

MULTIDISCIPLINARY ASSESSMENT OF A YEAR 2035 TURBOFAN PROPULSION SYSTEM

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Abstract

A conceptual design of a year 2035 turbofan is developed and integrated onto a year 2035 aircraft model. The mission performance is evaluated for CO₂, noise and NO_x and is compared with a notional XWB/A350-model. An OGV heat exchanger is then studied rejecting heat from an electric generator, and its top-level performance is discussed. The fan, the booster and the low-pressure turbine of the propulsion system are subject to more detailed aero design based on using commercial design tools and CFD-optimization. Booster aerodynamic modelling output is introduced back into the performance model to study the integrated performance of the component. The top-level performance aircraft improvements are compared to top-level-trends and ICAO estimates of technology progress potential, attempting to evaluate whether there is some additional margin for efficiency improvement beyond the ICAO technology predictions for the same time frame.

Keywords: Turbofan, integrated generator, multidisciplinary engine analysis, high-speed booster

1. Introduction

Lee et al [1] report an eightfold improvement in transport efficiency, that is mass of CO₂ per revenue passenger kilometer since 1960. Although the improvement pace levels off, future important advances are still to be gained. Dray et al predicts that a 3.2% annual reduction in lifecycle CO₂ per revenue passenger is possible until to 2050 [2]. Achieving this impressive annual reduction pace, strongly depends on the availability of sustainable aviation fuels which is attributed to more than half of the improvement.

On aircraft level, not including sustainable aviation fuels, an annual average improvement of approximately 2.7% was noted for the time period 1960 to 2000 [3] and a predicted future annual reduction of 1.4% was reported in [4] for the time period 2000 to 2040. Cumpsty et al [5], estimate that goals for achievable improvements may be set to 1.28% on twin aisle aircraft and 1.22% for single aisle aircraft respectively.

In this work we study an advanced XWB concept estimated to enter service in 2035, hence the annual improvement of 1.22% should serve as a first prediction on the new aircraft's feasible improvement potential. The current work allows the top-level achievements to be quantified and compared to ICAO predicted trends. In addition, noise and NO_x predictions are developed and compared with environmental goals. The methods used for NO_x and noise prediction have been outlined more in detail in [6, 7]. The development of the propulsion system was conducted as several levels of detail in a Swedish university collaborative effort. Chalmers University of technology has worked on system level performance, integration of heat exchangers for electric component cooling, Lund University has focused on turbomachinery aerodynamic design and electric component design and KTH has concentrated on mechanical design and composite technology integration. The VIND project is a continuation of an earlier project, VINK, which concentrated on establishing a detailed design of a high-speed booster [8].

2. The year 2035 engine and aircraft model

The target for this collaborative project is to be able to develop concepts from a notional aircraft representation to whole engine modelling through component zooming as schematically illustrated in Figure 1. The work progresses along the steps of flight mission analysis, cycle definition, performance of the engine including noise/NO_x evaluations, conceptual propulsion system design and then on to the detailed 3D study of selected modules. This includes evaluating new concepts such as integration of generators and its cooling within the engine.

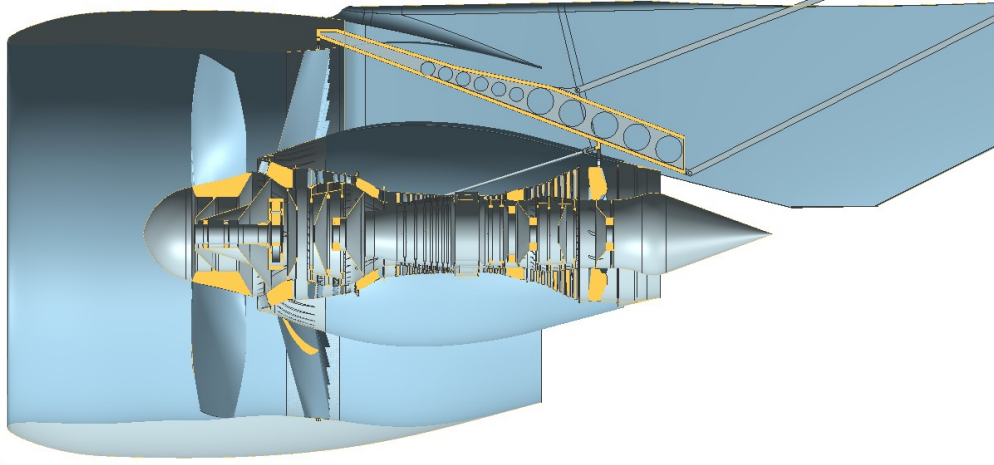


Figure 1: whole engine model used as part of VIND project

2.1 Aircraft and engine performance modelling

As a baseline aircraft the A350-XWB aircraft has been modelled in the commercial tool Pacelab APD [9]. Some key parameters can be obtained from the Airbus Aircraft Characteristics Airport Maintenance Planning report [10], key outputs are collected in Table 1 below together with the corresponding data for the 2035 aircraft.

Table 1: Basic input for the notional A350-900 reference model and for the year 2035 aircraft

	Notional A350-900 model	Y2035 derivative
Wing loading	640.5 kg/m ²	640.5 kg/m ²
Wing area	443 m ²	391.5 m ²
Cruise Mach	0.85	0.85
Engine	2 Rolls-Royce XWB-84	Y2035 engine model
Output / Flat rating	2 x 83.7 klbf / ISA+15 C	2 x 73.6 klbf / ISA +15
Max TO Weight	281 tonnes	247 tonnes
Operational empty weight	142 tonnes	129 tonnes
Max fuel	114 tonnes	90.4 tonnes
Initial cruise altitude	35 kft	35 kft
Max time to initial cruise	25 minutes	25 mins
Take-off field length	2446 m	2160 m
Landing field length	1230 m	1283 m
Fuel reserves	5% cont. fuel, 200 NM diversion, 30 min hold	5% cont. fuel, 200 NM diversion, 30 mins hold
Design mission distance	8100 NM	8100 NM
Design mission payload	30657 kg (325PAX)	30657 kg (325PAX)
Design mission block fuel	108671 kg	87800 kg

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Some basic validation of performance against the payload range capability of the existing A350 data was undertaken, see Figure 2 below.

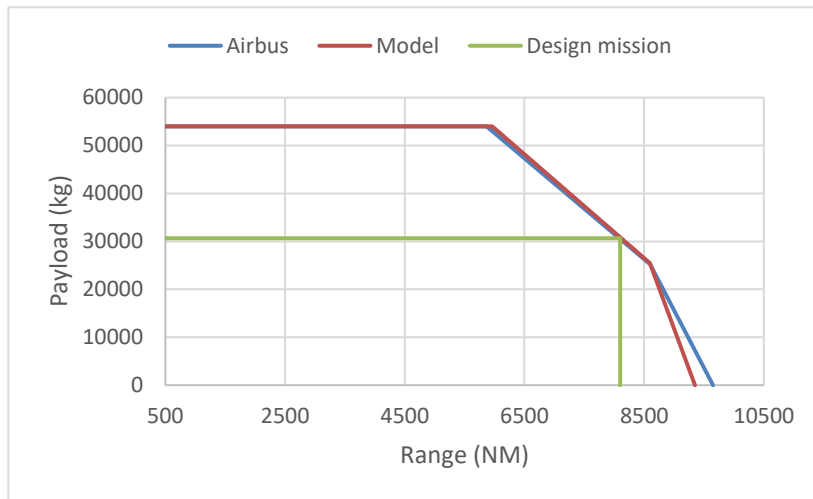


Figure 2: validation of payload range diagram for reference aircraft model compared to public data [10].

The year 2035 model is developed around the A350 notional model but with advances in a number of key technology areas. The input to the aircraft optimization assumes improvements from reductions in structural mass arising from carbon fiber reinforced polymers applied to the wing and fin, fuselage, the landing gear, and the nacelles. Reductions in interior furnishing weight and improvements from advances in Gust Maneuver Load alleviation systems as well as increased laminar flow area in the nacelles will be assumed. Further improvement in wing aspect ratio driven by advances in foldable wing technology is assumed.

2.2 Conceptual design performance and system level assessments

The basic assumptions for the year 2035 propulsion system are found in Table 2 below.

Table 2: Basic parameter assumptions for the year 2035 propulsion system

Parameter	Value	Parameter	Value
Mach	0.84	η_{HPC} (polytropic)	0.9075
DT ISA (K)	10	Cooling ratio	20%
Alt (meter)	10668	η_{HPT} (polytropic)	0.9169
π_{LPT}	1.44	η_{LPT} (polytropic)	0.9138
η_{LPT} (polytropic)	0.92	BPR	13.693
π_{IPC}	3.465	W_2 [kg/s]	625.60
η_{IPC} (polytropic)	0.905	T4	1904 K
π_{HPC}	16.594		

To estimate weight and validate the feasibility of the efficiency assumptions a conceptual engine model was developed, as illustrated in Figure 3. The conceptual tool trends efficiency as well as assumptions on materials towards a year 2050 engine design as described in [11] and engine models developed within the ULTIMATE project [12]. Technology assumptions from [12] are interpolated for year 2035 to establish the conceptual design. For the Y2035 engine a three-stage low pressure turbine was evaluated but since the blade speed was set by the AN2, this increased the aerodynamic stage loading to a too high value and instead a relatively straight hub line could be chosen for the four-stage design. This design choice also alleviates LPT noise.

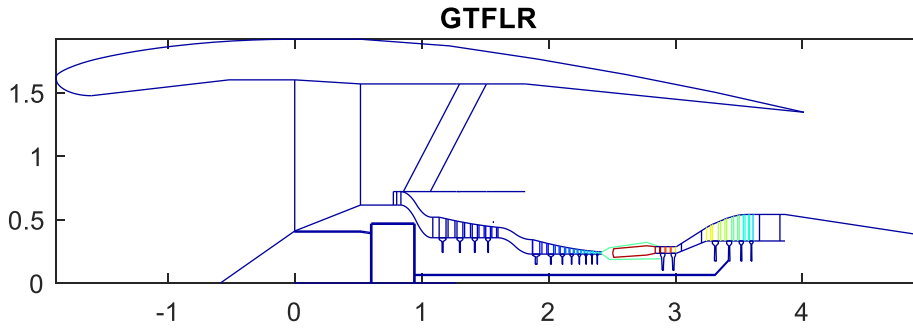


Figure 3: Schematic engine layout for Y2035 concept

Evaluating the resulting fuel burn reduction from the concept the year-on-year improvement rate is around 1.0% per annum. This almost exactly predicts the ICAO's moderate technology long term scenario [13] stating an 0.96% annual improvement rate. The comparison is not obvious since a fleet value cannot be directly compared with a particular aircraft type. We believe our top-level prediction to be somewhat conservative, partly because we may have overestimated the performance of the reference engine. The amount of public data is scarce, however while carrying out the conceptual design of the reference engine, the diameter predicted at top-of-climb came out as larger than the publicly reported data. This indicates that the specific thrust may be higher on the real engine and that the real engine performance may be somewhat lower than what we have predicted. This is to some extent compensated for by the weight estimation included in the design evaluation, a too high fan diameter would overpredict weight.

2.3 Noise and emissions

Estimating noise for future propulsion installations is challenging for a number of reasons. Uncertainties in trajectories, model input and models accumulate to pose a challenging problem. On the same time key parameters can often be weight from a multidisciplinary perspective, that is using information from several disciplines to better pin-point adequate values. Here we present the first estimates of noise for the engine and aircraft under study.

	Y2035 aircraft compared with baseline
Sideline noise EPNL	-4.3 dB
Cutback noise EPNL	-0.6 dB
Approach noise EPNL	-0.6 dB
Cumulative EPNL	-5.4 dB

The main benefit derives from the reduced specific thrust at take-off. We expect the Cutback noise to be possible to improve further by a more noise optimal trajectory. The approach noise is limited by the higher LPT noise of the engine, and it may be challenging to make substantial improvement on this point.

For a combustor technology level consistent with the current state-of-the-art, a semi-empirical correlation derived for modern Rich-burn Quick-quench Lean-burn (RQL) single annular combustor designs for high overall pressure ratio (OPR) gas turbines is selected. The correlation, as published in [14] and given in the equation shown below, was established based on the NO_x emissions measurement data from the ICAO engine emissions databank and verified within the European Union collaborative research project NEWAC [15].

$$EINO_x = (8.4 + 0.0209 * e^{0.0082 * T_3}) * \left(\frac{P_3}{P_{3,ref}} \right)^{0.4} * e^{19 * (h_{SL} - h)} * \left(\frac{\Delta T_{comb}}{\Delta T_{comb,ref}} \right)^{TF}$$

where P₃ and T₃ are the compressor outlet total pressure and total temperature in kPa and K, respectively; h is the ambient humidity in kg H₂O/kg dry air; ΔT_{comb} is the temperature increase through combustion; SL is the subscript for sea level condition and ref is the subscript for the reference condition. The exponent TF may be used as a technology factor for adapting the correlation to

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aggressive future cycles while the default value is zero. $P_{3,ref}$ and $\Delta T_{comb,ref}$ are 3000 kPa and 300 K respectively.

For the Y2035 aircraft which aims for a future application, a lean direct injection (LDI) concept can be assumed. Semi-empirical correlations found in [16] are adopted as it is conducted with high pressure experimental data, which has a marginally lower P3 and T3 levels compared to the high-pressure compressor (HPC) exit of the Y2035 engine sea level static take-off operation.

$$EINO_x = 0.104 * P_3^{0.68} * e^{\frac{T_3}{185}} * FAR^{1.32} * \Delta P_{comb}^{-0.36}$$

where P3 and T3 are the compressor outlet total pressure and total temperature in kPa and K, respectively; ΔP_{comb} is the pressure drop through combustion in percentage; FAR is the fuel air ratio. From the correlations presented above, it is obvious that, the temperature and pressure of the air entering the combustion chamber and the temperature and pressure change through combustion are the dominating factors for NO_x generation. ICAO LTO cycle standards are used together with the correlations stated above for the NO_x emissions comparison of all the aircraft. Furthermore, besides the standard LTO cycle, the cruise NO_x production, as an important parameter which should be considered for the aviation's impact on climate change, is assessed and compared.

		A350-900 public data	A350-900 XWB model	Year 2035 aircraft	
		<i>Emissions databank</i>	<i>RQL combustor</i>	<i>RQL combustor</i>	<i>LDI combustor</i>
Fuel flow kg/s	T/O	2.411	2.418	2.192	2.192
	C/O	1.980	2.004	1.797	1.797
	Approach	0.715	0.715	0.648	0.648
	Idle	0.270	0.252	0.228	0.228
EINO_x g/kg fuel	T/O	36.59	37.54	109.53 (10083)	59.23 (5452)
	C/O	28.5	29.75	80.14 (19008)	39.79 (9438)
	Approach	10.51	9.74	17.78 (2766)	5.08 (789)
	Idle	4.38	4.53	6.09 (2170)	0.69(245)
LTO total NO_x g		14800	15135	34027	15924

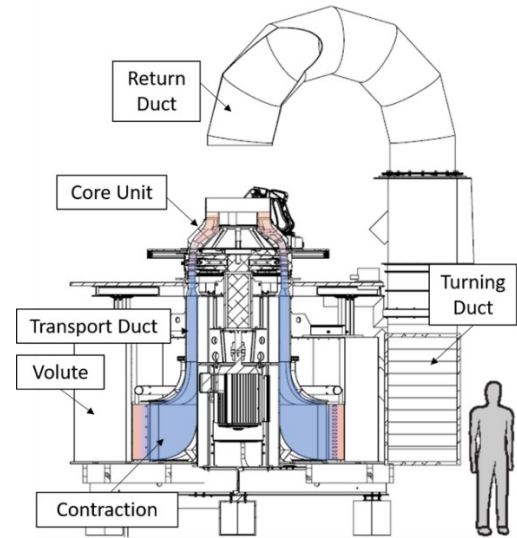
3. Engine components and zooming

As a part of the overall engine analysis, key components directly influenced by the new type of architecture are analyzed in more detail, both with respect to aerodynamics and structural performance. Major efforts have been devoted to the high-speed booster, the high-pressure compressor and the low-pressure turbine.

3.1 High speed booster

Table 3: Booster design parameters [17] and sketch of rig design in development [17]

Rotational Speed	1920 rpm	Avg. Tip radius	620mm
Mass flow	17 kg/s	Avg. Hub radius	540mm
Pressure ratio	1.07	Nr. stator Blades (IGV),(s1),(OGV)	75,124,126
Tip Speed	100 m/s	Nr. rotor Blades (r1),(r2)	61,69
Axial Velocity	70 m/s	Avg. Aspect Ratio	2.157
Rotor Re_c	6×10^5	Avg. Tip Clearance	0.75mm



Details on the booster compressor was already reported as part of the VINK project, the predecessor to the current project [8]. Note that the design data for the engine was also made publicly available [18]. The conceptual design studies performed in the VINK project was subsequently developed into a full design of a compressor test rig [17]. The basic design data are repeated here. Note that the rig data summarized in

Table 3 represent a low-speed design similar design of the studies performed in the VINK project.

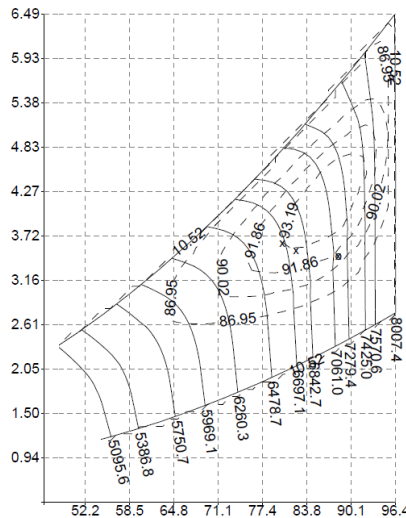


Figure 4: booster map integrated into performance modelling tool

The high-speed booster design is used to predict the compressor performance, Figure 4, in terms of a map, then integrated into the system performance model. A booster bleed model needed to be integrated to allow simulating lower thrust conditions needed for emissions and noise predictions.

3.2 HPC/HPT and LPT

The main efforts towards new turbomachinery design is herein directed towards the high-pressure compressor, the high-pressure turbine, and the low-pressure turbine. Each of the mentioned components are influenced by the geared design. The most prominent influence is for the low-pressure turbine. The higher speed level will profoundly impact the architecture — several critical design-related, sometimes fundamental features like the actual stage count. In addition, the inlet to the low-pressure turbine is by virtue of the firing level, and spool work distribution will introduce cooling for the low-pressure turbine. Cooling the first turbine stator offers little complexity, but the rotor is more difficult simply because of issues related to getting the cooling onboard the spinning blade. One way

to avoid this is to design the first stage with an unusually low reaction level to reduce the relative inlet temperature to a suitable level. This feature will carry several consequences into the design and key aspects like the turbine stage count.

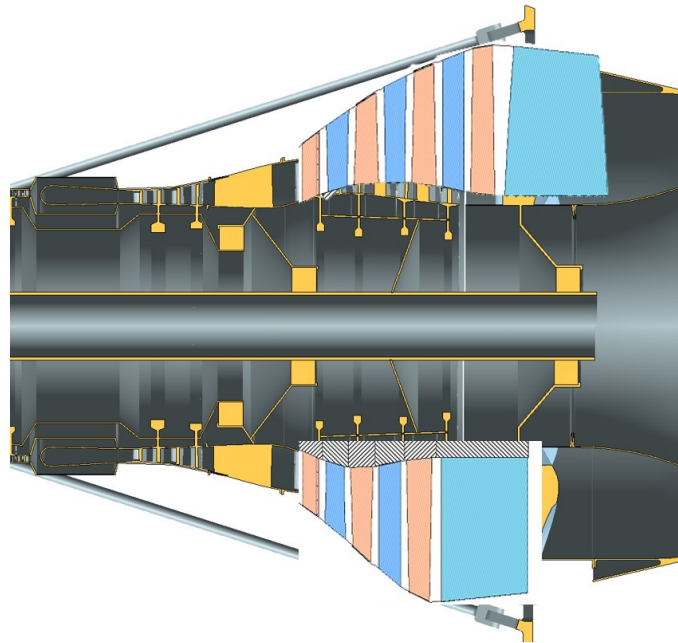


Figure 5: Four (upper) and three (lower) conceptual low pressure turbine design.

The choice of having a three- or four-stage design, see Figure 5, is indeed complex and is not readily answered. The discussion above related to cooling is one part, but important matters growth margin and turbine exit swirl will have an impact. The latter will, for example, influence the design of the outlet guide vanes.

3.3 Integrated generator performance

A generator design is studied where the integrated cooling is included in the system level model. The heat rejection requirement is defined by the generator design and the system level impact is simulated. Some comments on the feasibility of heat rejection are done.

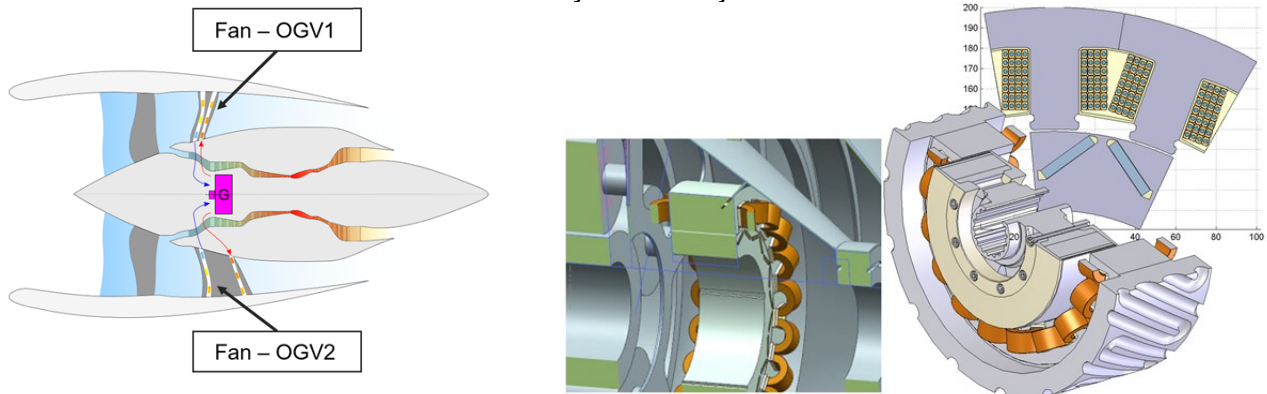


Figure 6: Fan integrated cooling system for generator design [19].

3.4 Heat rejection system integration

As shown in Figure 6 ideas how to reject heat from the generator as integrated into the OGV has been explored within the project. In Figure 7 below the heat transfer for the OGV is shown for the cruise condition.

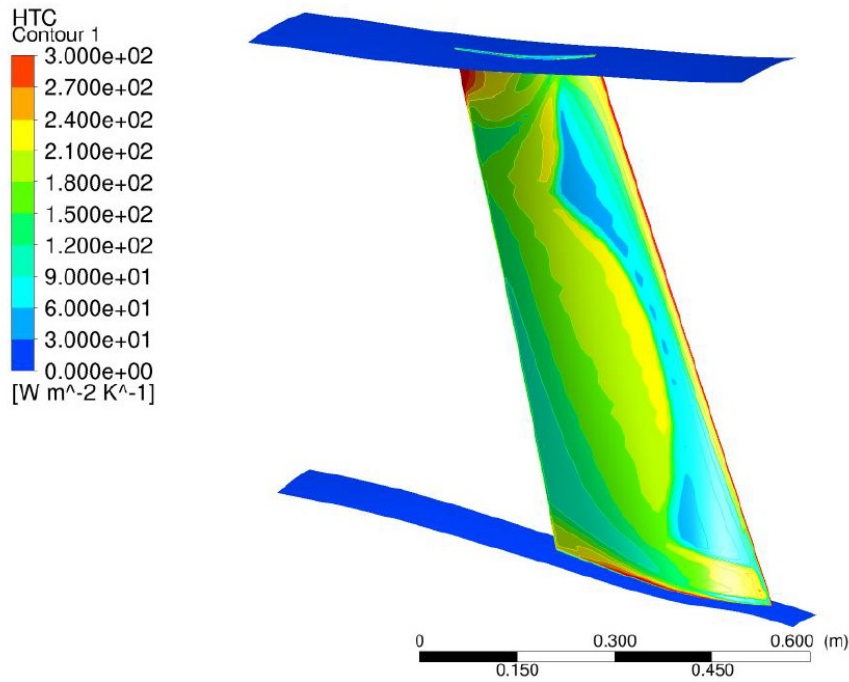


Figure 7: Simulated cruise heat rejection

A 20 kW heat rejection requirement was defined for the OGV, for which the ground idle was shown to be the most critical case. Even with a simple 2-pass configuration the heat rejection was deemed feasible for a low pumping power [20].

3.5 Detailed mechanical design studies

Several innovative methods were tested with goal to improve the aeromechanical performance of the components. HCF (High Cycle Fatigue) due to blade vibrations is one of the paramount challenges in the design of turbomachinery for aero engines. Mastering different approaches which could minimize the risk for HCF would enable engine designs with improved efficiencies and lighter components. One such approach that potentially could lead to more robust aeromechanical designs and that was considered in the current study is the implementation of intentional mistuning. The unavoidable presence of mistuning on a rotor blisk leads usually to an amplification of the vibrational amplitudes when subjected to resonance.

A mistuned blisk implies a difference in shape or material properties for each of its sector blades, where the vibrational energy is spread in a localized manner, affecting the traveling waves and giving rise to high stresses. Mistuning can be defined either as probabilistic that is due to manufacturing tolerances or intentional mistuning when the sector blades are modified in a controlled manner. The amount of mistuning and its pattern are the main parameters that are taken into consideration when assessing the effects on the forced response. The use of intentional mistuning has proven the ability to control the blade response on certain engine orders excitations for the investigated rotor.

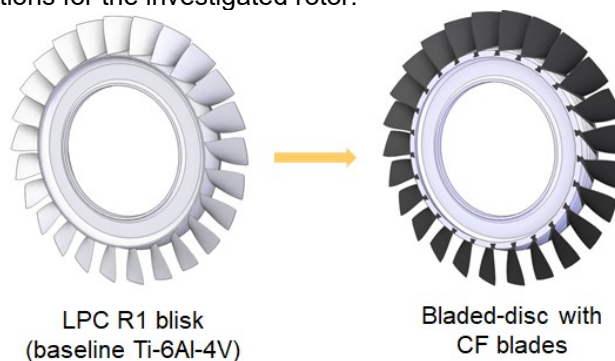


Figure 8: Bladed disk with carbon fibre blades as option to conventional titanium blisk

In attempt to reduce the weight of the front stage compressor blisk, carbon fiber reinforced plastic has

emerged as an alternative for blades, due to its light weight and anisotropic properties. Replacing the reference metallic compressor blades traditionally made in titanium alloy, with carbon fibre blades, Figure 8, would potentially reduce the weight of the considered rotor by nearly 65%. The reduced weight of the blades also consequently implies further weight reduction on the engine level and load supporting structure. The anisotropic nature of composite materials has also fueled the curiosity to investigate if it can be used to enhance mechanical performance and provide aeroelastic stability where traditional metallic blades would fall short of requirements. Several different composite layups stacking strategies were investigated and comparison was made with respect to the modal behavior of the blades and aerodynamic damping i.e. flutter stability. It is found that if carefully designed, the composite blades can provide higher aeroelastic stability than the reference metallic blade.

4. Discussion and outlook

A number of technologies for a year 2035 engine installation has been discussed both with the aim of exploring new concepts and technologies as well as to quantify a new aircraft top-level capability to reduce its environmental footprint. For the latter an approximate reduction rate of 1.0% is observed which lines up well with the ICAO long term moderate technology scenario. As discussed, we believe that the concept studied herein could be further optimized against the reference aircraft to provide additional benefits. Key observations are that new cycles will challenge NO_x emission technology, in particular for the radical reductions being targeted by the aviation community. Also, the LPT turbine did, in our current design, limit the noise reduction potential for approach. A multidisciplinary trade study considering both the mechanical limits posed by the conceptual design and the aerodynamics and noise emission should be undertaken to explore this further. The OGV heat rejection capability was observed to be sufficient for the generator cases explored.

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