601 - HELICOPTER TURBOSHAFT ENGINE: THE SPECIFICITIES TO MEET AIRFRAMER REQUIREMENTS AND CUSTOMER NEEDS

Frederic RIPOLLES, frederic.ripolles@safrangroup.com

SAFRAN Helicopter Engines
64511 Bordes (France)

Abstract

The helicopter turboshaft engine is not a simple equipment supplying the necessary propulsive power but a highly integrated mechanical system featuring many interfaces with the airframe structure and systems. Far beyond the airplane turboprop or turbofan engine, the helicopter turboshaft engine controls the main rotor speed and therefore directly affects the flight capability, safety and transient manoeuvers of the helicopter.
The first part of this paper describes the main characteristics of the turboshaft engine with magnitude orders.
We will, then, go through the specificities of the helicopter turboshaft engine.
It will be shown how they impact the turboshaft engine design and how the engine manufacturer should take them into account in the early stage of the development process.
In this high competitive business, the engine manufacturer has to innovate and develop new concepts and systems to continuously improve, operability, performance and availability and reduce manufacturing and ownership costs.

1. INTRODUCTION

The helicopter is not a mass transport. It's a fantastic specialized transportation tool assigned to a wide variety of specific missions for which its vertical take-off/landing and hovering capability is necessary.
As for the airplane turboprop engine, the helicopter turboshaft engine has to comply with aircraft manufacturer requirements and customer needs, in terms of performance, safety, reliability, cost, maintenance. However, it has to be designed to cope with the helicopter specific frame and missions.
The helicopter turboshaft engine is not a simple equipment supplying the necessary propulsive power but a highly integrated mechanical system featuring many interfaces with the airframe structure and systems. Far beyond the airplane turboprop or turbofan engine, the helicopter turboshaft engine controls the main rotor speed and therefore directly affects the flight capability, safety and transient manoeuvers of the helicopter. The helicopter operating characteristics and specific missions impact the turboshaft engine design and the engine manufacturer has to take them into account in the early stage of the development process.
In this high competitive business, the engine manufacturer has to innovate and develop new concepts and systems to continuously improve, operability, performance and availability and to reduce manufacturing and ownership costs.

2. NOTATIONS

Safran HE: Safran Helicopter Engines
ISA: International Standard Atmosphere
HP: High Pressure
N1: Gas Generator rotational speed
N2: Power Turbine rotational speed
OEI: One Engine Inoperative
SFC: Specific Fuel Consumption
FOD: Foreign Object Damage
CFD: Computer Flow Dynamics

3. TURBOSHAFT ENGINE MAIN CHARACTERISTICS

3.1. General principle

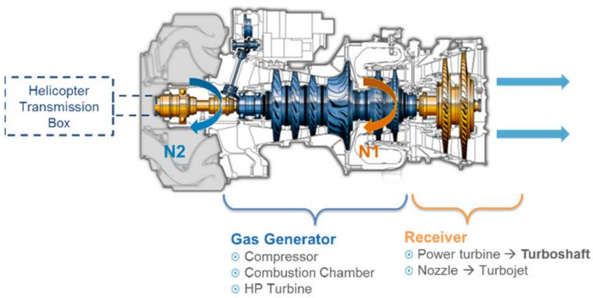


Figure 1: Turboshaft engine general principle

All turbomachinery engines are based on the Brayton Cycle and have almost the same main architecture with a Gas generator and a Receiver.

The gas generator consists of:

- a compressor to generate air mass flow and pressure
- a combustion chamber to induce a high energy level into the fluid
- a high pressure turbine to drive the compressor

The Receiver consists of:

- a power turbine to produce mechanical energy in the case of Turboshaft Engine
- a nozzle to increase kinetic energy in the case of Turbojet Engine

3.2. Magnitude orders: ARRIUS engine

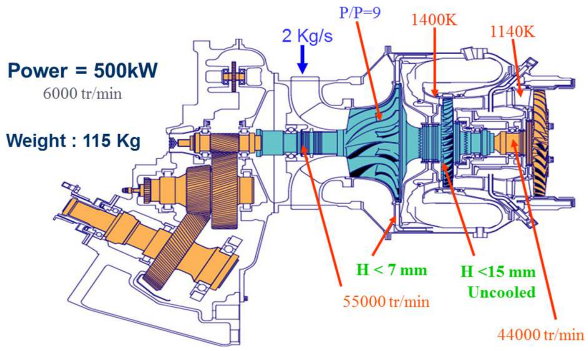


Figure 2: ARRIUS engine

The ARRIUS engine is the smallest turboshaft engine in the whole SAFRAN Helicopter Engines family. Its design was driven by willingness of simplification with minimum number of high performance components. The ARRIUS provides around 500 kW at Sea Level, ISA Take Off and its weight is 115 kg including the reduction gearbox.

It's like a F1 car racing engine, rotating three times faster and able to run 200 grand prix or 300 000 km before overall.

4. HELICOPTER TURBOSHAFT ENGINE SPECIFICITIES

Although all aircraft turboshaft, turboprop and turbofan engines share the same operating principle, the helicopter turboshaft engine shows a number of specificities to comply with the helicopter operating characteristics and specific missions.

4.1. A wide mission spectrum

Figure 3: Helicopter main mission distribution

Compared to civil airplane, the helicopter mission spectrum is much wider. It goes from classic transport cruising most of the time (Off shore, VIP corporate) to utility applications or military fight.

The engine mechanical and thermal loads are significantly different and the cycle consumption can vary from 0.3 cycles/h (transport, off shore…) to 5 cycles/h (tactical flight, search and rescue, aerial work…).

4.2. Component design constraints due to small size

The helicopter are limited in size due to main rotor diameter and therefore the turboshaft engines that power them are much smaller than the airplane turbofans. Moreover, to be installed in the helicopter cell, the turboshaft must be extremely compact with optimum power/weight ratio with as simple as possible architecture to optimize robustness and cost.

The Safran HE turboshaft family powers light single and twins helicopters to heavy helicopters. They sizes are significantly small compared to turbofan engines using the same thermodynamic principle and cycle.

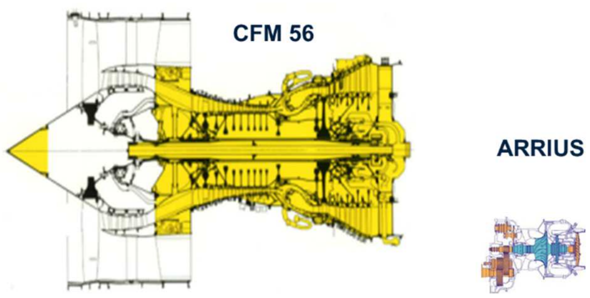


Figure 4: Same scale comparison between Safran AE CFM 56 and Safran HE ARRIUS

At the first glance, one could tell: “small engine, small difficulties”. Nothing could be further from the truth!

The small size of the helicopter engine brings lots of thermodynamic, mechanical and thermal constraints.

4.2.1 Limited OPR thermodynamic cycle

To get high engine thermal efficiency, the cycle pressure ratio (OPR) must be as high as possible. For single stage or limited stage number compressors, high pressure ratio means narrow exit compressor vanes (impeller exit blade and diffuser vane heights) and small HP turbine blades. Too small parts are difficult to produce with satisfactory geometrical tolerances.

For example, the ARRIUS2 engine with single compressor stage and a pressure ratio of 9, has less than 7 mm diffuser vanes and less than 15 mm HP turbine blades.

To optimize the engine efficiency and size, Safran HE adapts the compressor architecture to the Power Class.

For a given radial size:

- An axial compressor can provide 6 times more air mass flow than a centrifugal compressor
- A centrifugal compressor can provide 6 times more pressure ratio than an axial compressor

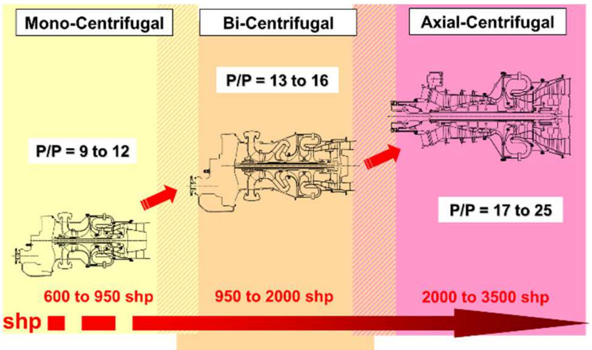


Figure 5: Compressor architecture choice

4.2.2 High mechanical loads

For turbomachinery, high performance level lies in advanced aerodynamics and therefore high Mach numbers in the gas path.

Compared to larger engines like the Safran AE turbofan CFM-56, an ARRIUS turboshaft engine must maintain the same level of Mach number in its gas path. To achieve this, its compressor and turbine blade linear speeds must be maintained as well. With much smaller diameter, the rotational speed of ARRIUS compressor and turbines must be significantly greater. Therefore the ARRIUS Gas Generator runs 3 to 4 times faster than the CFM-56 HP Spool (55 000 rpm vs 15 000 rpm).

The centrifugal force applied to rotating parts is:

$$Fcent = m\omega^2 R = \frac{mv^2}{R} \quad (1)$$

The stress applied to blade roots, bearings and disks will not be smaller on ARRIUS engine as the mass is compensated by rotational speed.

Moreover, due to reduced size, technological effect like lack of space, machining and casting limits, axial reduced dimensions make the situation more severe.

4.2.3 Turbine blade high temperature

The extremely small size of HP blades (below 15 mm on most Safran HE engines) combined with the need for simplicity and limited cost, do not allow turbine blade cooling:

- Casting and manufacturing of cooling air canals in the blade not achievable
- Unacceptable degradation of turbine efficiency due to secondary air system impact on flow quality

The HP turbine blades are subject to creep which affect the mechanical properties. At Emergency rating temperature level (around 1600K), a turbine entry temperature increase of 10K reduces by half the lifetime of an uncooled HP turbine blade.

4.2.4 Tip clearance control between small size rotor and stator

To achieve high component efficiencies, it is necessary to minimize the tip clearances between rotors and stators. On the other hand, theses clearances must be big enough to avoid rubs at high ratings or during specific manoeuvers. Typical running clearance is 0.2 to 0.4mm.

The isentropic efficiency of a turbine stage is function of the relative tip clearance which is the ratio between the gap and the blade height. A variation of 1% of relative tip clearance costs roughly 1pt of turbine isentropic efficiency (for example: 0.85 → 0.84). And 1pt of HP turbine isentropic efficiency reduction costs up to 2.5% of engine output power.

It is therefore, crucial for engine performance to control the turbine running tip clearance to a minimum value. This is even truer in the case of small turboshaft engines and the running clearance impact is a first order effect.

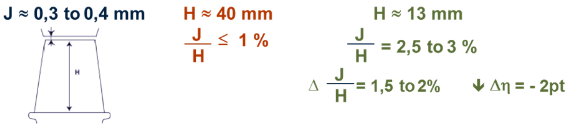


Figure 6: Blade height effect on relative tip clearance and on turbine efficiency

4.2.5 Sensibility to altitude effects

The performance of any turboshaft or turbofan engine is highly dependent on the ambient conditions: temperature and pressure.

Power or Thrust decreases when:

- Ambient pressure decreases (proportionally)
- Ambient temperature increases (approximately -1 % per °C)

However, it is necessary to take an important secondary effect into account: the Reynolds effect.

Reynolds number expression:

$$Re = \frac{Density * Velocity * Linear\ dimension}{Viscosity} \quad (2)$$

When the P0 decreases, the density/viscosity ratio decreases and the Re drops below 10^5 and the air is less efficiently deflected by the vanes, and turbulence begins to occur, resulting in losses of efficiency and power.

Due to the presence of the linear dimension term, this phenomenon begins to occur at lower altitudes for small engines compared to large turbofan.

4.3. A binding rating structure

4.3.1 Helicopter engine rating structure

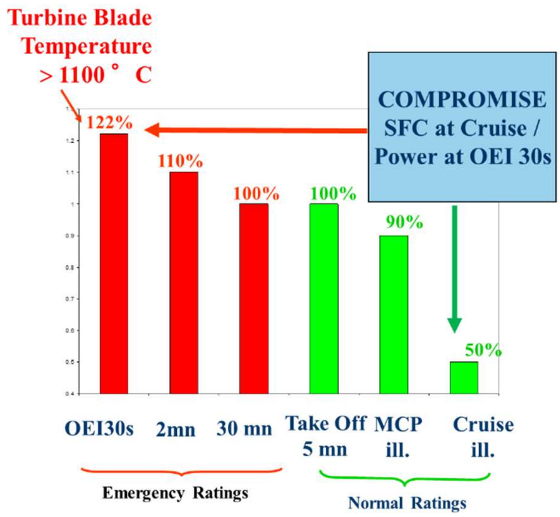
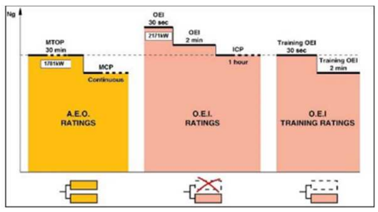


Figure 7: The rating compromise: a brainteaser

Engine Ratings are the "maximum" power levels appropriate to the various flight phases where the power demand is critical. They are associated with a period of time. The power values of the Engine Ratings correspond to a provisional requirement of the helicopter, and are often determined after a dialogue between the Helicopter Manufacturer and the Engine Manufacturer. The design of the engine and the Ratings must take both the capability of the engine to complete the 150 hours of endurance and the service life requirements into account.

For twin or multiple engine helicopter, two types of ratings exist:

- AEO ratings (All engines Operatives): normal ratings
- OEI ratings (One Engine Inoperative): emergency rating in case of one engine failure



RATINGS	Nb of valid engines	Max. period
Maximum Continuous	2 engines (AEO)	unlimited
Take-Off / Maximum 30min	2 engines (AEO)	5min / 30min
Intermediate Contingency (Continuous OEI)	1 engine (OEI)	unlimited
Maximum Contingency (OEI 2min)	1 engine (OEI)	2min
Super Contingency (OEI 30s)	1 engine (OEI)	30s

Figure 8: Engine ratings with OEI 30s structure

The Super Contingency and Max Contingency ratings are significantly above the Take Off rating in terms of output power. Engine components must be sized in order to provide the necessary OEI power and to sustain the extremely high temperatures in the engine hot sections. The compressor air mass flow must be high enough to avoid unacceptable HP Turbine inlet temperature at high ratings. In other words, the engine thermodynamic cycle and components sizing is matched for high ratings: Take Off and OEI ratings. OEI ratings being, at least, remote. For twin-engine helicopter applications, the engine is oversized.

4.3.2 Specific Fuel Consumption

However, the helicopter will fly most of the time in cruise mode at low power compared to Take Off rating. At cruise speed around 120 knots, the power demand on both engines is about 50% to 60% of the maximum Take Off power. At these low power level, turbine temperature is not critical anymore but the fuel consumption is a key parameter for economic reasons and for the helicopter range. For cruise, the key parameter is the Specific fuel Consumption (SFC).

Due to the thermodynamic cycle characteristics (pressure ratio, combustion exit temperature) and components efficiency evolution, the SFC is optimum around Take Off power but significantly worse at part load (Cruise).

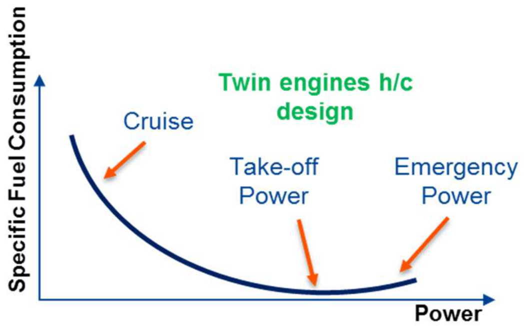


Figure 9: SFC evolution with power level

4.3.3 Higher turbine temperatures

The engine “oversizing” for OEI ratings further degrades the part load SFC and the engine manufactured must limit it as much as possible by rising as much as possible the cycle turbine inlet temperatures. To achieve this goal, Safran HE has set up a dedicated Advanced HP Turbine Research Center working on:

- Turbine material: new generation of super alloy, single crystal blades with improved creep life for high durability
- Cooling: integrated optimized design of cooling circuit, aerothermal–mechanical casting and machining.
- Thermal barrier coating
- Inspection

4.3.4 Variable geometry compressors

Another way of improving part load SFC while maintaining OEI power is to optimize compressor characteristics (flow and efficiency) to better match the power demand and improve surge margin. To achieve this goal, one or several stages of variable guide vanes and stator can be implemented to optimize SFC at low power. An actuator piloted by engine FADEC control laws, modifies the angle of the stator vanes as function of compressor speed. The cruise SFC can be reduced up to 7%, but there is penalty on weight, cost and increased complexity.

4.4. Severe installation constraints

The helicopter turboshaft powerplant is mechanically and aerodynamically highly integrated within the aircraft. Once installed, the turboshaft engine performance, durability and operability are strongly affected the helicopter operation.

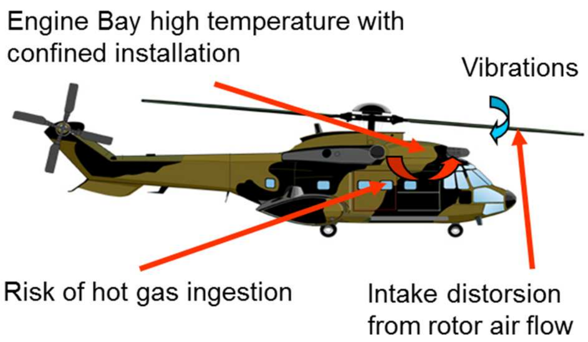


Figure 10: Installation constraints

4.4.1 Engine Bay confinement

To cope with mechanic and aerodynamic constraints, the engines are located inside the helicopter frame in a very confined space called the Engine Bay.

Figure 11: Examples of engine installation

On the over hand, the engine power levels induce very high thermal rejections outwards impacting engine equipment's (pumps, valves, sensors, actuators…) and associated harnesses: certification issue but also reliability issue. Arrhenius law for electronic component durability (D) function of environmental temperature (T):

$$D = D_{ref}.e^{(T_a/T)} \quad (3)$$

When the equipment environmental temperature increases by 10°C, its lifetime is divided by 3.

The engine manufacturer has to anticipate and insure satisfactory equipment aerothermal integration during engine development as the installation on the helicopter and first flight occurs late in the certification process. The aerothermal integration of engine equipment's process involve three work steps:

1. Qualification of engine equipment's at suitable temperature level according to standard EUROCAE ED-14G / RTCA DO-160G
2. Judicious equipment implantation on the engine

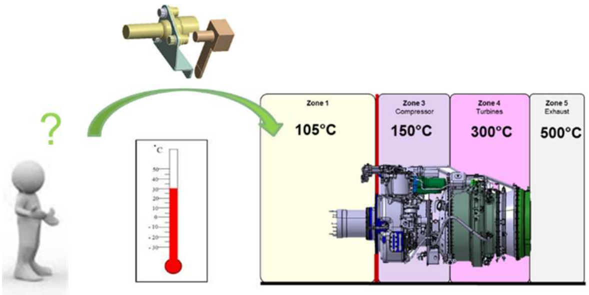


Figure 12: Equipment positioning

The engine is the heat source generating conduction and radiation transfers. The engine manufacturer will locate temperature sensitive equipment's at the front of the engine (coolest part) on the reduction or accessory gearbox for example. He will also optimize the bracket between the equipment and the engine flange. When necessary, he will add thermal protections.

3. Successful installation on the helicopter with adequate venting system sizing :

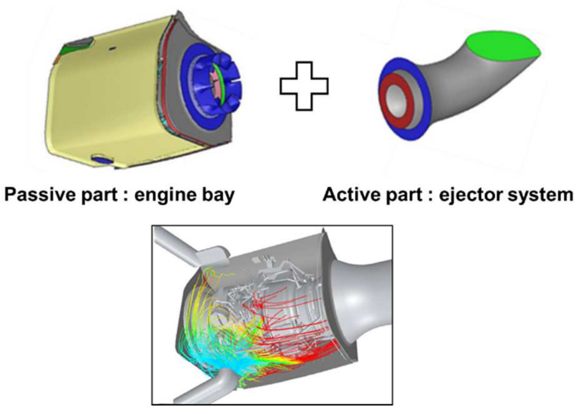


Figure 13: Examples of engine installation

The engine bay is the passive part, generating pressure loss. The bay has one or several openings (static or dynamic).

The venting air flow can be generated in the active part using the ventury effect from the exhaust system incorporating a primary nozzle and an ejector. An extraction fan can also be used.
In both cases, it is essential to control the engine bay leaks in order to "pilot" the cooling air pathway around the engine and its thermally sensitive equipment's.
But, when the engine is shut down, there is no venting anymore!
The hot air concentrates in the upper part of the bay, increasing the soak back for equipment's located in this area.

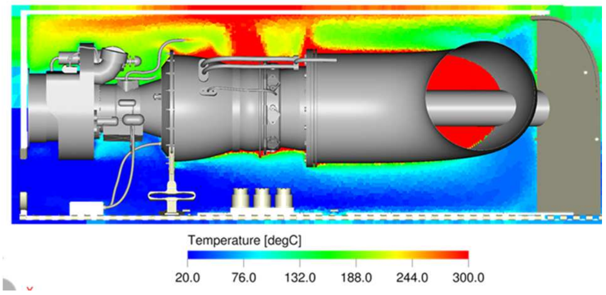


Figure 14: Bay temperature field after engine shut down

4.4.2 Vibrations, hot gas re-ingestion

Helicopter generates high level of vibrations and lot of stress on the engine itself but also on engine mounting, pipes and equipment's.

Another issue linked to engine installation on the helicopter is the risk of hot gas ingestion from the exhaust pipe to the compressor inlet. This can happen at low helicopter speed or in hover with rear wind. The aggravating factors are, low exhaust gas speed in turboshaft application, the reduced distance between exhaust and inlet and the main rotor flow effect. It can also occurs during forest fire overflight or during rocket or missile firing.

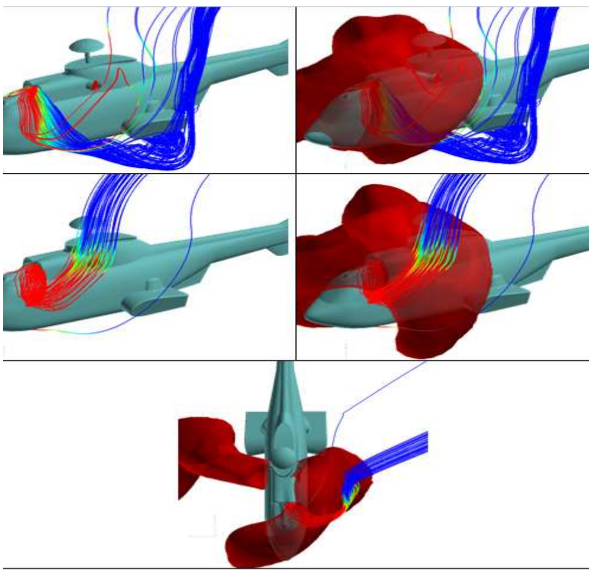


Figure 15: Air flow trajectories colored with temperature with rear wind

Sudden hot gas ingestion can induce compressor surge as the engine control is not fast enough to reduce the fuel flow.

The engine manufacturer specifies the maximum temperature speed change and amplitude in the engine installation manual and works with the helicopter manufacturer to overcome this phenomenon using specific control laws in anticipation.

4.4.3 Engine performance installation loss

Turboshaft engine performance is established by the engine manufacturer to comply with power and fuel flow consumption specification at different ratings in the flight envelope. This performance is called “non-installed”. It corresponds to an engine running on an ideal test bench with no intake and exhaust losses.

Once installed on the helicopter, when it runs, the engine faces external effects called “installation effects”. These effects significantly affect the engine performance and most of the time they correspond to losses that reduce the engine performance level. These losses are the result of a variety of mechanisms at the interfaces between aircraft and engine

In addition to this basic losses, there are additional sources of loss associated with the fitment of specific items or aircraft role equipment, such as intake sand filters, additional electrical generation, air bleed extraction or infra-red suppressors.

It is important to understand the impact of these losses on the overall performance of the helicopter so that basic aircraft mission performance is not unnecessarily sacrificed.

The configuration of the powerplant, its location on the helicopter, the quality of its design and integration into the vehicle has a huge influence about the engine performance.

A bad engine integration into the helicopter can lead to a level of power installation losses as high as 15 %. That means, on the helicopter, the engine will deliver 15% less power compared with the engine on the test bench.

The various installation losses:

- Pressure losses in the air intake: *1% of inlet pressure loss costs 2% of Power*.
- Pressure distortion in the air intake*: impact on surge margin, operability and performance*
- Increase in temperature in the air intake: *1°C of temperature rise costs 0.7% of Power*

- Temperature distortion in the air intake: TC120: *impact on surge margin, operability and performance*
- Swirl in the air intake: *dissymmetry between left and right engines*
- Pressure losses at the exhaust pipe outlet: *1% of exhaust pressure loss costs 1% of Power*.
- Back-pressure at the exhaust pipe outlet: impact on performance and reduces the bay venting efficiency

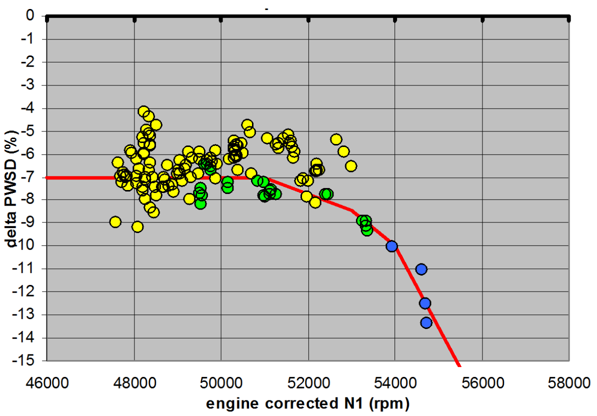


Figure 16: Example of Power losses in level flight with static side intake.

The helicopter air intake as a major impact on engine performance. Air intake design is always a compromise between contradictory requirements: helicopter cell drag, distortion at the entry of the engine, pressure losses, FOD protection, ice and snow protection, sand filtration, noise…

Engine manufacturer must be able to propose solutions to optimize the design of the helicopter air intake, to minimize installed engine performances losses.

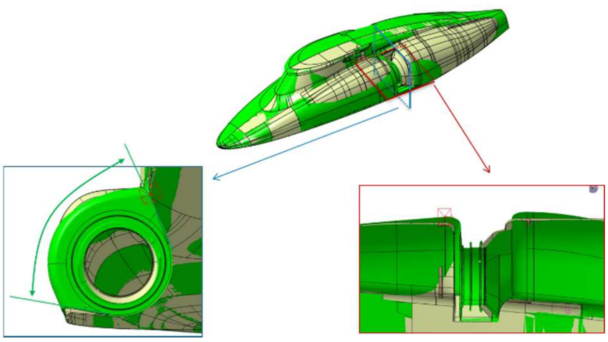


Figure 17: Helicopter inlet views

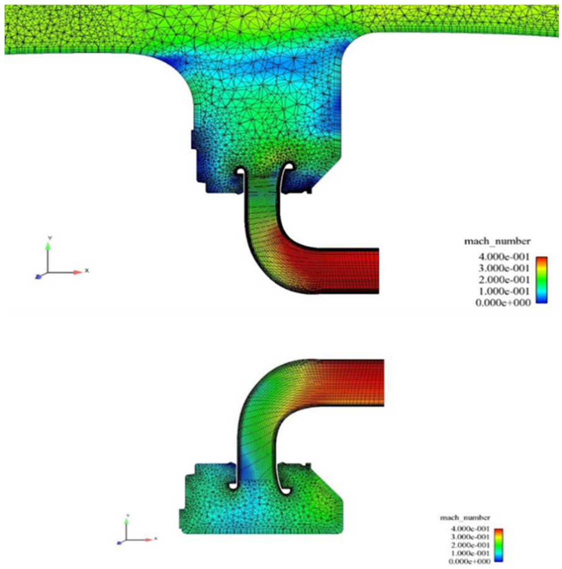


Figure 18: Mach number distribution in a lateral static helicopter inlet.

4.5. A highly integrated control system

4.5.1 Engine control system: a strategic component

From the very first Safran HE turboshafts, control system skills are considered as strategic as bare engine skills.

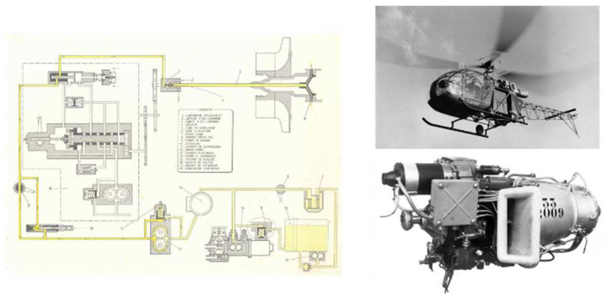


Figure 19: ARTOUSTE Fuel Control Unit (1951)

The engine control system is a strategic component for helicopter turboshaft application:

- Enhances the engine performance and its operability
- **Directly acts on the helicopter handling qualities and on the performance of NR speed control**

- Contributes to the pilot workload reduction and to the aircraft safety
- Insures helicopter mechanic chain torsional stability
- Embeds monitoring and diagnosis functions
- Counts for 15 to 20% of engine production cost and has become a major technical and economic issue

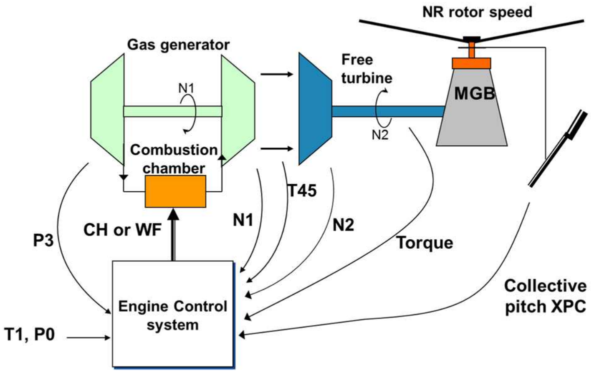


Figure 20: Engine control system general presentation and interfaces with helicopter

4.5.2 Torsional stability

The helicopter transmission is a complex mechanical chain including main rotor blades and mast, main gearbox, rear rotor, transmission shafts and engines. This kinematic chain cannot be considered as a simple inertial load.

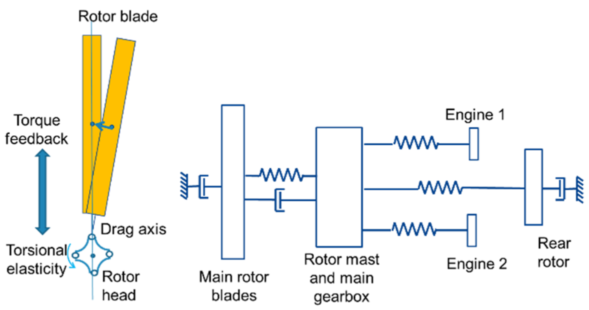


Figure 21: Main rotor drag mode and helicopter transmission kinematic chain

The control system and the engine can excite the helicopter modes. To avoid this phenomenon, the engine manufacturer generally adds a filter on the N2 measurement in order to modify the transfer function « control / engine / helicopter » and to ensure global stability. The N2 filter's goal is to damp the helicopter's modes below 6dB, but always with correct phase and gain margins (ARP704 standard). The filter is generally active upon 2Hz, trying not to modify the low frequencies characteristics (time response).

The filter efficiency and the torsional stability is demonstrated during flight tests where the pilot carries out collective pitch excitations from 1Hz to 5.5Hz.

4.6. High level operability and transient capability

The helicopter frequently operates close to the ground with marked relief. It must be capable of great agility and most of its flights includes many manoeuvers with power demand changes. The engine operability must be at the highest standard to cope with all missions requirements. The power variations demand are frequently within 1s.

But the key point is that the helicopter turboshaft engine controls the main rotor speed and therefore directly affects the flight capability, safety and transient manoeuvs of the helicopter.

The main rotor speed guarantees the helicopter sustentation like the wing of an airplane with forward speed.

However, the helicopter rotors and transmission system kinetic energy is 5 to 10 times smaller than the kinetic energy of an airplane.

When the pilot makes a power demand on the collective pitch, the turboshaft response cannot take long time to come: it must be nearly instantaneous.

Typical Safran HE engine response times:

- Accelerations:
  - **2.5s** from zero to Max Take Off power at Sea Level
  - **0.8s** from Max Continuous power to Emergency OIE 30s power at Sea Level
- Decelerations:
  - **1.5s** from Max Take Off power to zero power at Sea Level

This transient performance need is a great challenge for the engine manufacturer as two dangerous phenomena can occur during these phases:

- **Compressor surge** during accelerations
- **Combustion Chamber** flame out during deceleration

Safran HE turboshaft engine are at the top of the state of the art in terms of operability and transient performance. The long experience of turboshaft engine development, centrifugal compressor mastery and substantial investments in research and development maintain Safran HE one step ahead of the competitor in this field:

- Innovative compressor aerodynamic design
- Innovative combustion chamber design
- Robust validation method
- Adapted control and limitation laws

4.7. Very severe environment conditions

Helicopters are designed to take-off, land and operate on every types of terrain and environment which, in a large majority of cases, differ from still and clean sky…

Figure 22: Helicopter severe operational conditions

The deterioration due to particles in the atmosphere is highly dependent on operating and maintenance conditions.

When focusing on sand and dust, the engine degradation depends on particles size and chemical composition. Typical impacts are:

- Erosion on rotating and static parts of air path
- Unbalance by accumulation
- Perturbation of secondary air system (cooling)
- Melted material deposit on hot sections

These impacts are known and are taken into account by engine manufacturers during the design phase

Tests are performed to check potential engines vulnerabilities and determine maintenance criteria.

4.7.1 Erosion

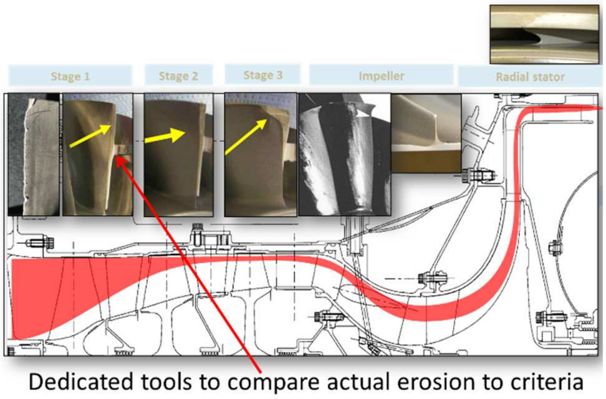


Figure 23: Typical erosion on a compressor

For helicopter missions in sand or dust environment, and there are lots of them, compressor parts erosion will occurs rapidly and will significantly reduce engine performance and operability. Facing sand ingestion like operating just above a sandy area (beach or desert), the engine lifetime can be reduced to few hundreds of hours. The use of sand filter will significantly increase the lifetime but there is price to pay with large engine performance loss (5 to 10%). For recent military operations, the battle zone is often in sandy deserts like Mali or Afghanistan and hot and high condition with extra helicopter weight due to weapons and shielding. In that case, the use of sand filter can have an unacceptable impact on the mission and in that case, is not even fitted.

Mitigation and future orientations:

- Maintenance: maintenance periodicity can be adapted depending of in service experience (In the maintenance documentation a conservative approach is always adopted)
- Anti-sand filters: with an air filtration capacity around 95%, the engine life is multiplied by 20 with regards to erosion. A further filtration capacity increase of 1% will lead to a further increase of 20% of engine life. However, sand filters generate intake pressure loss and reduce engine performance. Typical power loss is between 5 to 10% depending on filter technology, flight condition and clogging level.

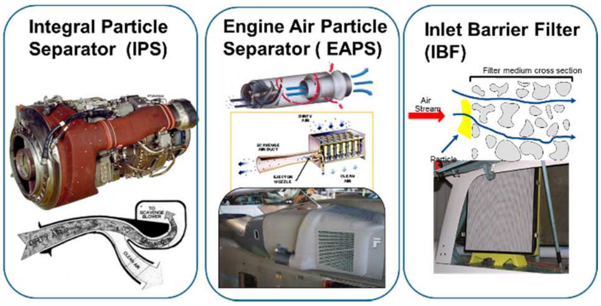


Figure 24: main types of sand filtration

- Materials: the erosion is proportional to material density, for example steel is better than titanium but heavier. Protection coating materials for compressor blades and vanes are under investigation.

- Compressor blade and vane aerodynamic profile design: the component are designed to be much more erosion and FOD resistant :
    - ➢ Sufficient thickness
    - ➢ Moderate blade angle evolution at leading edge

  The erosion computing chain is based on Fluent and Elsa CFD codes to calculate the particle trajectory coupled with rebound correlations and metal pullout for titanium/quartz couple.

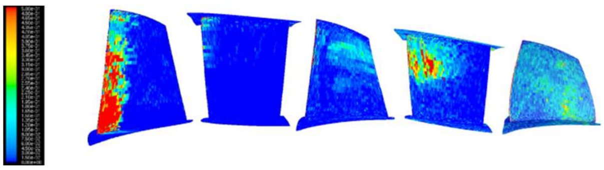


Figure 25: Axial compressor erosion modelling

4.7.2 Internal Air System pollution

Sand and dust not only erode the compressor parts in the engine gas path, but can also penetrate inside the engine throughout the internal secondary air system. This secondary air system function is to cool the turbines hot parts, to pressurize the bearing chambers to avoid oil leakage and to balance the axial loads. The pollution of this complex air system network made of holes, labyrinths, pipes and vortexes could affect the engine integrity:

- Partial blockage of cooling holes leading to over temperature
- Accumulation of sand or laterite in rotating shafts creating unbalance and vibrations

To avoid or limit these phenomena, air system engineers need to innovate and develop new features. Secondary air bleed picking through rotating tubes is one of them.

The classic way of picking pressurized air from the compressor gas path to dispatch it to hot turbine parts throughout the engine shaft is to machine holes in the compressor hub. In this case the air flow from the hole down to the shaft is a free vortex and the air speed follows the following free vortex relationship:

(4) $$\dot{m}\,\frac{d(RV\theta)}{dR} = 0$$

Where: $\dot{m}$, R and $V\theta$ represent respectively the air mass flow, the radius position and the tangential velocity.

As a result, the tangential speed is maximum close to the center at low radius position and therefore the air static pressure is minimum close to the shaft. This reduce the feeding pressure for the hot part section cooling and the delta pressure to generate air flow up to the turbines could not be enough.

The second problem is the capitation of particles (sand or dust) inside the engine.

A way to overcome these 2 problematics at the same time, is to use rotating tubes under the compressor hub.

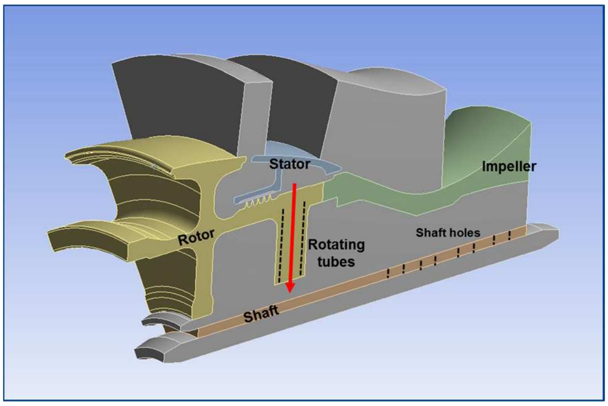


Figure 26: Rotating tubes in secondary air system

This time the air flow from the hole down to the shaft is a solid rotation and the tangential air speed is a linear function of the radius position

(5) $$V\theta = R\omega$$

The tangential speed is minimum at the center and the static pressure is greater in this case for a better air feeding to the rear of the engine.

Moreover, with the solid rotation, the sand or dust particles are centrifuged and ejected back to the main gas path avoiding secondary air system pollution.

5. NEW CHALLENGES IN THE PROPULSIVE POWER PACK FOR VTOL AIRCRAFT

Disruptive Technologies are changing the state of the art of the design, manufacturing process and services:

- Additive manufacturing
- Digital era and services
- Smart industry
- **Propulsive System transformation**

Disruptive Technologies are changing the state of the art of the design and the manufacturing process. It allows the assessment of new technical and industrial advanced optimization and engineering concepts which have not yet been explored. Moreover, typical architectures of rotorcraft may be strongly modified in a short time scale by using power hybridization technics and innovative distributed propulsion vehicle. These technological shifts will transform the future of our usage of flying objects.

5.1. Hybridization

Electrical machine and power electronics improvements since 15 years and next decade predictions open up new prospects.

The typical small and medium power range Turboshaft engine power density is 5 to 7 kW/kg.

Today's power density for Electrical Pack (Electrical Machine + Power Electronic) is 2kW/kg and should rise up to 6kW/kg in 2035.

However, the energy storage still remains problematic for "Full Electric" applications. The fuel energetic density prediction for 2030 is still 10 times greater than battery pack.

Battery Pack energetic density:

- 2016 → 150 Wh/kg
- 2030 → 400 Wh/kg (optimistic scenario)
- Kerosene → 4000 Wh/kg engine thermal efficiency included!

For flights duration above 30 min and beyond 50 kW power, a thermal engine is needed.

5.2. Propulsion system new modes

Two functions allow for NEW MODES of the propulsive system and the gas turbine. These modes can be coupled.

FUNCTION	MODE		Category
	Propulsive System	Power Management	
ELECTRIC ⇨ MECHANICAL Producing mechanical power	ECO Mode	Standby Reactivation	Fuel Consumption Range
	BOOST Mode	Additional Power : - Transient Assistance - OEI Assistance - Autorotation Assistance	Safety Performance
MECHANICAL ⇨ ELECTRIC Producing/Storing electrical power	Power Distribution	Turbo-generation	Multi-Rotors Handling Safety

Figure 27: Propulsion system new modes

Thermal-Electrical Hybridization can be used to optimize conventional Helicopters and to pave the way to new type of aircrafts (distributed power to multiple rotors).

5.2.1 First generation of hybrid systems to optimize current architecture helicopters

The first generation of Safran HE system consists of a gas turbine combined with backup electric motor to provide "eco mode", fast restart and OEI assistance for:

- Efficient cruise mode
- Emergency electrical assistance
- Better power-to-weight ratio

Engines are used at partial power during cruise on twin engine applications and the Specific Fuel Consumption (SFC) is not optimum.
The Cruise Eco Mode principle for twin or multiple engine helicopter is to put one engine in standby mode and to run the other one at higher power close to the optimum SFC. In case of failure of the active engine, the standby engine must be started and accelerated to emergency rating within 10s. The electric motor is used for fast reactivation. It is also used to supply additional power to the valid engine during OEI phases.

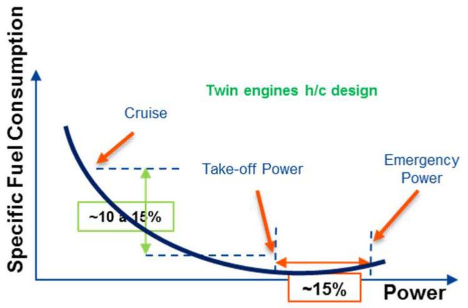


Figure 28: First generation hybrid system gains

5.2.2 Second generation of hybrid systems to distribute propulsion for new architecture aircrafts

Thermo-electric concepts give access to new architectures for new aircrafts.

Several electric motors fed by a gas turbine distributing power to same number of rotors for new missions and to improve safety and handling.

Figure 29: New aircraft architectures

The potential increasing number of power sources and rotors implies advanced POWER MANAGEMENT. The Propulsive System is INDISSOCIABLE from the VTOL configuration and its missions.

The full chain of power supply and power management is in the core business of Safran.

5.3. What will be the future?

Conventional helicopters will continue to fly for many decade thanks to their superiority on many missions.

In these conventional architectures, the use of electric will remain limited to complementary power supply and noise reduction

BUT, the electric and control systems improvements are paving the way to new architectures of VTOL capturing a segment of the market and generating new missions

Hybridization finds its way when associated to technologies exploiting the benefits of electric systems but not as an alternative of conventional solutions.

Designing « WITH, but NOT AS A SUBSTITUTE of existing propulsive system »