Adaption of a turbofan engine for high power offtakes for a turbo-electric propulsive fuselage concept

Sebastian Samuelsson and Olivier Petit
sebastian.samuelsson@chalmers.se
Chalmers University of Technology
Division of Fluid Dynamics
Gothenburg
Sweden

Rasmus Merkler
MTU Aero Engines AG
Munich
Germany

Guido Wortmann
Siemens AG
Erlangen
Germany

ABSTRACT

To lower the fuel consumption and its associated emissions, several new aircraft concepts are being investigated. One such concept is the turbo-electric propulsive fuselage concept (PFC) that is being studied in the EU Horizon 2020 project CENTRELINE for a 2035 entry into service (EIS). The PFC makes use of a rear-mounted electric fuselage fan to ingest part of the fuselage boundary layer. The fuselage fan is powered by power offtakes from two under-wing podded geared turbofans. In this paper, a design of the under-wing main power plants is presented and compared to an engine for a conventional reference aircraft with the same EIS year. A free power turbine (PT) stage for the large power offtake required is added aft of the low pressure turbine (LPT). The PT is connected to an electric generator on the same shaft that is integrated in the PT hub. The addition of the PT allows for mechanically decoupling the electric machinery from the LP spool, which is considered beneficial for the electric machinery operation. It also allows for a removal of one LPT stage compared to the reference engine. The power plants for the PFC show a reduction of fan diameter by 11%, as well as a reduction in engine weight of 13% excluding the electric machinery weight.

Keywords: propulsive fuselage; turbo-electric aircraft; geared turbofan; large power offtake; aircraft engine performance; aircraft engine conceptual design; free power turbine

NOMENCLATURE

ACOC	Air-cooled oil cooler
B	Burner
CENTRELINE	Concept validation study for fuselage wake-filling propulsion integration
comb	Combustor
EIS	Entry into service
GBX	Gearbox
GEN	Generator
GESTPAN	General stationary and transient propulsion analysis
GTF	Geared turbofan
HP	High pressure
HPC	High pressure compressor
HPT	High pressure turbine
IPC	Intermediate pressure compressor
LP	Low pressure
LPT	Low pressure turbine
NEWAC	New aero engine core concepts
OPR	Overall pressure ratio
PFC	Propulsive fuselage concept
PT	Power turbine
R2035	Reference 2035 aircraft/engine
SFC	Specific fuel consumption
T_4	Burner exit temperature
VITAL	Environmentally friendly aero engine
WEICO	Weight and cost estimation

1.0 INTRODUCTION

In the CENTRELINE project a propulsive fuselage concept (PFC) is studied, as described in [1]. The concept aims to reduce fuel burn by means of an electrically driven fuselage fan mounted in the rear of the aircraft. The fuselage fan is used to re-energize the wake caused by the fuselage, thereby reducing the effects of fuselage drag in the aircraft wake. The electric power required to drive the fuselage fan is generated through power offtake from two under-wing podded geared turbofan (GTF) engines, see Figure 1. The GTF engines further serve to generate thrust for the aircraft, just as in conventional jet aircraft. This means that compared to a conventional GTF for a same size aircraft, less thrust needs to be produced but instead a higher mechanical power offtake is extracted. The PFC in CENTRELINE is targeted at a year 2035 entry into service (EIS).

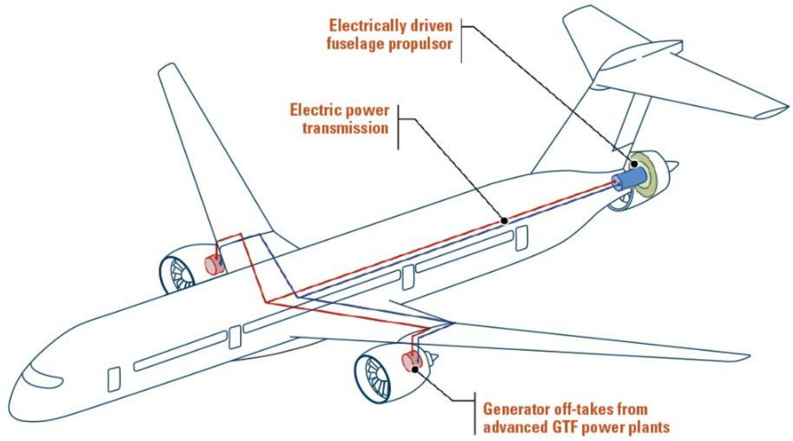

Figure 1. Overview of the PFC aircraft illustrating the power train concept [1].

The large power offtake required to drive the fuselage fan also requires the integration of a significantly larger generator into the GTFs than is the case for conventional aircraft. This means that an engine architecture must be chosen that facilitates the inclusion of the generator and its required auxiliary systems such as the rectifier power electronics and the cooling system. In addition, the engine design should ensure that the best balance between engine performance and weight, and the generator performance and weight is found.

In the present paper, the performance characteristics as well as an engine weight breakdown is presented both for the PFC aircraft and for a conventional reference aircraft (R2035) with the same entry into service year.

2.0 MODELING APPROACH

For the PFC main power plants, the generator design was considered together with integration aspects of the generator into the engine as well as engine operability implications. An engine architecture with the generator driven by a free power turbine (PT), as shown in Figure 2, was considered the most promising, taking the above-mentioned aspects into account. The integration aspects are treated in detail in [2].

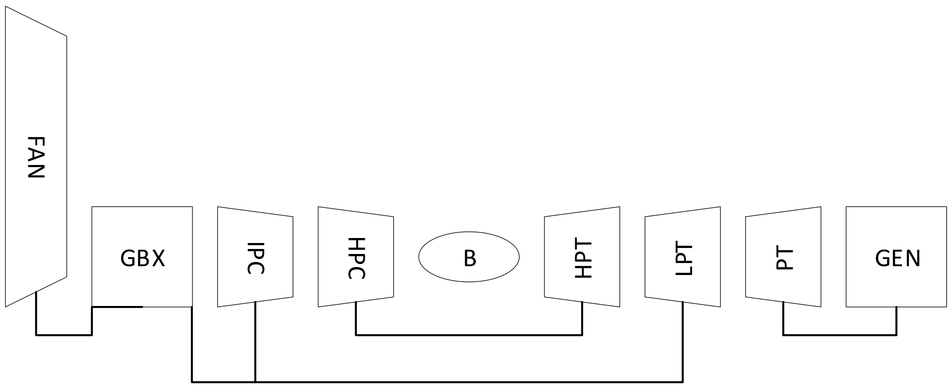

Figure 2 Schematic layout of the geared turbofan engine architecture adapted for the large power offtakes required by the PFC aircraft.

A potential benefit of this choice of engine layout is that the PT is mechanically decoupled from the low pressure (LP) shaft which is expected to alleviate some of the challenges associated with part-load operation in points with a low thrust setting but high power offtake, such as during initial descent. Moreover, a mechanical decoupling could provide a benefit in case of torque oscillations and peaks in the electric machinery that could occur during abnormal operation [3].

The addition of one turbomachinery component increases the mass of the engine itself, but at the same time facilitates the generator to run at a freely selected rotational speed, which enables flexibility for the electric machinery design. Furthermore, when the power offtake is taken from a separate turbine, the number of LPT stages could be reduced from four to three compared to an engine where the fuselage fan power offtake is taken from the LP shaft, thus gaining back some of the additional mass introduced by the PT.

Implications of this choice of architecture on the electric machinery design are treated in detail in [3].

The reference aircraft is a conventional two-engine twin-aisle aircraft with the engines podded under the wings. The engines are two-shaft geared turbofans and thus does not include a PT or a generator on the engine axis.

2.1 Method and modelling assumptions

The power plant performance is modelled using Chalmers University's in-house developed code GESTPAN [4]. The engine conceptual design, including flow path layout and weight assessment, is done in another Chalmers program, WEICO [5]. WEICO has been validated in the EU funded research projects NEWAC [6] and VITAL [7] and is based on methods contained in [8]. WEICO uses performance data from multiple operating points, such as take-off, top-of-climb and mid-cruise, to correctly size the engines. The material limits assumptions used for both the PFC and R2035 engines have been defined by Bijewitz et al. in the power plant pre-design exploration study [9] and are shown in Table 1.

Table 1
Assumed material temperature and stress limits for 2035 EIS aircraft

Parameter	Unit	Value
Burner exit temp.	K	2050
LPT inlet temp.	K	1350
HPC outlet temp.	K	1050
AN^2 last HPT rotor	m^2/s^2	9000
AN^2 last LPT rotor	m^2/s^2	13500

The fan is assumed to include a variable area fan nozzle to ensure operational stability at take-off and part-load settings. The generator will require cooling due to its heat losses. In this concept oil cooling is envisioned and the air-cooled oil cooler (ACOC) will use air in the bypass duct. This will, together with the integration of the rectifier in the bypass channel cause additional pressure losses in the bypass duct of around 0.2% [2], which are considered in the engine performance model.

Due to the addition of a free power turbine for generator power offtake in the PFC, the amount of power that the LPT is required to produce is reduced significantly compared to the R2035 engine. Analysis of the LPT stage loading showed that a three-stage LPT was optimal for a configuration including a PT. Power offtake to drive the auxiliary systems, such as the environmental control system (ECS) is extracted from the high pressure (HP) spool in both the PFC and the R2035.

The free power turbine is located behind the LPT. The PT must be able to provide a specified power output as defined by the overall integrated aircraft sizing. Since the thrust setting needs to be able to be set independently from the power offtake setting, an additional control variable is necessary in the form of the turbine area. This area variability, however, also provides the opportunity to set the rotational speed of the PT independently from the thrust setting and LP shaft speed. The variability can be obtained using variable stator vanes, i.e. a variable PT nozzle. This will introduce an additional mass compared to fixed stator vanes and the area variability will also lead to a component efficiency penalty in operating points where the area is reduced or increased compared to the reference (maximum efficiency) area [10]. This efficiency penalty is, however, not included in the present paper.

3.0 RESULTS

3.1 Engine performance characteristics

Selected performance characteristics of the under-wing engines for the PFC and R2035 are shown in Table 2. The design requirements such as Mach number, altitude, thrust and power offtake levels, as well as the cycle settings such as overall pressure ratio (OPR) and burner exit temperature (T_4), are obtained from the work in [9]. It should be noted that the SFC values are higher for the PFC than for the R2035. This is due to the definition of SFC as fuel flow divided by net thrust from the power plant. The substantial power offtake increases the fuel flow relative to the net thrust and hence higher SFC values are obtained. The potential benefit from the PFC configuration instead comes from the reduced thrust requirement resulting from the boundary layer ingesting fuselage fan. Compared to the reference R2035 engine, the fan diameter of the PFC power plant is substantially reduced, by 11%, due to the lower thrust requirements.

Table 2
Performance characteristics of the PFC main power plant and the R2035 engine

Parameter	Unit	PFC	R2035
Flow-path design point top-of-climb (M0.82, FL350, ISA+10K)			
Net thrust	kN	47	58
HP power offtake	kW	600	600
PT power offtake	MW	3.2	-
Customer bleed	kg/s	0	0
Fan diameter	m	3.04	3.39
Burner exit temperature (T_4)	K	1750	1750
Overall pressure ratio	-	60	60
SFC	mg/Ns	17.0	13.9

3.2 Engine flow-path layout

The basic general arrangement and flow path layout of the PFC engine are shown in Figure 3. A configuration with the PT located directly after the LPT has been chosen. This limits the weight and length of the engine compared to if an additional mid-turbine frame, between the LPT and PT, is included. The complete rationale behind this choice, as well as the envisioned bearing arrangement is treated in [2]. The conceptual design model shows that a stage configuration with 1(Fan)-3(IPC)-9(HPC)-2(HPT)-3(LPT)-1(PT) is optimal for the PFC power plant. The R2035 engine does not contain any PT stage but instead requires one additional LPT stage, as shown in Figure 4.

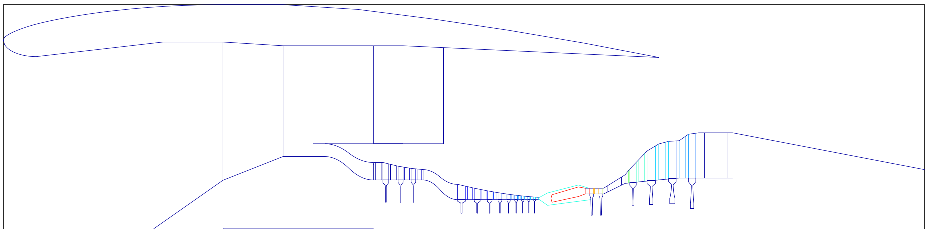

Figure 3 General arrangement and flow path layout of PFC engine

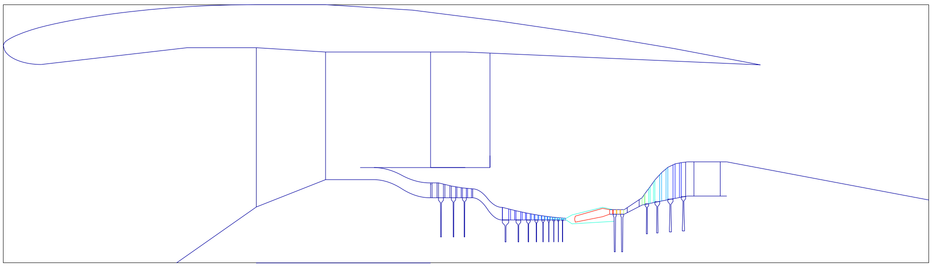

Figure 4 General arrangement and flow-path layout of the R2035 engine

3.3 Engine weight breakdown

The mass of the PFC power plant is estimated at 7700 kg, excluding the weight of the electric machinery. A breakdown of this mass on the different components is shown in Figure 5. The R2035 engine mass is 8800 kg, mainly due to its larger fan diameter. It is evident from Figure 6 that the fan and nacelle make up a larger part of the total engine weight for the R2035 engine compared to the PFC. It should be kept in mind, however, that the additional electric machinery weights that are introduced in the PFC are not included in the weight presented here. The additional weight of the generator and its associated systems are included in the integration study carried out in [2].

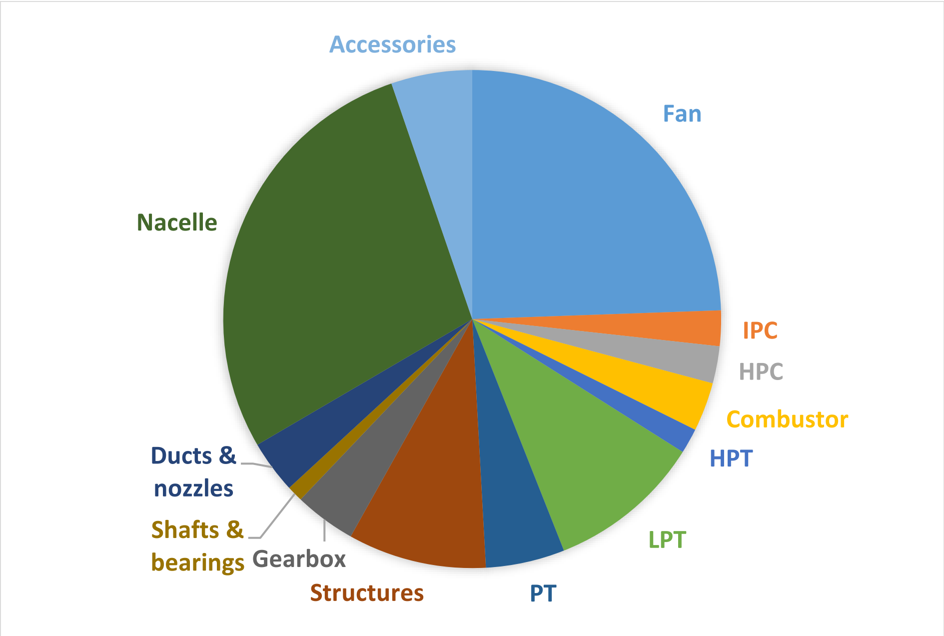

Figure 5 Component weight breakdown of the PFC main power plants. The total mass per engine is calculated to 7700 kg

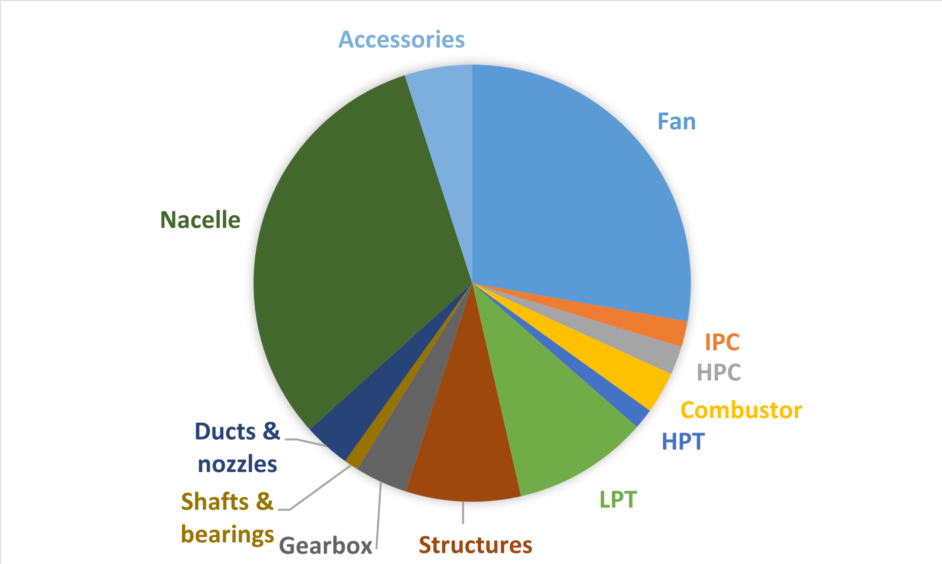

Figure 6 Component weight breakdown of the R2035 power plants. The total mass per engine is calculated to 8800 kg

4.0 CONCLUSIONS

The results presented in this paper indicate that the size of the main power plants of a propulsive fuselage concept can be reduced significantly compared to a conventional aircraft for a 2035 EIS. The savings in mass come from a reduced fan diameter that is the result of a reduced thrust requirement for the PFC aircraft compared to the R2035. It also shows that despite the introduction of an additional turbomachinery component, the PT, the mass of the PFC power plants can be limited by allowing for the removal of one LPT stage compared to the R2035.

The inclusion of a free power turbine for the required large power offtakes provides flexibility in the design of the electric drive train due to the ability to select a suitable rotational speed of the power turbine and generator. Furthermore, it facilitates the integration of the generator in the rear of the engine. Benefits of a free power turbine are also expected in part-power operating points as well as for electric machinery design and operation.

ACKNOWLEDGMENTS

The authors would like to thank the partners in CENTRELINE for their contributions in providing input to the power plant design. The CENTRELINE project has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No. 723242.

REFERENCES

[1] A. Seitz, “Concept validation study for fuselage wake-filling propulsion integration,” in *ICAS 2018*, Belo Horizonte, Brazil, 2018.

[2] R. Merkler, S. Samuelsson and G. Wortmann, “Integration aspects for large generators into turbofan engines for a turbo-electric propulsive fuselage concept,” in *ISABE 2019*, Canberra, Australia, 2019.

[3] G. Wortmann, “Electric machinery preliminary design report (D4.4),” CENTRELINE public deliverable, 2018.

[4] T. Grönstedt, “Development of methods for analysis and optimization of complex jet engine systems,” Ph.D. thesis, Chalmers University of Technology, Gothenburg, Sweden, 2000.

[5] L. Larsson, T. Grönstedt and K. Kyprianidis, “Conceptual Design and Mission Analysis for a Geared Turbofan and an Open Rotor Configuration,” in *ASME Turbo Expo 2011*, Vancouver, Canada, 2011.

[6] G. Wilfert, J. Sieber, A. Rolt, N. Baker, A. Touyeras and S. Colantuoni, “New environmental friendly aero engine core concepts,” in *ISABE 2007*, Beijing, China, 2007.

[7] J.Korsia and G. Spiegeler, “VITAL - European R&D programme for greener aero engines,” in *ISABE 2007*, Beijing, China, 2007.

[8] E. Onat and G. Klees, “A method to estimate weight and dimensions of large and small gas turbine engines,” NASA, 1979.

[9] J. Bijewitz, A. Seitz and M. Hornung, “Power Plant Pre-Design Exploration for a Turbo-Electric Propulsive Fuselage Concept,” in *AIAA Joint Propulsion Conference*, Cincinnati, 2018.

[10] D. Edmunds, “Multivariable control for a variable area turbine engine,” Aeronautical Systems Division, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, United States, 1977.