ConcEpt validatioN sTudy foR fusElage wake-filLIng propulsioN intEgration

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The CENTRELINE Project – In Short

- **Call**: MG-1.4–2016-2017: Breakthrough innovation
- **Budget**: EUR 3,680,519.78 (100% financed by the EU)
- **Duration**: 36 months, June 2017 – May 2020

High-level objectives at aircraft level:

- Proof-of-concept (target TRL at the end of the project: 3-4)
- 11% CO\textsubscript{2} reduction vs. R2035 (–40% CO\textsubscript{2} vs. Y2000 SRIA ref.)
- 11% reduction of NO\textsubscript{x} emissions vs. R2035 (–84% NO\textsubscript{x} vs. Y2000 SRIA ref.)
The Design Paradigm Shift for CENTRELINE

Optimised fuselage fan (FF) integration for turbo-electric drive:

- FF location at very aft-tip of fuselage
- Minimised FF net specific thrust
- Optimised aerodynamics, structural integration and power train design
- Minimised electrical power installation
CENTRELINE – Research Focal Points

➤ Addressing the main challenges for a Propulsive Fuselage aircraft concept

➤ Design of the fuselage fan turbo-electric powertrain

➤ Understanding of the aerodynamic effects of fuselage wake-filling propulsion integration

➤ Multi-disciplinary aircraft design integration and optimisation

➤ Synergistic aero-structural integration of the BLI propulsor
CENTRELINE – Methodological Approach

- High end & high fidelity simulation techniques
  - Overall aircraft and fuselage fan aerodynamics
  - Key structural elements
  - Components of the turbo electric powertrain
- Low speed wind tunnel and BLI fan rig testing
- Multi-disciplinary aircraft pre-design integration and optimisation
- Rigorous concept assessment and benchmarking

Figure: Meridional view of the BLI fan rig at the University of Cambridge (top) & Computational domain of the BLI fan rig running with inlet distortion (bottom) (Ref.: Gunn and Hall, ASME GT2014-26142, 2014)

Figure: PFC design and performance refinement based on 2D-axisymmetric CFD-in-the-loop performed in FP7 DisPURSAL (Ref.: Seitz et al., Proceedings of EC-Aerodays 2015)
Targeted PFC technology EIS in 2035
- Medium-to-long range wide-body aircraft segment determined most impactful
- R2000 baseline aircraft: Airbus A330-300 featuring RR Trent 700 Series engines: stretched to accommodate 340 Pax

R2035 aircraft definition
- Advanced aerodynamic, structural and systems technologies for EIS 2035
- UHBR geared turbofan power plants
- Systems sizing for product family including stretch and shrink versions of the baseline aircraft by +/- 15% payload capacity

### Basic aircraft top level requirements

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
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<tbody>
<tr>
<td>Technology freeze / Entry-into-Service</td>
<td>2030 / 2035</td>
</tr>
<tr>
<td>Design range</td>
<td>6500 nmi</td>
</tr>
<tr>
<td>Design payload</td>
<td>340 PAX in 2-class arrangement</td>
</tr>
<tr>
<td>Airport compatibility limits (ICAO Annex 14)</td>
<td>Code E (52 m &lt; x &lt; 65 m)</td>
</tr>
<tr>
<td>Take-off Field Length (MTOW, SL, ISA)</td>
<td>≤ 2900 m</td>
</tr>
<tr>
<td>Second segment climb</td>
<td>340 PAX, DEN, ISA+30°C</td>
</tr>
<tr>
<td>Landing Field Length (MLW, ISA)</td>
<td>≤ 2400 m</td>
</tr>
<tr>
<td>Approach speed (MLW, SL, ISA)</td>
<td>≤ 145 KCAS</td>
</tr>
<tr>
<td>ETOPS Capability</td>
<td>240 mins</td>
</tr>
<tr>
<td>Design Service Goal</td>
<td>50000 Cycles</td>
</tr>
</tbody>
</table>

### R2035 (Baseline Family Member) Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing span</td>
<td>65 m</td>
</tr>
<tr>
<td>Operating Empty Weight</td>
<td>120.2 t</td>
</tr>
<tr>
<td>Maximum Take-off Weight</td>
<td>222.9 t</td>
</tr>
<tr>
<td>Maximum Wing Loading</td>
<td>644 kg/m²</td>
</tr>
<tr>
<td>Design block fuel vs. year 2000 baseline (R2000)</td>
<td>–27%</td>
</tr>
</tbody>
</table>
PFC aircraft configurational determination based on qualitative down-select

Gauging of alternate PFC designs using semi-empirical methods

Evaluation based on “Power Saving Coefficient” (cf. L.H. Smith, 1993):

\[ P_{SC} = \frac{P_{Ref} - P_{PFC}}{P_{Ref}} \]

Target Design Point

11.5% LPT power savings for PFC target design in cruise

~2% penalty for additional aircraft gross weight due to turbo-electric power train included in power savings

Synthesis of Initial PFC Aircraft Target Design

- Multi-disciplinary PFC aircraft / propulsion conceptual sizing
  - Inclusion of conceptual modelling / preliminary assessments for the
    - Aft-fuselage propulsion installation
    - Turbo-electric power train
    - Main power plant design and performance

<table>
<thead>
<tr>
<th>Initial PFC Design Property</th>
<th>Δ vs. R2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing Span</td>
<td>– 0.2%</td>
</tr>
<tr>
<td>Main Landing Gear Height</td>
<td>+ 11%</td>
</tr>
<tr>
<td>Maximum Wing Loading</td>
<td>+/− 0%</td>
</tr>
<tr>
<td>Operating Empty Weight</td>
<td>+ 5.7%</td>
</tr>
<tr>
<td>Design Payload Weight</td>
<td>+/- 0%</td>
</tr>
<tr>
<td>Design Block Fuel</td>
<td>– 11.3%</td>
</tr>
<tr>
<td>Maximum Take-off Weight</td>
<td>– 0.5%</td>
</tr>
</tbody>
</table>

- 47% ToC Thrust
- 6% ToC Thrust*

- 1.4 Design FPR Electric Fan
- 8 MW Motor (Design Power)
- 95% Motor Efficiency
- 2.34m (92 inch) Fan Diameter

- 4.6 MW Generator
- 95% Generator Efficiency

- 73.2 klbf max. TO Thrust**
- GTF UHBH Engines
- 3.05m (121 inch) Fan Diameter
- 1.37 Design FPR

*) Net thrust after BLI (cf. book-keeping acc. to Bijewitz et al., 2016)
**) SLS, ISA
Initial Aero-Shaping and Structural Design Concept

➤ **Aero-numerical analysis**
- Initial aero-shaping refinement using MTFLOW and RANS CFD in ANSYS Fluent®:
  - 2D axisymmetric steady state RANS
  - k-ω-SST, y+ ≈1
  - BLI fan actuator disk model: axial momentum & energy volume sources in fan plane

➤ **Numerical analysis of structural design**
- Strain, stress and local displacement assessment for CS-25 load cases
- Focus on weights prediction for:
  - the fuselage;
  - the fuselage-wing junction;
  - the aft-fuselage nacelle; and,
  - the empennage group
- Learn more: Presentation on structural modelling by Prof. Goraj, Session 1.10, 11:00hrs, Thursday
Design of the Turbo-electric Powertrain

Focus of the design and development activities:

- Power generation system (gas turbine engine, multi-megawatt generator, the power electronics and the cooling system)
- Fuselage fan drive system (fuselage fan motor, the power electronics and the cooling system)
- Power transmission (at reduced level of detail)

Initial systems architectural layout:

- DC power transmission from main power plants to fuselage fan
- Four independent DC lanes for each power plant
- Main power plant layout:
  - Initial stage configuration
    1 (Fan) 3 (IPC) 9 (HPC) 2 (HPT) 3 (LPT) 1 (PT)
  - Generator integrated in hub of a free Power Turbine (PT)
Aerodynamic Testing – Overall Configuration

- Testing of modular PFC aircraft wind tunnel model at low-speed facilities of TU Delft

- Open Jet Facility (OJF): closed-loop wind tunnel with open test section, octagonal outlet section 2.85 m wide, maximum velocity: 30 m/s

- Low-Turbulence Tunnel (LTT): octagonal test section with a 1.80 m x 1.25 m cross-section, 2.60 m in length; operational velocity up to 120 m/s, freestream turbulence intensity below 0.1%.

- Initial test results from generic model:

  - Propeller performance at \( V_\infty = 25 \text{m/s} \): approx. 14% reduced power due to BLI
Aerodynamic Testing – BLI Fuselage Fan

➤ Low-speed BLI Fan Rig facility at the University of Cambridge
  ➤ Emulation of ingested velocity profile by 3D-printed variable porosity distortion gauzes
  ➤ 3D steady velocity and pressure fields determination by 5-hole pressure probe at 5 traverse planes
  ➤ Rig currently modified incl. new hub & casing geometry
  ➤ Fan stator by 3D printing + rotor machined from aluminium

➤ Stepwise approach to fuselage fan aerodynamic analysis
  ➤ Development and computational assessment of 3 fan designs
    ➤ 1. Rig-scale fan optimized for clean inflow
    ➤ 2. Rig-scale fan optimized for BLI conditions
    ➤ 3. Full-scale fan optimized for BLI conditions
  ➤ Manufacturing and detailed testing of fan design #2
  ➤ Full-annulus, unsteady CFD of operational behavior for fan design #3

Distortion gauze
Flow straightener
Rotor
Stator
Throttled exhaust to atmosphere

Ref.: Gunn and Hall, ASME GT2014-26142, 2014
Propulsive Fuselage Technology Roadmap

CENTRELINE Project Focus

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Thank you for your attention!