Innovative Engine Integration Solutions for Transport Aircraft: Current Research and Future Challenges

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ONERA
THE FRENCH AEROSPACE LAB
1. Introduction
   Context, why new engine integration concepts?

2. Boundary Layer Ingestion

3. Towards Distributed Hybrid Electric Propulsion

4. Conclusions
• Evolution of major transport aircraft products:

• No revolution in aircraft architecture!
• More a continous evolution through incremental improvements and optimisation of components with frozen architecture:
  • tube-and-wing architecture,
  • under-wing mounted engines (>100 pax),
  • from 4-engines to 2-engines

• Advantages of under-wing, podded engines architectures:
  • Engine ingesting unperturbed flow (better from the engine perspective)
  • Clear separation between engine and airframe:
    • Independent design & manufacturing
    • Clear industrial breakdown, responsibilities between engine and airframe manufacturers
• Overall A/C performance (Breguet-Leduc) formula:

\[
\text{Range} = c \cdot M \frac{L}{D} \frac{1}{s \cdot \text{TSFC}} \ln\left(\frac{W_{\text{empty}} + W_{\text{fuel}}}{W_{\text{empty}}}\right)
\]

• Major trends (from an aircraft architecture point of view):
  • Better aerodynamics (L/D): higher wing aspect ratio, winglet, …
  • Better engines (TSFC): higher bypass ratio (bigger engine), thermodynamic cycle,…
  • Lighter structures (\(W_{\text{TO}}/W_{\text{empty}}\))
Introduction (3)

Why investigating new engine integration solutions?

1. Limits of under-wing, podded engines architectures:
   - Current BPR of 10-12
   - Envisaged UHBR of 15-20 for N+1 A/C generation
   - Integrating such big engines under the wing raises intricate issues:
     - Longer landing gear needed
     - Stronger engine-airframe aerodynamics coupling
     - Nacelle weight/drag

2. Maximising overall aero-propulsive efficiency of the aircraft+engine as a whole can push us away from podded engine architectures

\[
\text{Range} = c \cdot \frac{M}{D} \frac{1}{\text{TSFC}} \ln \left( \frac{W_{\text{empty}} + W_{\text{fuel}}}{W_{\text{empty}}} \right)
\]

(Drela, 2009)
1. **Introduction**  
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Basic principles/physics of Boundary Layer Ingestion gains

- How can we expect to gain with BLI:

  ![Image](source.png)

  (Source: A. Steiner et al., BHL)

  - For the **same net longitudinal force** («thrust=drag»)
  - **Less mechanical power** is required in the case of BLI to produce the same thrust ($\Delta V$):
    - the fan accelerates a slower flow ($V_0^{BLI} < V_0^{non-BLI}$) and power scale as $V_0^2$
Experimental BLI investigation in ONERA-L1 WT

- **Objectives** of the RAPRO2 L1-WT tests:
  - to acquire accurate and detailed aerodynamic data for validation of CFD-based BLI evaluation methodology
  - to confirm BLI concept potential (Mach 0.2)
Experimental BLI investigation in ONERA-L1 WT

Analysis of the BLI efficiency: 

\[ PSC = \frac{P_{\text{non BLI}} - P_{\text{BLI}}}{P_{\text{non BLI}}} \]

as a function of net axial force

Aero/propulsive efficiency improvement through BLI is confirmed experimentally @ M 0.2 : ~ 20% (D_w/D_a = 1)
Validation of numerical methods for BLI investigations

- Importance of CFD-based simulation for the design of efficient BLI aircraft
- Require careful validations of the capability of CFD-based process to capture all the flow physics involved by BLI:
  - BL development and wake advection
  - Fan/BL interaction

Use of overset and Cartesian grids techniques (elsA)

CFD simulation of the powered nacelle using Actuator Disk (elsA)
Development of NOVA Aircraft Configurations for Large Engine Integration Studies

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NOVA
Targeted architectures for UHBR

- **Baseline**
  - UHBR engine
  - Wide lifting fuselage
  - High AR wing
  - Downward oriented winglets

- **Gull wing**
  - Increased inner wing dihedral to limit landing gear length

- **Podded**
  - Engines mounted on aft fuselage side

- **BLI**
  - Engine inlet ingesting the fuselage boundary layer
By embedding the engine into the fuselage, savings in fuel (due to reduced wetted area and jet/wake losses) and mass are expected.

**Deliberately «aggressive» design:**
- Engine ~40% buried
- Short inlet (inlet length/fan diameter ratio ~1)

When ingesting the fuselage boundary layer, the engines tend to minimize the aircraft footprint in the surrounding airflow, indicating better thrust-drag balance.
NOVA
Power saving VS stream-wise force

\[ PSC = \frac{P_{Podded} - P_{BLI}}{P_{Podded}} \]

5.2%
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BLI ➔ Distributed propulsion ➔ Electric propulsion

• Links between BLI and Distributed Propulsion:
  • Efficiency ↑ with fraction of BL ingested ($D_w/D_A$)
  • Many architectures can be envisaged:

  ![Distributed propulsion architectures](Source: A. Steiner et al., BHL, ICASE2012)

• Distributed propulsion has additional advantages:
  • Redundancy/reconfiguration (safety)
  • Use differential thrust for control

• Links between Distributed Propulsion and (Hybrid) Electric:
  • Electric ducted fan is an enabling technology for multifan and “massively” Distributed Propulsion architectures
  • Distributed propulsion calls for separation of thrust and power production functions, making the use of hybrid energy source more natural.
Distributed Electric Propulsion studies
in the AMPERE Project
Objective: Increase maturity of DEP technology
- Aerodynamics of Electric Ducted Fan (EDF) integration
- A/C Control/command through EDF and conventional moving surfaces (considering potential resizing)

Means: Numerical and experimental approaches
- Aerodynamic design of EDF integration
- Wind tunnel experiments
  - L2 very low speed WT (Lille, France)
  - Powered 1:5 scale Mock-up with on the shelf components
- Control Law definition using both control surfaces and EDF
- 6DoF Simulation tool using aerodynamic model and Control law for robustness analysis and demonstration
AMPERE
Aircraft Pre-design

Estimated MTOW ~2400 kg

Example of arrangement of electrical propulsion architecture

Estimated weight of advanced power architecture (Propulsion) ~890 kg
Numerical investigation of DEP with blowing effect (2D)

Preliminary investigations

Clark Y

\[ h/c = 10\% \quad (=\text{EDF with 40mm diameter}) \]
\[ h/c = 12.5\% \quad (=\text{EDF with 50mm diameter}) \]
\[ h/c = 4\% \quad (=\text{reference from previous study}) \]

NACA 23012

Actuator disk \( \rightarrow \)

Imposed pressure variation

Engine location sensitivity analysis

Selection criteria upon \( C_{z\text{max}} \), stall behavior (stability and progressivity)

CFD RANS 2D

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Numerical investigation of DEP with blowing effect (3D)

- CFD 3D computations, viscous, stationnary (RANS), on a wing section with 1 EDF (which models a wing with an infinity of EDF)
- Fan modelled by an actuator disk (pressure gap)
- Guide vanes integrated into computations
- 3D effects integrated to handle «squaring the circle» issue (to go from a circle section to an square one)

$C_z^{\text{max}}$ in 3D close to 4.7 instead of 5.7 with 2D CFD assessment
Tests were ended early 2017
Analysis on going
Outline

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4. **Conclusions:**
   - Future challenges of BLI and DEP
Conclusions:
Main challenges of BLI

- Experimental proof of benefits in transonic conditions
- Design fan/OGV tolerant to distortion
- Aero-elastic behaviour of the fan with distortion
- Design air inlet suitable for all operating conditions (Active Flow Control)
- Impact of BLI engine integration architecture on structure and mass
- Aero-acoustic characterisation of BLI configuration
Conclusions: Main challenges of Distributed Propulsion

✓ Performance in transonic conditions

✓ Experimental proof of benefits at Low-Speed (Take-off and Landing)

✓ Impact of DP architecture on structure and mass

✓ Engine integration issues
  ✓ Thermal aspects for large passenger Aircraft
  ✓ Electromagnetic compatibility
Thanks for your attention. Any questions?
Far-field exergy based breakdown

Rationale

✓ Context

· Design tool: post-processing code

(Drela, 2009)
Far-field exergy based breakdown
Application to BLI

Exergy = Stagnation enthalpy – $T_{ambient} \times$ Entropy

- Energy convertible in mechanical work
- Energy provided to the system (Engine)
- Dissipations (viscosity + thermal losses + shock waves)

-10% of required energy
Less losses in wake (jet)
Less required exergy
Same axial force

Energy provided to the system (Engine)
Dissipations (viscosity + thermal losses + shock waves)