Mechanical Design of Turbojet Engines

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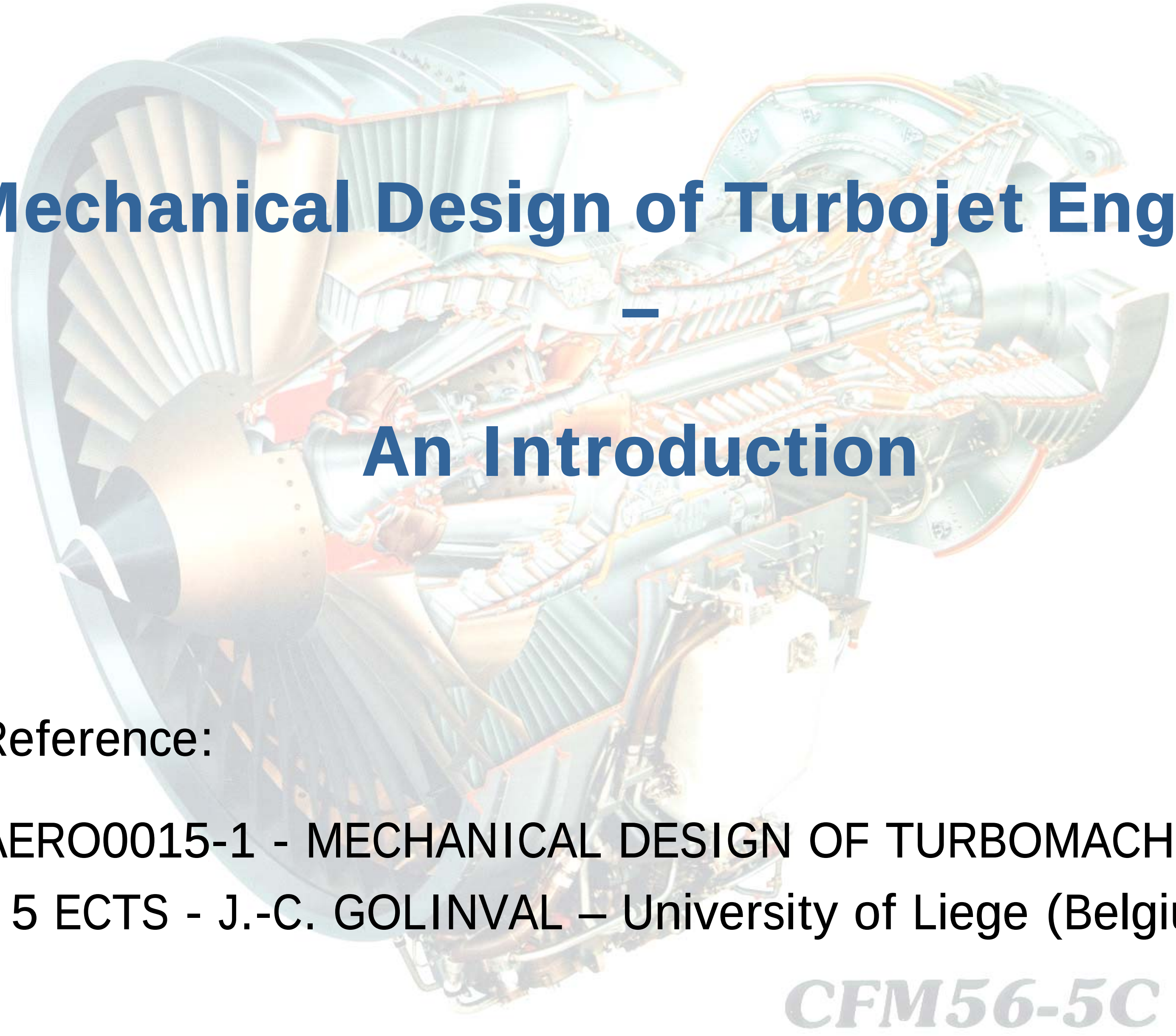
An Introduction



Reference:

AERO0015-1 - MECHANICAL DESIGN OF TURBOMACHINERY - 5 ECTS - J.-C. GOLINVAL – University of Liege (Belgium)

Content

Challenges of turbojet technology

Evolution of turbojet engines to the technology level of today

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

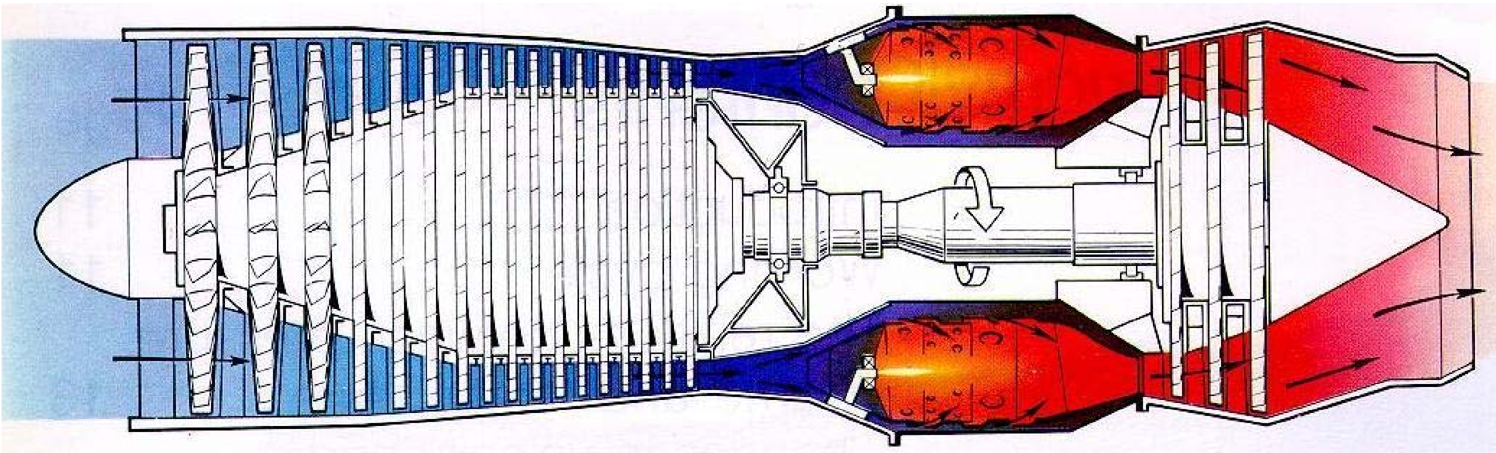
To achieve good performances, parallel research and development effort were undertaken in areas such as in aerodynamics, aerothermics, acoustics, combustion process, mechanics, metallurgy, manufacturing, ...

Aim of the course

Study the mechanical aspects of the design.

Challenges of turbojet technology

Principles of jet propulsion



Overall efficiency of a jet propulsion engine

$$\boxed{\eta_{\text{overall}} = \eta_{\text{thermal}} \times \eta_{\text{propulsive}}}$$

Thermal efficiency

Propulsive efficiency

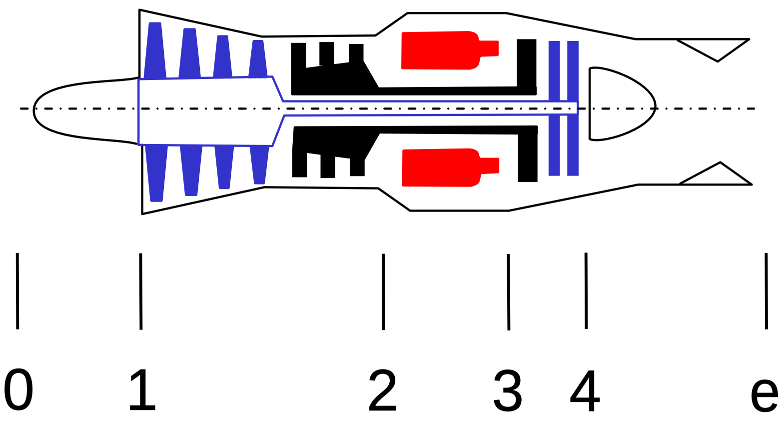
Challenges of turbojet technology

Thermal efficiency

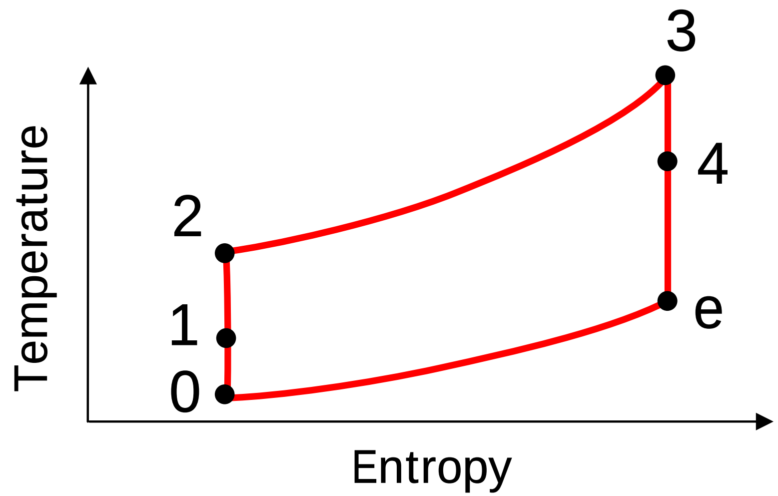
The thermal efficiency is defined as the ratio of the net power out of the engine to the rate of thermal energy available from the fuel.

According to the T-s diagram of an ideal turbojet engine, the thermal efficiency simplifies to

$$\eta_{\text{thermal}} = 1 - \frac{T_0}{T_3}$$



Thermodynamic cycle



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Challenges of turbojet technology

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

thrust

flight velocity

$$\eta_{\text{propulsive}} = \frac{F\,V_0}{\dot{W}_{out}} = \frac{2}{V_e / V_0 + 1}$$

total power output

exit velocity

Challenges of turbojet technology

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

1. Increase the thermodynamic cycle efficiency by increasing the compressor pressure ratio.
2. Increase the ratio of power-output to engine weight by increasing the turbine inlet temperature

What are the consequences of these goals on the mechanical design?

Mechanical challenges of turbojet technology

Goal n°1 - Increasing of the compressor pressure ratio (r)

Trend in compressor pressure ratios

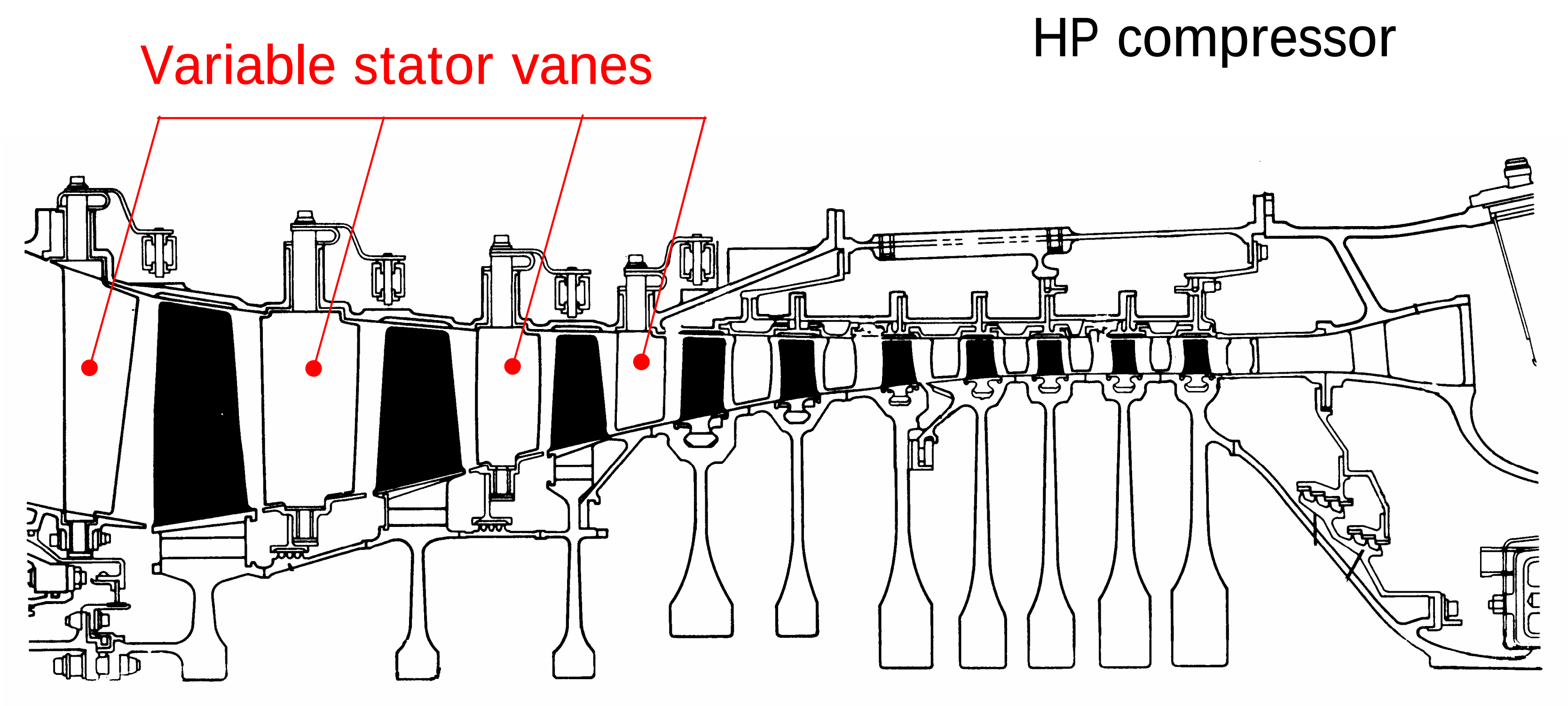
Calendar years	Compressor pressure ratio
Late 1930 to 1940	3:1 to about 6:1
Early 1950	About 10:1
1950 to 1960	20:1 to about 25:1
2000	30:1 to about 40:1

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

Mechanical challenges of turbojet technology

Solution n° 1 : concept of variable stator blades

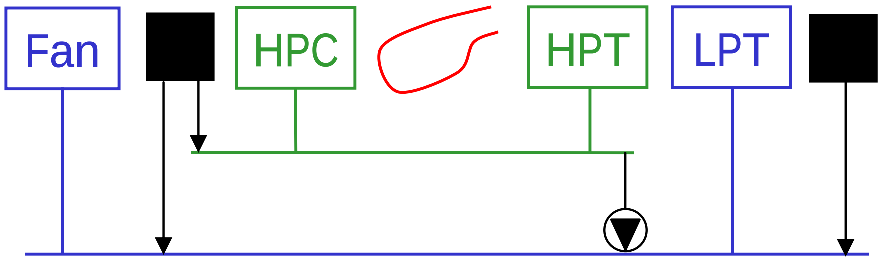
- Design of reliable airflow control systems
- Prevention of air leakage at the pivots of the vanes at high pressures (temperatures).



Mechanical challenges of turbojet technology

Solution n° 2: concept of multiple rotors (r ~ 20:1 - 30:1)

Example of a dual-rotor configuration



CFM56

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.

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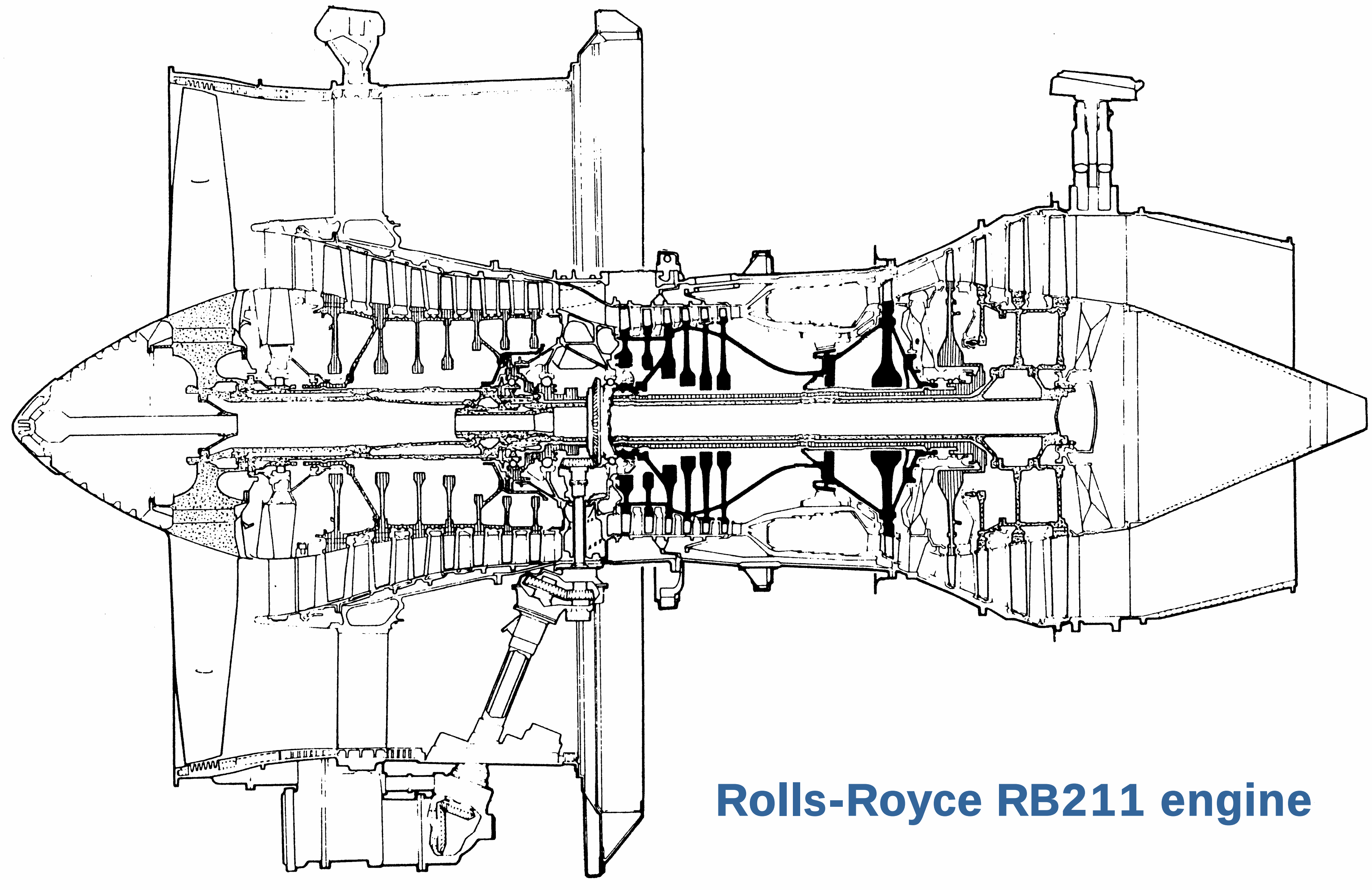
Mechanical challenges of turbojet technology



Rolls-Royce RB211 engine

Mechanical challenges of turbojet technology

Mechanical challenges

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

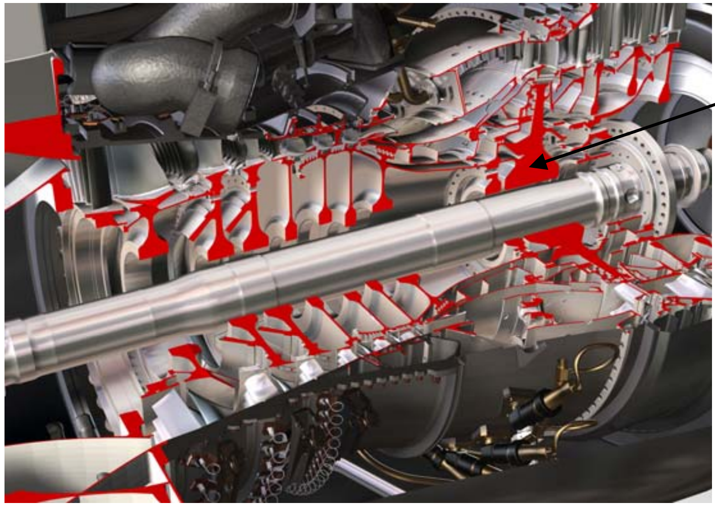
Structural dynamicists and mechanical engineers may have opposite requirements → optimisation process

Mechanical challenges of turbojet technology

Example of opposite requirements

- 2 (or even 3) coaxial rotors require to bore the HP discs to allow passing the LP shaft → the stress level doubles (hole) and increases with the bore radius → the LP shaft diameter should be as small as possible.

Low pressure turbine shaft



High pressure turbine disc

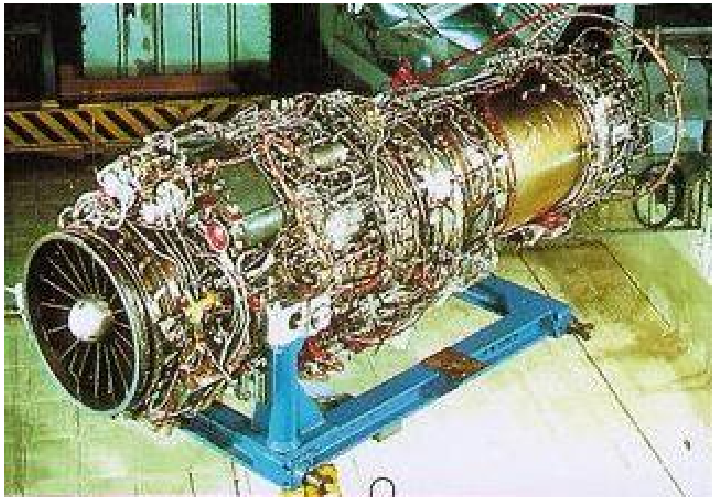
- To place the first critical speeds above the range of operational speeds, the LP shaft diameter should be as high as possible.

Challenges of turbojet technology

Depending on the types of applications, different development goals may be pursued.

Supersonic flight (military engines)

Maximum thrust is sought by increasing the exit velocity (at the expense of fuel economy) and decreasing the engine inlet diameter (i.e. of the aerodynamic drag)



Example

SNECMA M88 military engine (used on the RAFALE airplane)

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Challenges of turbojet technology

Subsonic flight (commercial engines)

A low thrust specific fuel consumption is sought by increasing the propulsive efficiency → the principle is to accelerate a larger mass of air to a lower velocity.

Solution: **principle of the by-pass engine (called turbofan)**

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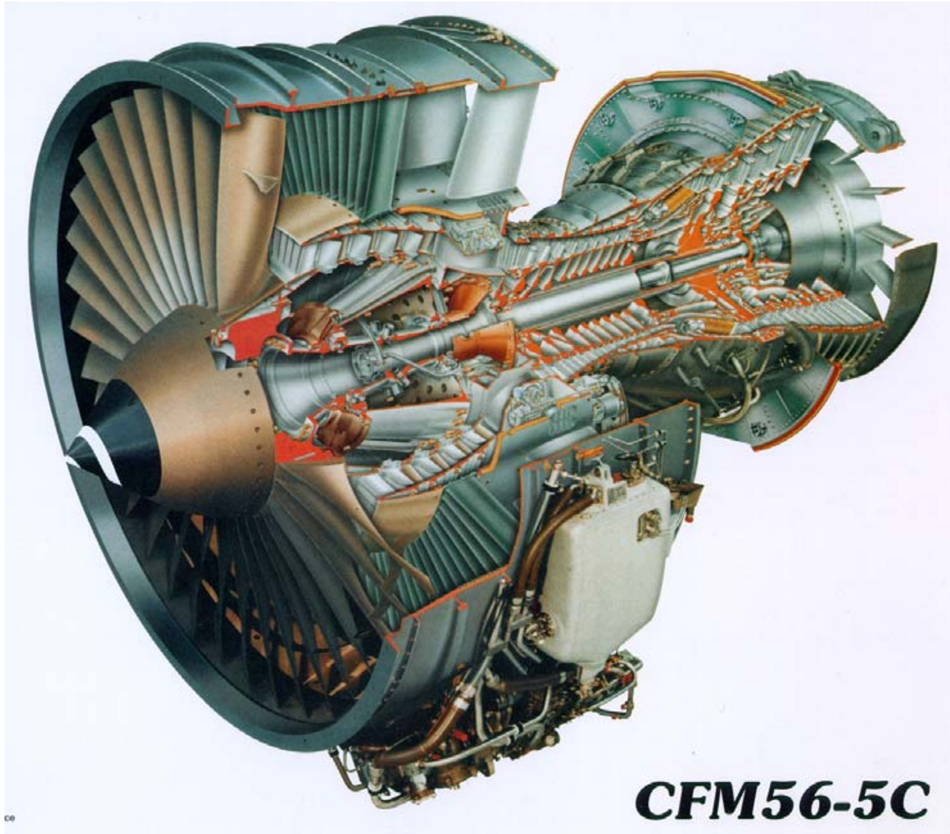
Challenges of turbojet technology

Solution: **principle of the by-pass engine (called turbofan)**



Drawback: the frontal area of the engine is quite large

→ more drag and more weight result

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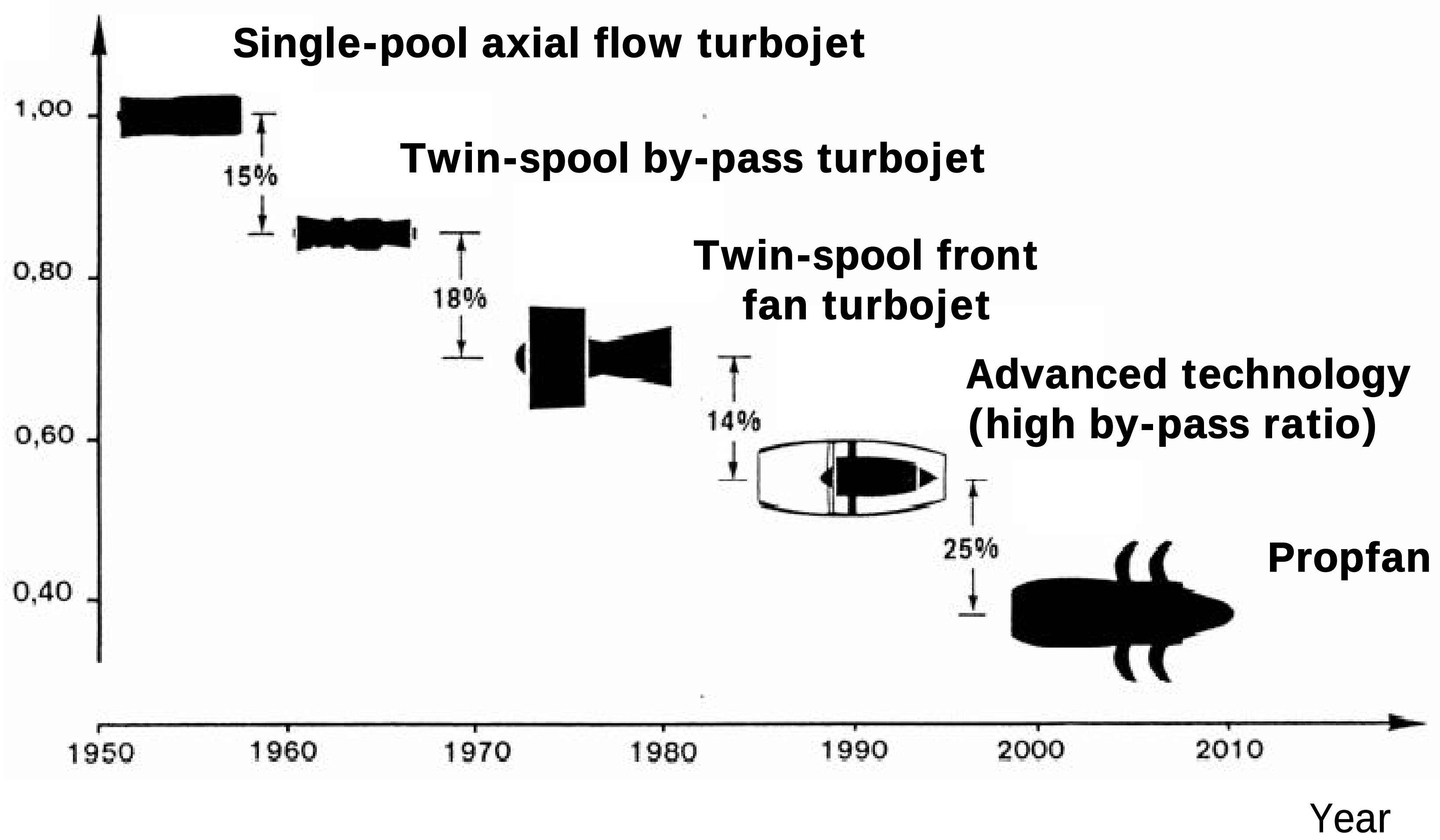
Challenges of turbojet technology

Trend in thrust specific fuel consumption



Mechanical challenges of turbojet technology

Development of high-bypass ratio turbofans

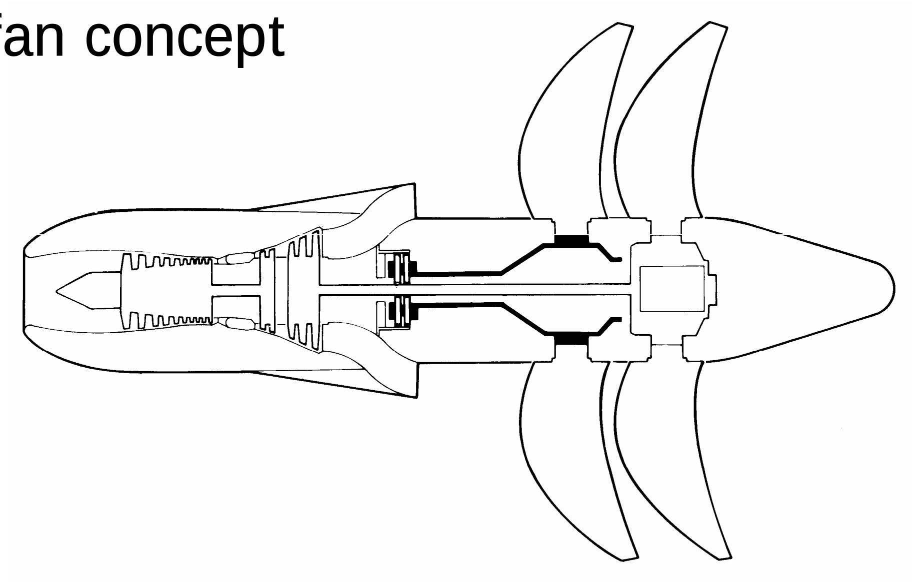
Main technological challenge: mechanical resistance of fan blades (without penalizing mass).

- 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,…).

Mechanical challenges of turbojet technology

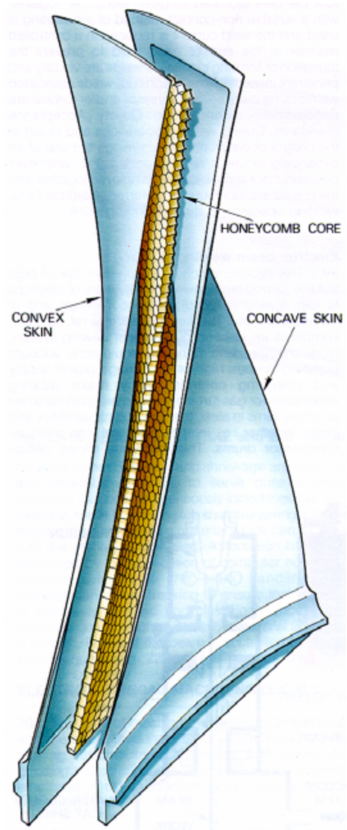
New concept: high by-pass engine → wide chord fan blade
→ the weight is maintained at a low level by fabricating the blade from skins of titanium incorporating a honeycomb core

Prop-fan concept



Contra-rotating prop-fan

This configuration is still in an experimental state



Wide chord fan blade construction

Challenges of turbojet technology

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

1. Increase the thermodynamic cycle efficiency by increasing the compressor pressure ratio.

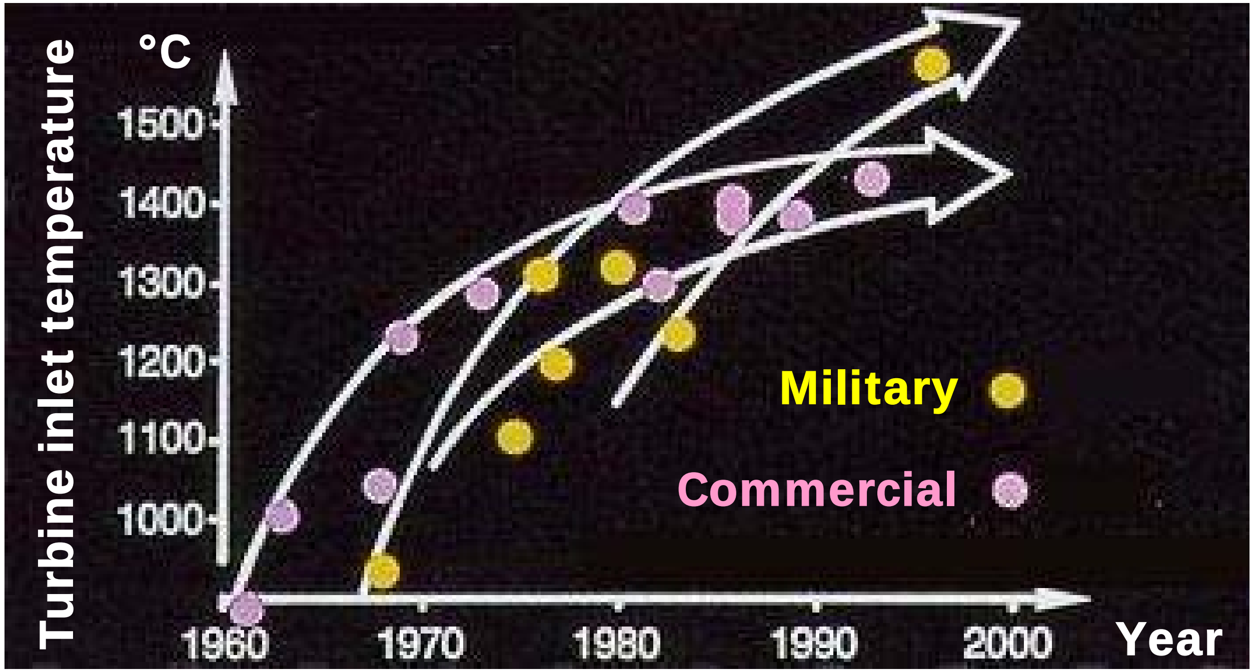
2. **Increase the ratio of power-output to engine weight by increasing the turbine inlet temperature**

What are the consequences of these goals on the mechanical design?

Challenges of turbojet technology

Goal n°2 - Increasing the turbine temperature capability

Trend in turbine inlet temperatures

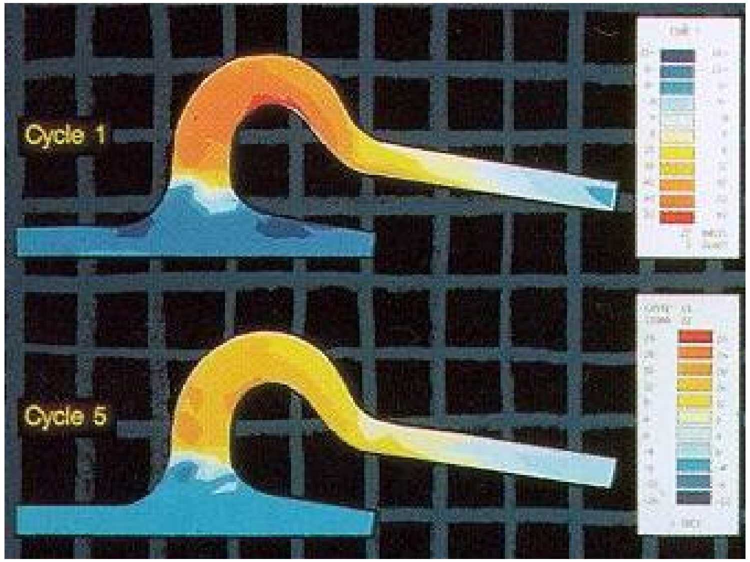


Mechanical challenges of turbojet technology

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

SNECMA combustion chamber

Stress distribution in a structural element of the combustion chamber



Mechanical challenges of turbojet technology

In early turbojet engines: solid blades → the maximum admissible temperature was directly related to improvement of structural materials (T_{max} ~ 1100 °C)

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

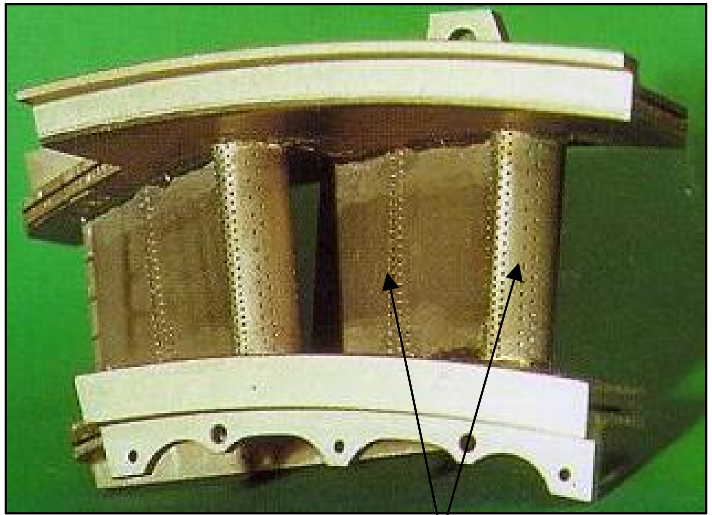
- hollow blades
- internal cooling of blades (casting using the 'lost wax' technique)

Mechanical challenges of turbojet technology

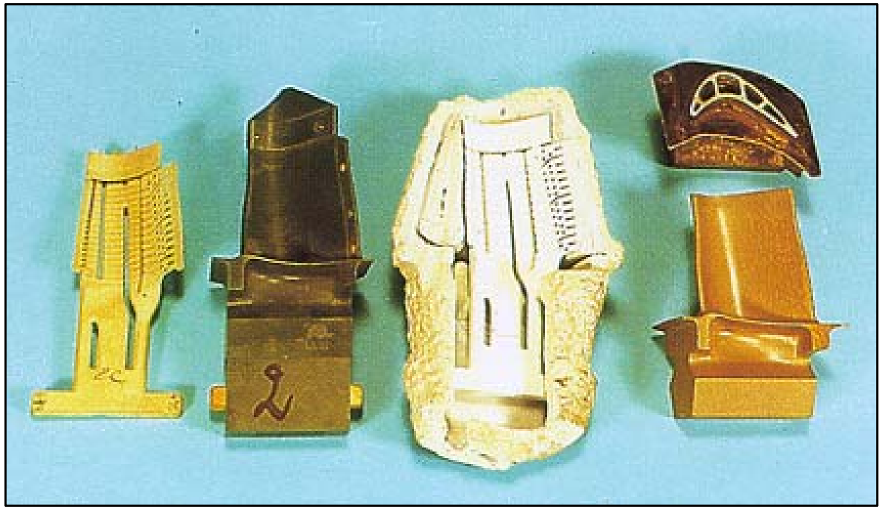
HP turbine blade cooling

Internal and film cooling

HP nozzle guide vane cooling

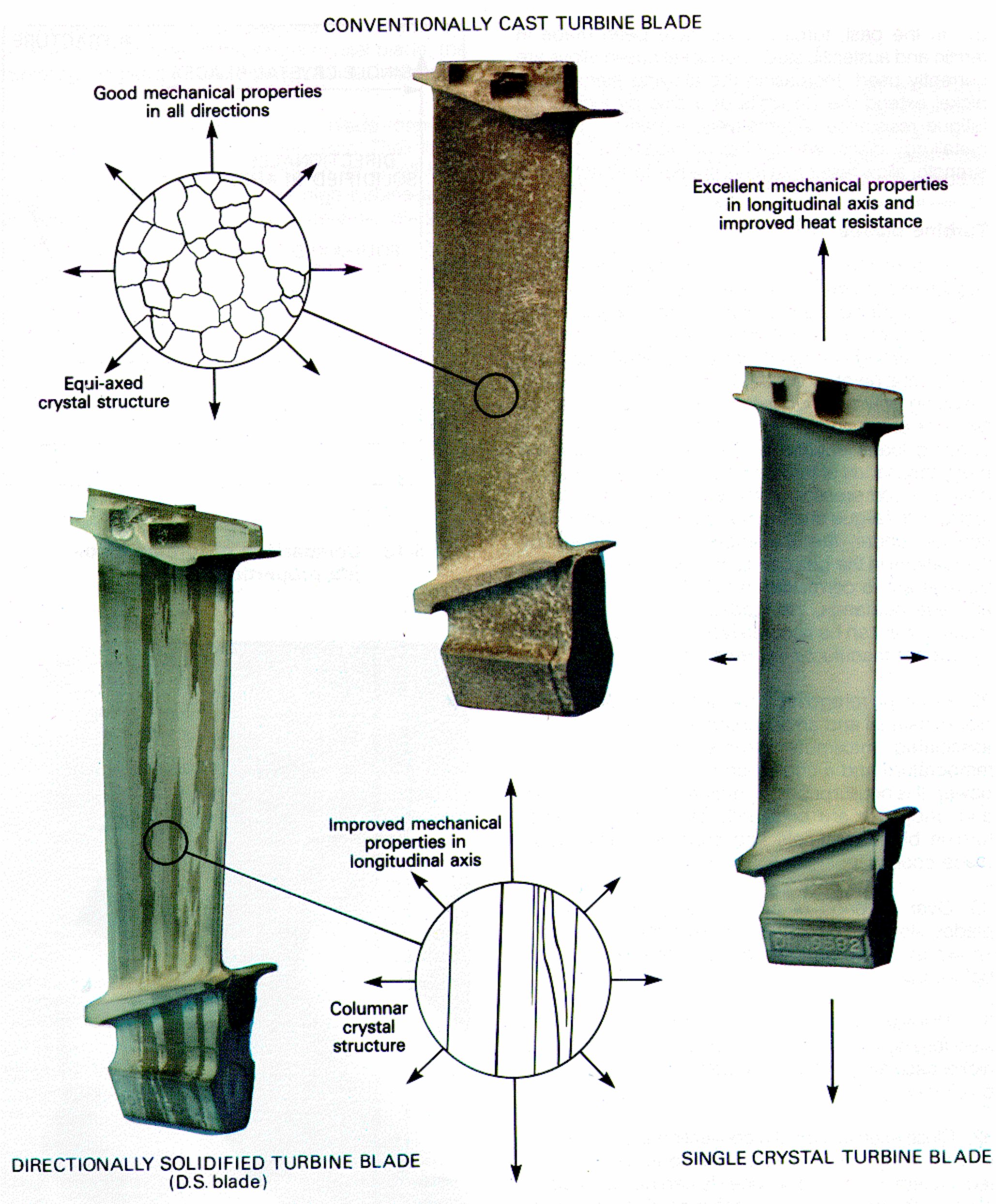


Film cooling holes



'Lost wax' process

Mechanical challenges of turbojet technology

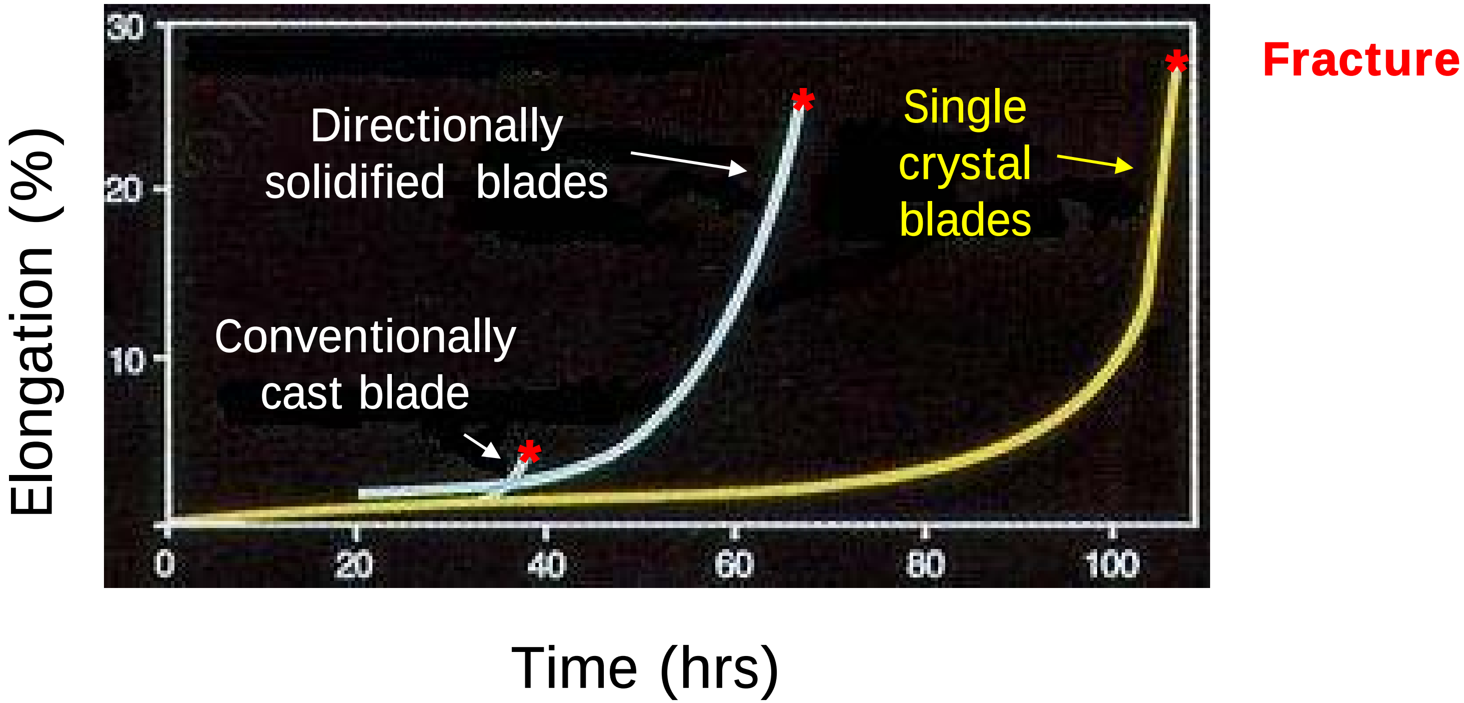


Today: single crystal casting

Mechanical challenges of turbojet technology

Comparison of turbine blade life properties

(fixed temperature and stress levels)

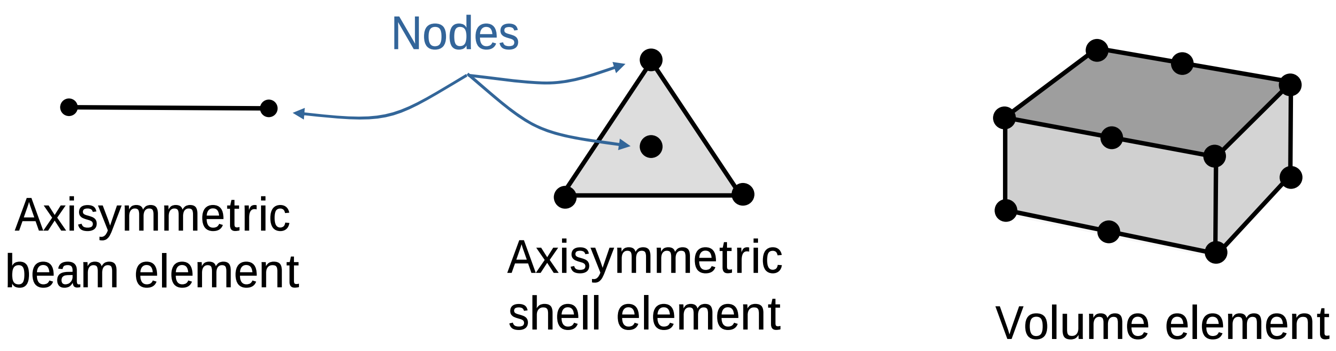


Dynamic analysis of industrial rotors

Dynamic analysis of industrial rotors

The **Finite Element Method** is commonly used in industry.

- 1D-model (beam elements): the most used for pilot-studies.
- 2D-model (plane or axisymmetric shell elements): practical interest for projects.
- 3D-model (volume elements): used for detailed analyses.



Dynamic analysis of industrial rotors

Equations of motion

Stiffness matrix of localized elements

$$\mathbf{K}_S + \Omega\,\mathbf{C}_{AS} + \mathbf{K}_\ell(\Omega)$$

Mass matrix

Matrix of circulatory forces

Structural stiffness matrix

$$\mathbf{M}\,\ddot{\mathbf{q}} + \mathbf{C}(\Omega)\,\dot{\mathbf{q}} + \mathbf{K}(\Omega)\,\mathbf{q} + \mathbf{f}(\mathbf{q},\dot{\mathbf{q}},\Omega) = \mathbf{g}(t)$$

vector of excitation forces

vector of nonlinear forces (associated to interaction elements)

$$\mathbf{C}_S + \Omega\,\mathbf{G} + \mathbf{C}_\ell(\Omega)$$

Damping matrix of localized elements

Gyroscopic matrix

Structural damping matrix

Type of analysis

- Stability analysis and determination of critical speeds (Campbell diagram).

$$\boxed{\mathbf{M}\,\ddot{\mathbf{q}} + \Omega\,\mathbf{G}\,\dot{\mathbf{q}} + \left(\mathbf{K}_S + \mathbf{K}_\ell(\Omega)\right)\mathbf{q} = 0}$$

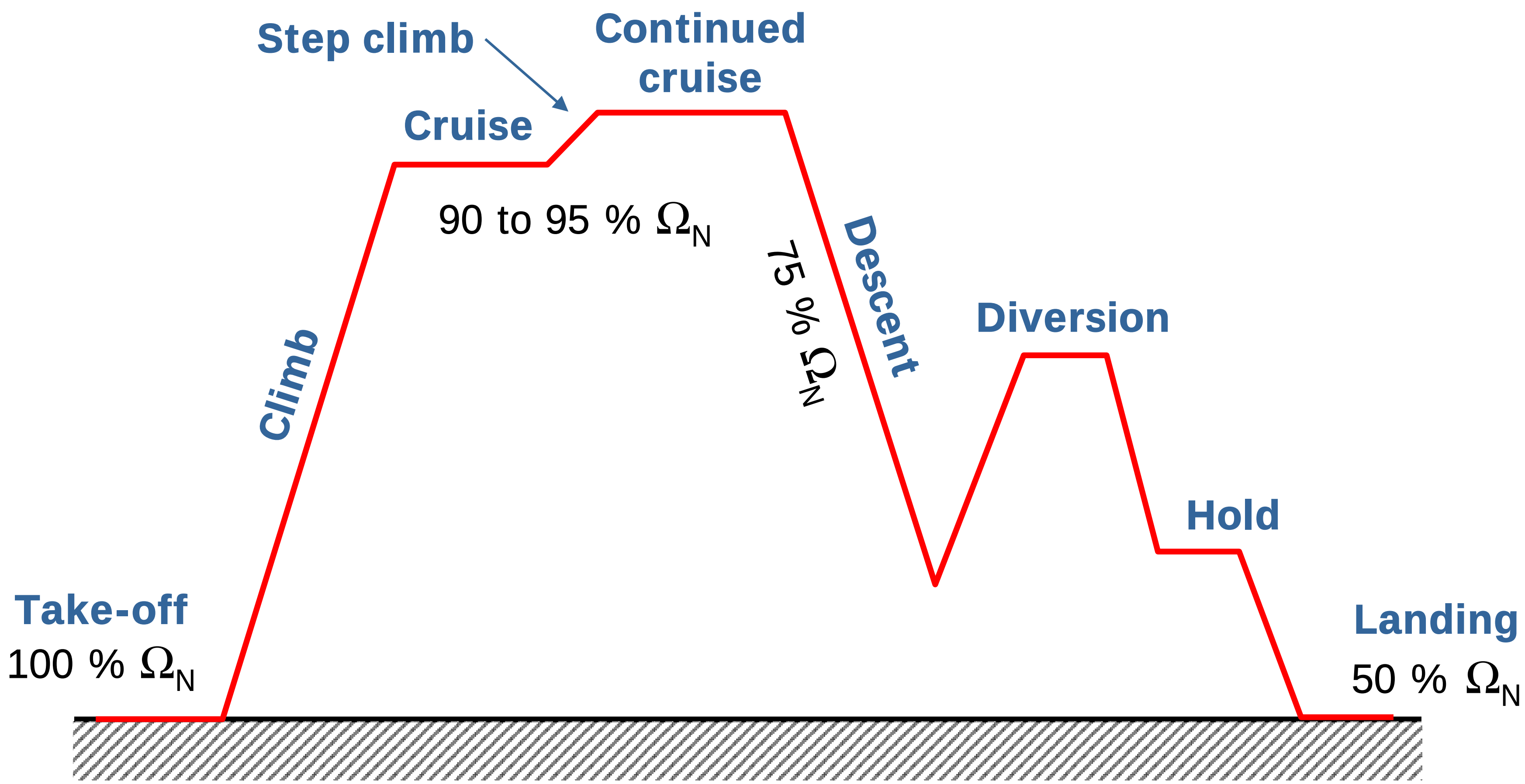
- Forced response to harmonic excitation.

$$\boxed{\mathbf{M}\,\ddot{\mathbf{q}} + \mathbf{C}(\Omega)\,\dot{\mathbf{q}} + \left(\mathbf{K}_S + \mathbf{K}_\ell(\Omega)\right)\mathbf{q} = \mathbf{g}(t)}$$

- Forced response to transient excitation (crossing of critical speeds).

Typical mission profile for a civil aircraft

Stability analysis



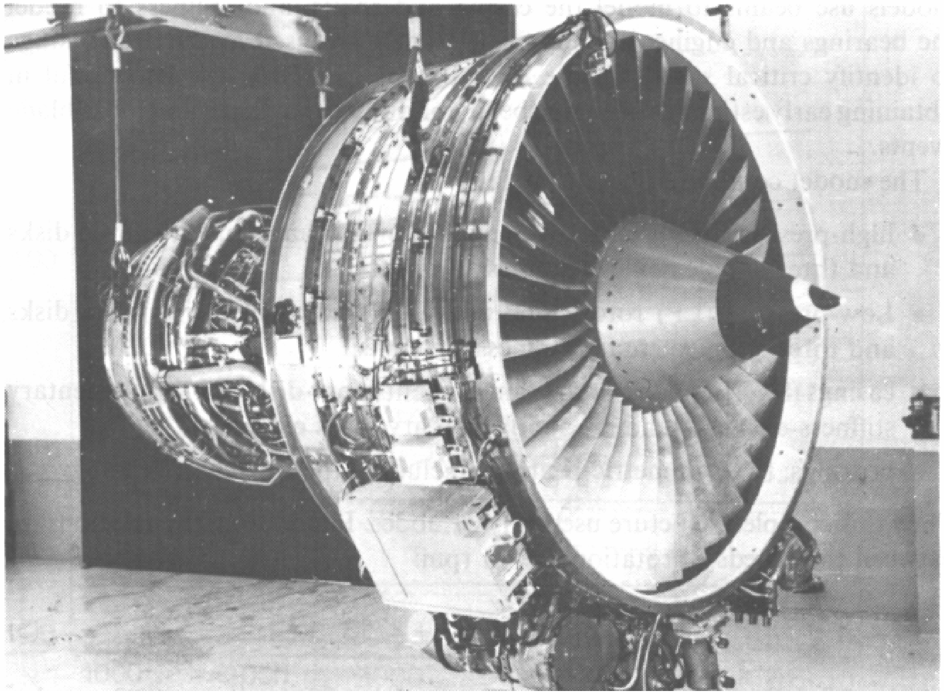
→ The critical speeds should placed outside two zones: 50 % and [75% - 110%] of the nominal speed.

The CFM 56-5 jet engine (Airbus A320, A 340)

Example of analysis

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

Take-off thrust of 11 340 daN

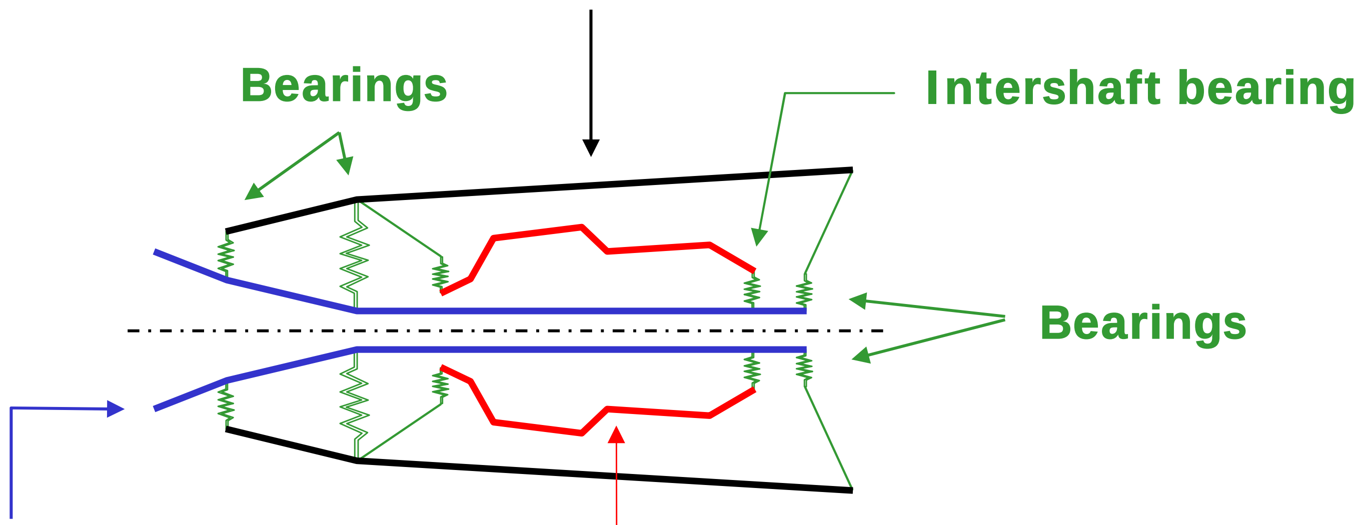


The CFM 56-5 jet engine (Airbus A320, A 340)

Schematic model of the jet engine

Casings

(15 nodes, 4 beam elements, 4 discs, 6 supplementary mass elements)



Low-pressure (LP) rotor

(9 nodes, 5 beam elements, 9 discs)

High-pressure (HP) rotor

(7 nodes, 3 beam elements, 7 discs)

$$\Omega_{HP} = 1.25 \times \Omega_{LP} + 8750 \quad (\text{rpm})$$

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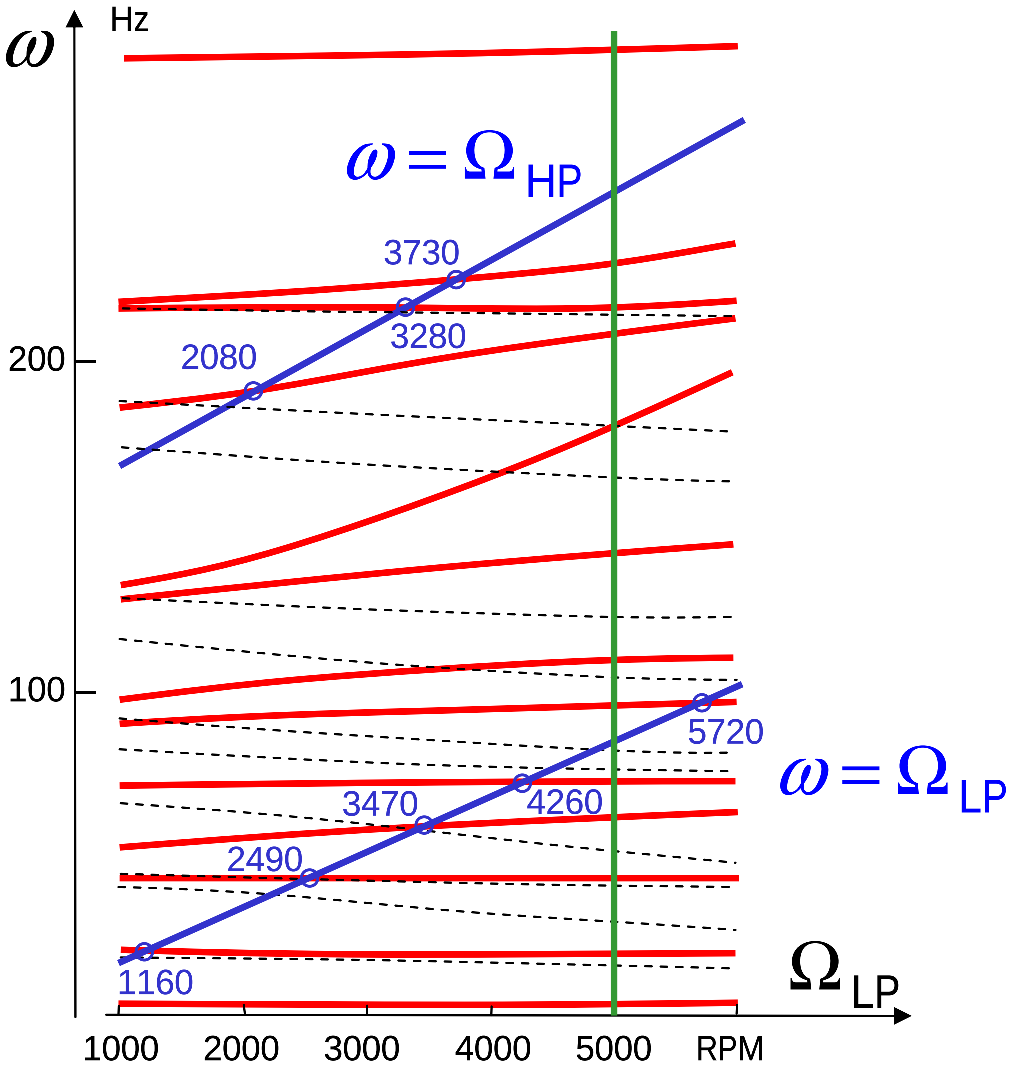
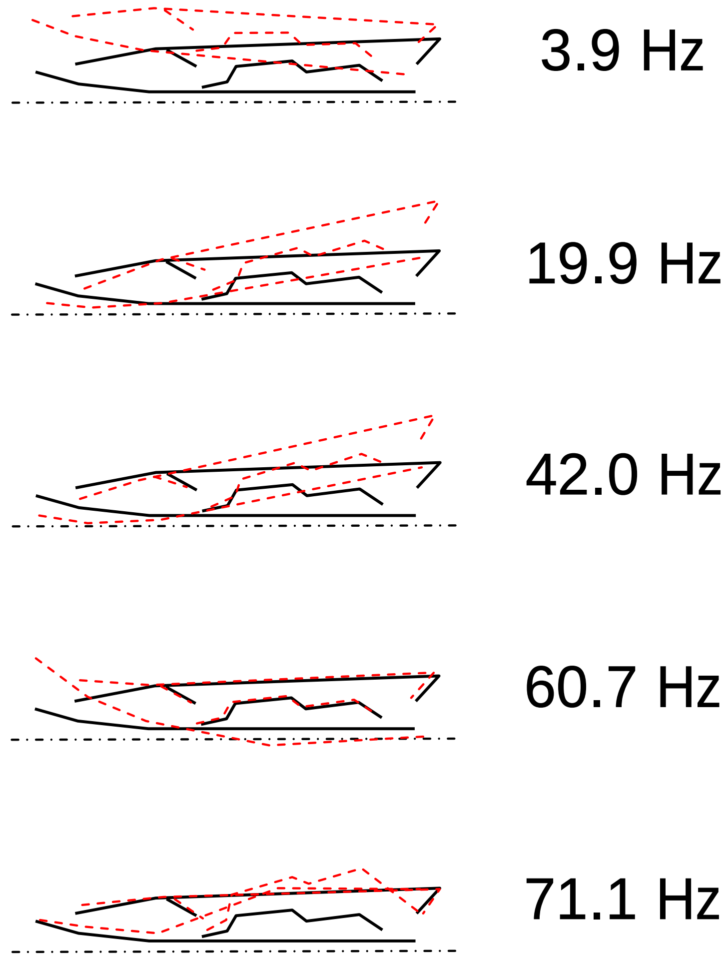
The CFM 56-5 jet engine (Airbus A320, A 340)

Campbell diagram

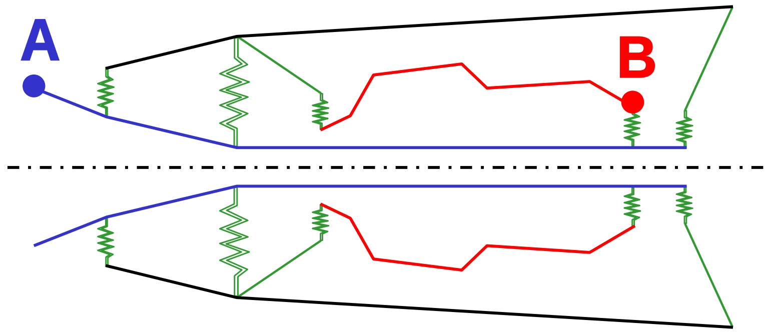


Mode-shapes at 5000 rpm

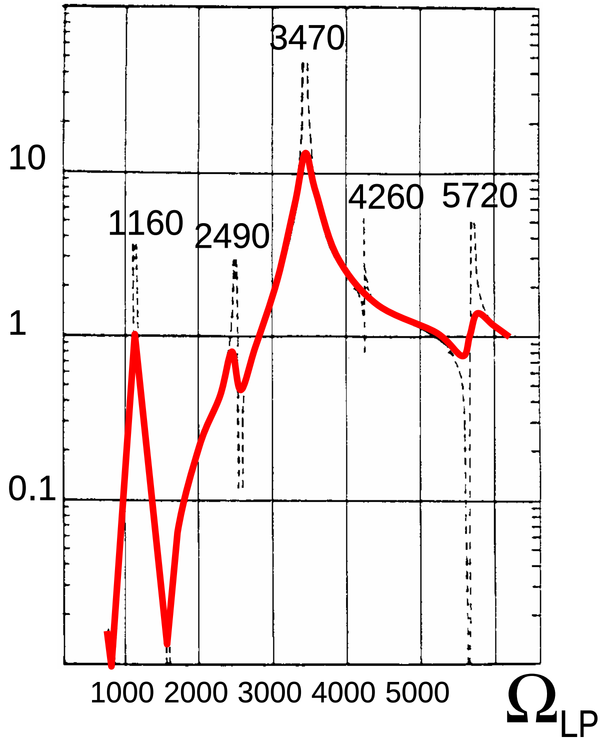


The CFM 56-5 jet engine (Airbus A320, A 340)

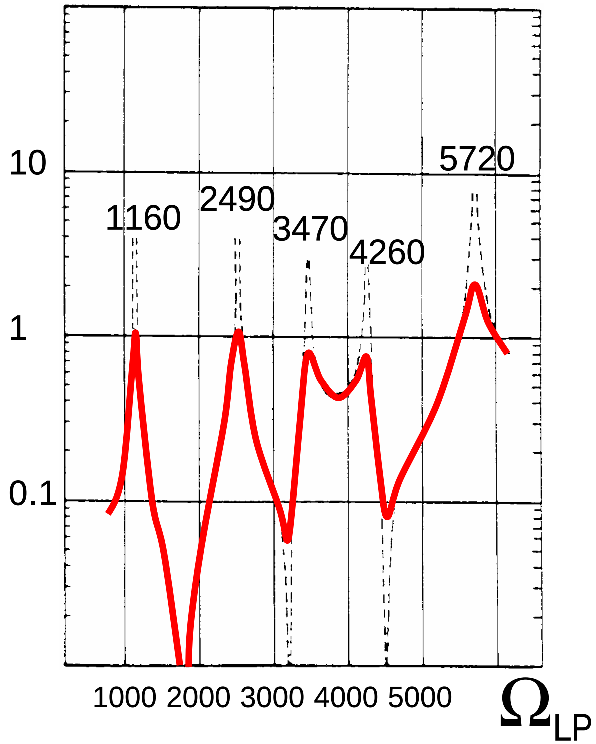
Response to mass unbalance on LP rotor (point A)



At point **A**



At point **B**



Structural dynamics of blades and discs

Structural dynamics of blades and discs

Vibration phenomena are the **main cause of failure** of compressor blades and discs.

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).

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Dynamic analysis methods for practical blades

Equations of motion

$$\mathbf{K}_S + \mathbf{K}_g(\boldsymbol{\sigma}_C) - \Omega^2\,\mathbf{M}_C$$

Centrifugal mass matrix

Mass matrix

Geometric stiffness matrix

Structural stiffness matrix

$$\mathbf{M}\,\ddot{\mathbf{q}} + \Omega\,\mathbf{G}\,\dot{\mathbf{q}} + \mathbf{K}(\boldsymbol{\sigma}_C,\Omega)\,\mathbf{q} = \mathbf{F}_C\left(\Omega^2\right) + \mathbf{g}(t,\mathbf{q},\dot{\mathbf{q}},)$$

Vector of external forces

Gyroscopic matrix

Vector of static centrifugal forces

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Dynamic analysis methods for practical blades

Type of analysis and solution methods

Static analysis

(in order to determine the stress distribution due to the centrifugal forces)

$$\left(\mathbf{K}_S + \mathbf{K}_g\left(\boldsymbol{\sigma}_C\right) - \Omega^2\,\mathbf{M}_C\right)\mathbf{q} = \mathbf{F}_C\left(\Omega^2\right) + \mathbf{g}$$

This equation is nonlinear, since $\boldsymbol{\sigma}_C$ is unknown a priori → the solution needs an iterative process, such as the Newton-Raphson method.

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Dynamic analysis methods for practical blades

Dynamic analysis

As the Coriolis effects can be neglected (this is usually so for radial blades), the equations of motion reduce to

$$\boxed{\mathbf{M}\,\ddot{\mathbf{q}} + \mathbf{K}\left(\boldsymbol{\sigma}_C, \Omega\right)\mathbf{q} = 0}$$

where $\mathbf{K}$ has been determined by a preliminary static analysis.

The solution of this equation for different values of Ω allows to construct the Campbell diagram.

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.

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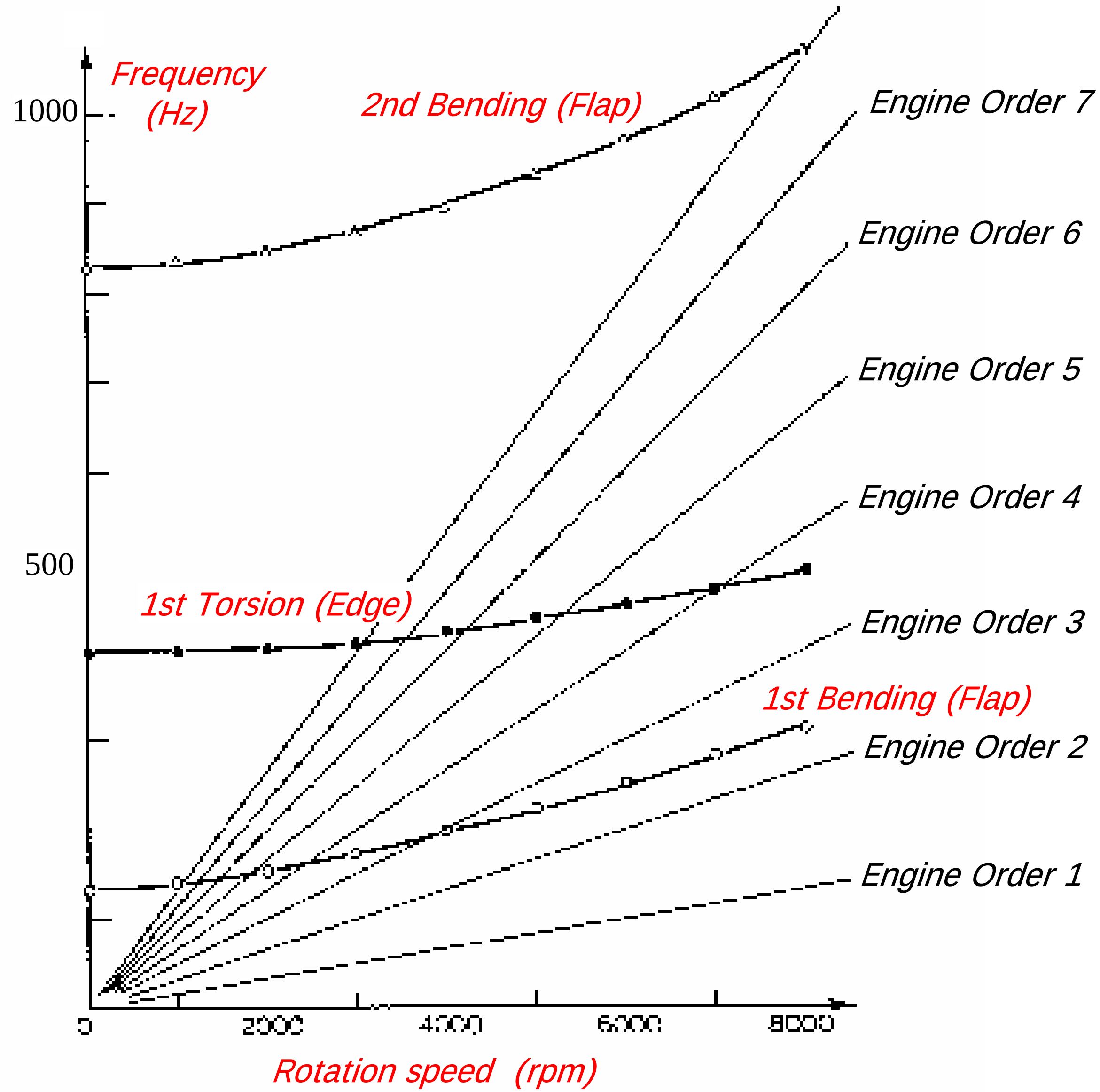
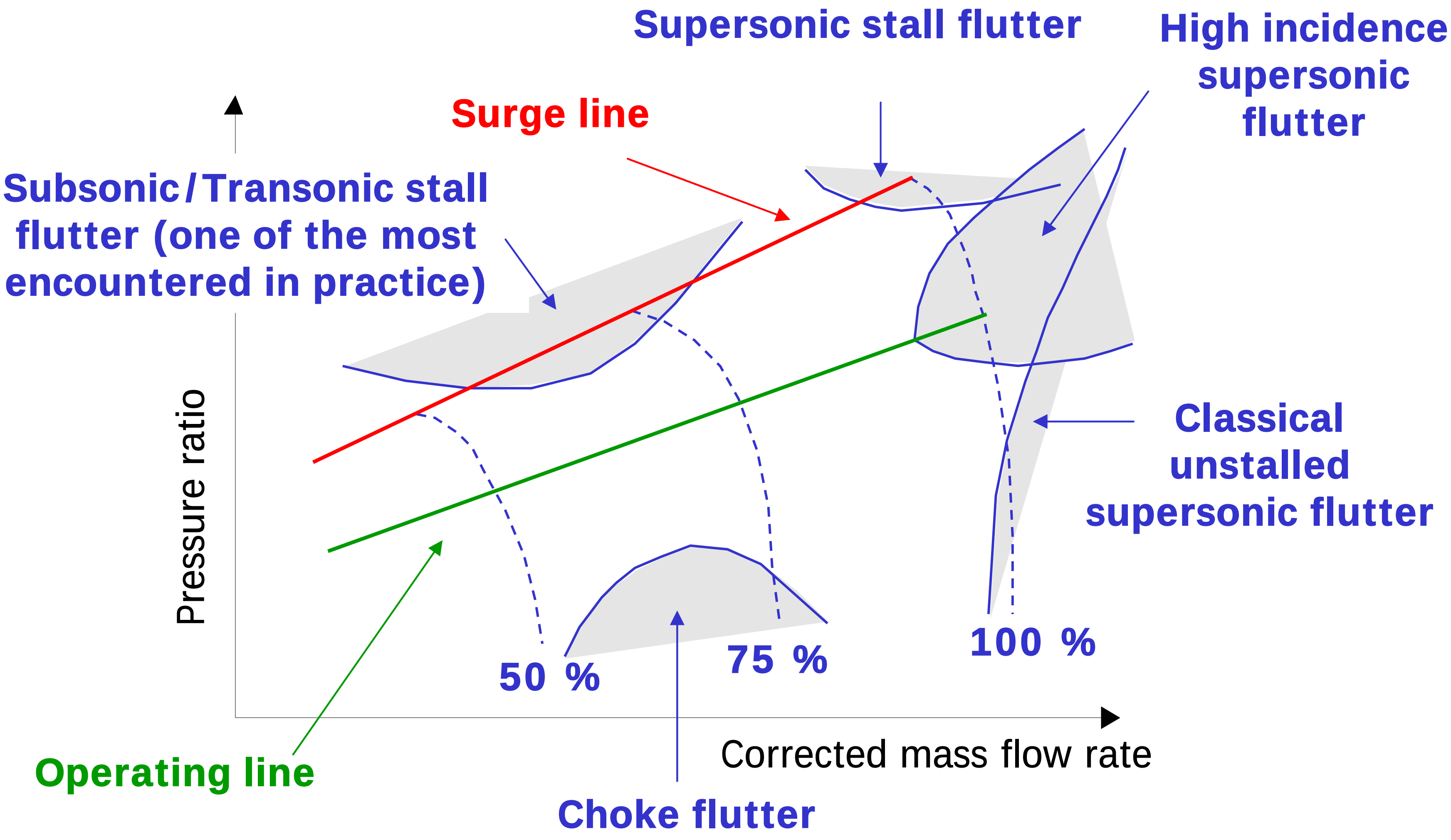
Dynamic analysis methods for practical blades

Campbell diagram of a compressor blade



Flutter design methodology

Types of flutter



Flutter design methodology

Shroud or interconnected tip?

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

Criterion:

1st natural frequency (torsion or bending)

$$c \ \mathrm{x} \ f_1 > \text{threshold limit}$$

chord

Flutter design methodology

First solution

1st natural frequency (torsion or bending)

Criterion $\boxed{c \times f_1 > \text{threshold limit}}$

chord

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

- shrouded blades $(h/c \simeq 2.5$ to $3)$
- or fixed tip $(h/c \simeq 3.5)$

⇨ Take care to the mechanical resistance (high centrifugal effect at the external diameter).

Flutter design methodology

Second solution

1st natural frequency (torsion or bending)

Criterion $\boxed{c \times f_1 > \text{threshold limit}}$

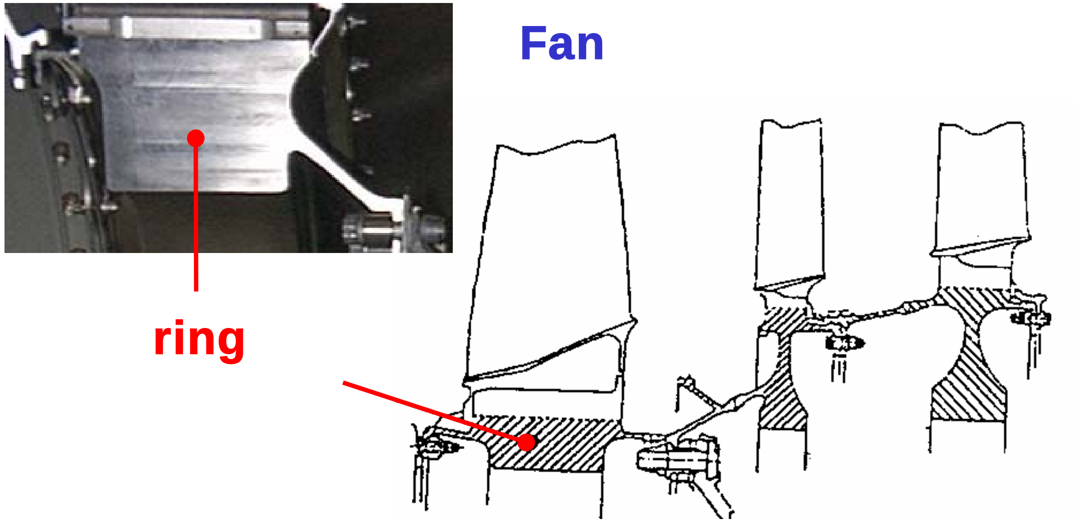
chord

Make the chord wider $(h/c \simeq 2)$

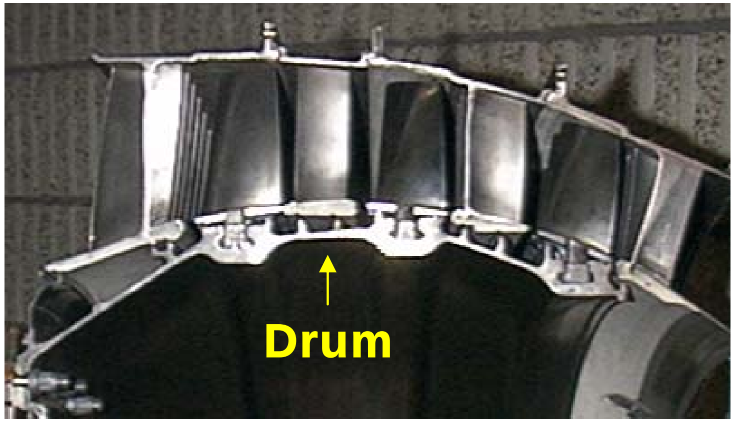
⇨ high weight ⇨ construction of the blade with a honeycomb core, which renders the fabrication more complex (high cost).

Mechanical design of discs

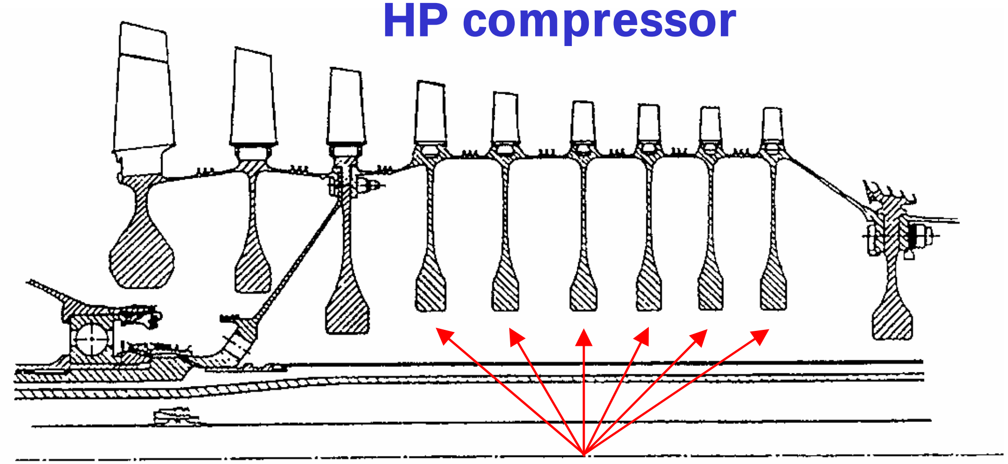
Discs may have different shapes depending on their location into the engine



LP compressor



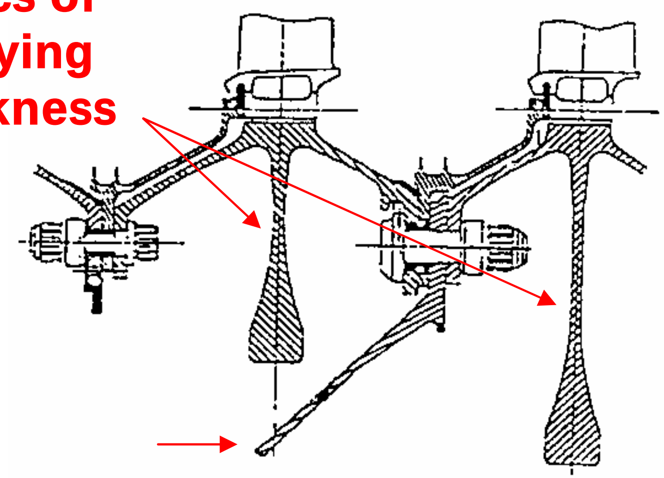
HP compressor



Hollow constant-thickness discs

HP and LP turbines

Discs of varying thickness



Driving flange

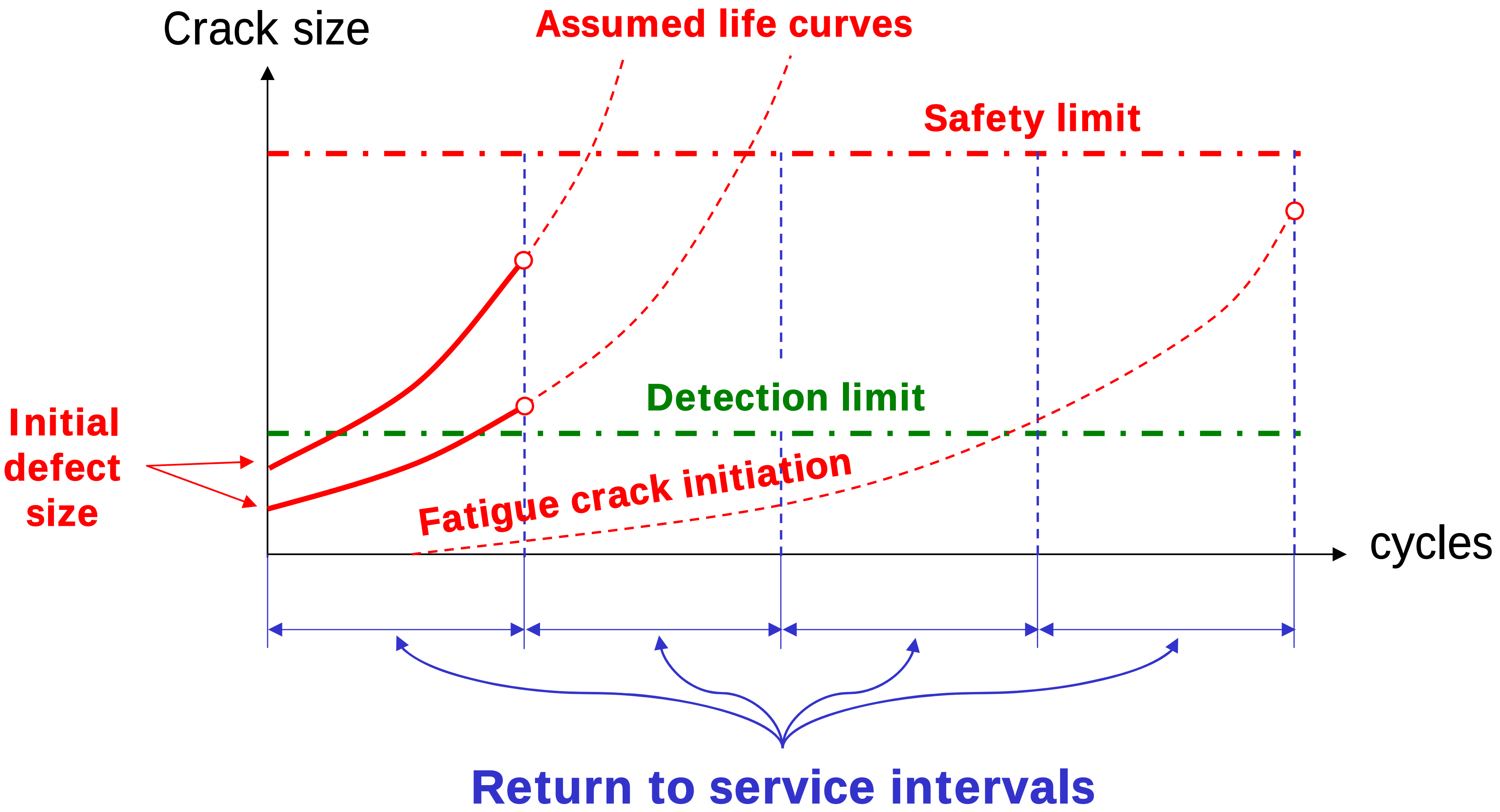
Mechanical design of discs

Sources of stresses in a rotor disc

- Centrifugal body force of disc material;
- Centrifugal load produced by the blades and their attachments to the disc;
- 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;

Mechanical design of discs

Damage tolerance philosophy



Mechanical design of turbine blades

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.

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Conclusion

In summary, the mechanical design of turbojets is challenging.

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

Then, depending on the engine component (blade, disc) 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.