technological breakthroughs are rare;
- advancements are rather due evolutionary improvements of the design.

To achieve good performances, parallel research and development effort were undertaken in areas such as in aerodynamics, aerothermics, acoustics, combustion process, mechanics, metallurgy, manufacturing, ...

Aim of this presentation

Focus on the mechanical aspects of the design.
Challenges of turbojet technology

Overall efficiency of a jet propulsion engine

\[ \eta_{\text{overall}} = \eta_{\text{thermal}} \times \eta_{\text{propulsive}} \]
The thermal efficiency is defined as the ratio of the net power out of the engine to the rate of thermal energy available from the fuel.

According to the Temperature-Entropy diagram of an ideal turbojet engine, the thermal efficiency simplifies to

\[ \eta_{\text{thermal}} = 1 - \frac{T_0}{T_3} \]
Challenges of turbojet technology

To progress to the performance capabilities of today, two goals were (and still are) being pursued to increase the thermal efficiency:

**Goal n° 1: Increase the compressor pressure ratio.**

Trend in compressor pressure ratios

<table>
<thead>
<tr>
<th>Calendar years</th>
<th>Compressor pressure ratio</th>
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<tbody>
<tr>
<td>Late 1930 to 1940</td>
<td>3:1 to about 6:1</td>
</tr>
<tr>
<td>Early 1950</td>
<td>About 10:1</td>
</tr>
<tr>
<td>1950 to 1960</td>
<td>20:1 to about 25:1</td>
</tr>
<tr>
<td>2000</td>
<td>30:1 to about 40:1</td>
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Increasing of the compressor pressure ratio (r)

→ «variable» geometry to adapt the compressor behavior to various regimes.

→ 2 solutions are possible
Concept of variable stator blades

**Solution n° 1**: concept of variable stator blades

- Design of reliable airflow control systems.
- Prevention of air leakage at the pivots of the vanes at high pressures (temperatures).
Solution n° 2: concept of multiple rotors (r ~ 20:1 - 30:1)

Example of a dual-rotor configuration

Advantages

- Selection of optimal speeds for the HP and LP stages.
- Reduction of the number of compressor stages.
- Cooling air is more easily taken between the LP and HP rotors.
- The starting of the engine is easier as only the HP rotor needs to be rotated.
Concept of multiple rotors

Rolls-Royce RB211 engine
Concept of multiple rotors

Mechanical challenges

- Analysis of the dynamic behavior of multiple-rotor systems and prediction of critical speeds.
- Design of disks.

Example

- 2 (or even 3) coaxial rotors require to bore the HP disks to allow passing the LP shaft
  - the stress level doubles (hole) and increases with the boring radius
- To place the first critical speeds above the range of operational speeds, the LP shaft diameter should be as high as possible.

Opposite requirements
The thermal efficiency is defined as the ratio of the net power out of the engine to the rate of thermal energy available from the fuel. According to the Temperature-Entropy diagram of an ideal turbojet engine, the thermal efficiency simplifies to

$$\eta_{\text{thermal}} = 1 - \frac{T_0}{T_3}$$
Goal n° 2: Increase the ratio of power-output to engine weight by increasing the turbine inlet temperature

Trend in turbine inlet temperatures
Increasing the turbine temperature capability

Main technological challenge: the HP turbine temperature is conditioned by the combustion chamber outlet temperature.
Increasing the turbine temperature capability

Example of the SNECMA M88 HP turbine

Rotational velocity
560 m/s

Centrifugal acceleration
80,000 g

Disk load induced by the blades
1000000 daN
In early turbojet engines: solid blades $\rightarrow$ the maximum admissible temperature was directly related to improvement of structural materials ($T_{\text{max}} \sim 1100 \, ^\circ\text{C}$)

From 1960-70: development of early air-cooled turbine blades

- hollow blades
- internal cooling of blades (casting using the ‘lost wax’ technique)
Mechanical challenges

HP turbine blade cooling

Internal and film cooling

HP nozzle guide vane cooling

Impingement tubes

Film cooling

‘Lost wax’ process
Mechanical challenges

Today: single crystal casting
Comparison of turbine blade life properties
(fixed temperature and stress levels)

- Directionally solidified blades
- Conventionally cast blade
- Single crystal blades

Elongation (%)

Time (hrs)

Fracture
Challenges of turbojet technology

Overall efficiency of a jet propulsion engine

Overall efficiency

\[ \eta_{\text{overall}} = \eta_{\text{thermal}} \times \eta_{\text{propulsive}} \]

Thermal efficiency

Propulsive efficiency
The propulsive efficiency is defined as the ratio of the useful power output (the product of thrust and flight velocity, $V_0$) to the total power output (rate of change of the kinetic energy of gases through the engine). This simplifies to

$$\eta_{\text{propulsive}} = \frac{F V_0}{\dot{W}_{out}} = \frac{2}{\frac{V_e}{V_0} + 1}$$
Goal n° 3: Increase the propulsive efficiency to lower the thrust specific fuel consumption (specially true for subsonic flight i.e. in the case of commercial engines).

⇒ the principle is to accelerate a larger mass of air to a lower velocity.
Principle of the by-pass engine (called turbofan)

Air flow rate ~ 5 to 7 times the air flow rate going through the gas generator

**Drawback:** the frontal area of the engine is quite large

→ more drag and more weight result
Trend in thrust specific fuel consumption

- Single-pool axial flow turbojet
- Twin-spool by-pass turbojet
- Twin-spool front fan turbojet
- Advanced technology (high by-pass ratio)
- Propfan

Year
Development of high-bypass ratio turbofans

**Main technological challenge:** mechanical resistance of fan blades (without penalizing mass).

- Improvement of structural materials such as titanium alloys.
- Design of shrouded fan blades with a high length-to-chord aspect ratio or of large-chord fan blades with honeycomb core.
- Knowledge of the dynamics of rotors stiffened by high gyroscopic couples and submitted to large out of balance forces (e.g. fan blade failure).
- Fan blade-off and containment analysis methods (e.g. blade loss).
- Use of Foreign Object Damage criteria (e.g. bird or ice impact on fan, ingestion of water, sand, volcanic ashes,...).
**New concept:** high by-pass engine → wide chord fan blade

→ the weight is maintained at a low level by fabricating the blade from skins of titanium incorporating a honeycomb core

Prop-fan concept

Contra-rotating prop-fan

This configuration is still in an experimental state

Wide chord fan blade construction
Mechanical design of industrial rotors
Type of analysis performed in industry

- Stability analysis and determination of critical speeds (Campbell diagram).
- Forced response to harmonic excitation.
- Forced response to transient excitation (crossing of critical speeds).
The critical speeds should be placed outside two zones: 50% and [75% - 110%] of the nominal speed.

Typical mission profile for a civil aircraft:
- Nominal speed at take-off
- Climb
- Cruise
- Continued cruise
- Descent
- Diversion
- Hold
- Landing
Summary of basic steps for the design

- position the critical speeds outside the range of operational speeds (e.g. a margin of 10% is usually taken).
- add external damping to lower the resonance amplitude peaks (in order to keep the rotor-stator gap at the minimum and thus to optimize engine performances).
- minimize excitation sources (balancing, alignment, optimization of gaps).
- select low support stiffness (flexible bearing supports) in order to reduce the dynamic load transmitted through the bearing to the stator.
The CFM 56-5 jet engine (Airbus A320, A 340)

Twin-spool front fan turbo-jet
(high by-pass ratio)

Take-off thrust of 11 340 daN
Schematic model of the jet engine

**Casings**
(15 nodes, 4 beam elements, 4 disks, 6 supplementary mass elements)

**Low-pressure (LP) rotor**
(9 nodes, 5 beam elements, 9 disks)

**High-pressure (HP) rotor**
(7 nodes, 3 beam elements, 7 disks)

\[ \Omega_{\text{HP}} = 1.25 \times \Omega_{\text{BP}} + 8750 \text{ (rpm)} \]
The CFM 56-5 jet engine (Airbus A320, A340)

Campbell diagram

\[ \omega = \Omega_{\text{BP}} \]

\[ \omega = \Omega_{\text{HP}} \]

Mode-shapes at 5000 rpm

- 3.9 Hz
- 19.9 Hz
- 42.0 Hz
- 60.7 Hz
- 71.1 Hz
The CFM 56-5 jet engine (Airbus A320, A 340)

Response to mass unbalance on LP rotor (point A)

At point A

At point B

Ω_BP

Ω_BP
Vibration phenomena are the main cause of failure of compressor blades and disks.

**Requirements**

Ability to predict:

- natural frequencies (i.e. to identify critical speeds);
- mode-shapes (i.e. to establish vulnerability to vibrate and locations of maximum stresses);
- damping levels (i.e. severity of resonance);
- response levels (i.e. fatigue susceptibility);
- stability (i.e. vulnerability to flutter).
Campbell diagrams

(Natural frequencies vs. Rotation speed)

Standard format for presentation of blade vibration properties in order to illustrate the essential features and regions of probable vibration problem areas.
Dynamic analysis methods for practical blades

Campbell diagram of a compressor blade

- Frequency (Hz)
- 2nd Bending (Flap)
- Engine Order 1 to 7
- 1st Torsion (Edge)
- 1st Bending (Flap)
- Rotation speed (rpm)
Flutter design methodology

Types of flutter

- Supersonic stall flutter
- High incidence supersonic flutter
- Classical unstalled supersonic flutter
- Choke flutter
- Surge line
- Subsonic/Transonic stall flutter (one of the most encountered in practice)

Diagram with axes:
- Pressure ratio
- Corrected mass flow rate

Operating line:
- 50%
- 75%
- 100%
Shroud or interconnected tip

The design of the first blades of the compressor is governed by aeroelastic problems.

Criterion: \( c \times f_1 > \text{threshold limit} \)

First solution

Make the chord wider

\( \Rightarrow \) high weight \( \Rightarrow \) construction of the blade with a honeycomb core, which renders the fabrication more complex (high cost).
Flutter design methodology

Criterion

\[ c \times f_1 > \text{threshold limit} \]

chord

1st natural frequency (torsion or bending)

Second solution

Make the first natural frequency \( f_1 \) higher (and bring damping)

- shrouded blades
- or fixed tip

\[ \implies \text{Take care to the mechanical resistance (high centrifugal effect at the external diameter).} \]
Disks may have different shapes depending on their location into the engine.
Mechanical design of disks
Sources of stresses in a rotor disk

- Centrifugal body force of disk material;
- Centrifugal load produced by the blades and their attachments to the disk;
- Thermo-mechanical stresses produced by temperature gradients between bore and rim;
- Shear stresses produced by torque transmission from turbine to compressor;
- Bending stresses produced by aerodynamic loads on the blades;
- Dynamical stresses of vibratory origin;
An « optimal » mechanical design requires:

1. The precise determination of physical parameters (temperature, stress and strain distributions) → use of refined finite element models, thermo-elasto-viscoplastic analyses.

2. The perfect understanding of the material properties and the conditions which lead to failure → this corresponds to the use of an equivalent safety factor of 1.5 or less.
Damage tolerance philosophy

Crack size vs. cycles

- Assumed life curves
- Safety limit
- Detection limit
- Fatigue crack initiation

Initial defect size

Return to service intervals
In summary, the mechanical design of turbojets is challenging.

One of the first challenge is the study of the dynamics of multiple rotor systems submitted to large gyroscopic couples.

Then, depending on the engine component (blade, disk) and on its location within the engine, problems are of very different nature:

- In the « cold » parts of the engine (fan, LP compressor, HP compressor), the mechanical design is based on the solution of dynamical problems (blade vibrations, aeroelastic flutter, bird impact).

- In the « hot » parts of the engine (HP compressor, combustion chamber, HP turbine), the design is based on creep and fatigue calculations and a damage tolerance philosophy is applied.