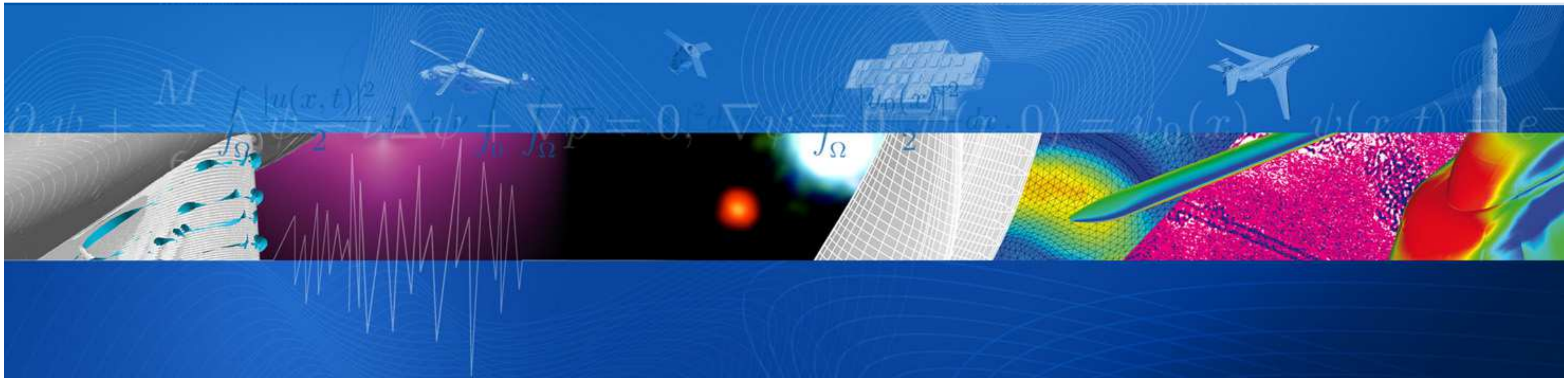

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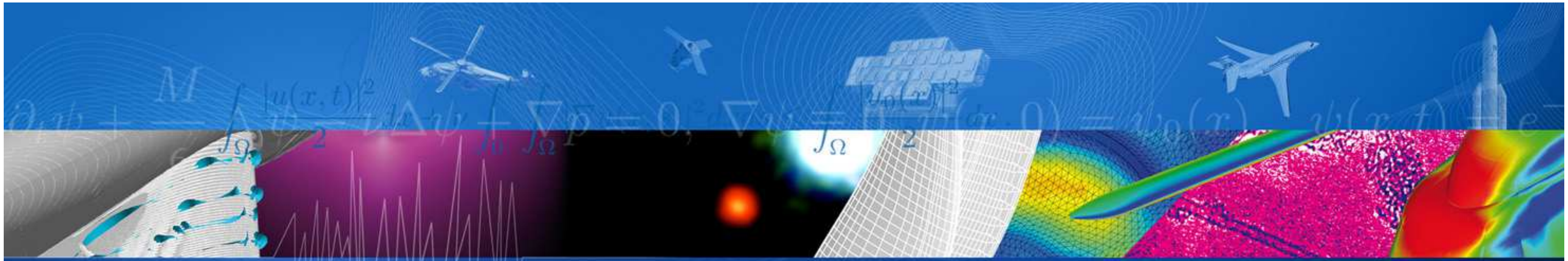

NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF THE BOUNDARY LAYER INGESTION (BLI) AND DISTRIBUTED PROPULSION CONCEPTS

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CEAS-SCAD
25-27 November 2014, Onera Toulouse, France

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Outline

- Introduction

  Context, motivations for new concepts, objectives

- DGAC project RAPRO-2 (BLI)
  - Definition of the WT test
  - Experimental investigation of BLI
  - Validation of numerical methods for BLI analysis
- European project DisPURSAL
  - Distributed propulsion
  - Propulsive fuselage
- Conclusion & Perspectives

Introduction
Context

- Drastic fuel burn, CO_2 and NOx emissions reduction are requested for next generations of commercial transport aircraft (NASA N+3 goals, ACARE/Strategic Research & Innovation Agenda)

➡ Needs for more than incremental improvements : new aircraft concepts

- Aircraft efficiency can be modeled by the Breguet-Leduc range equation:

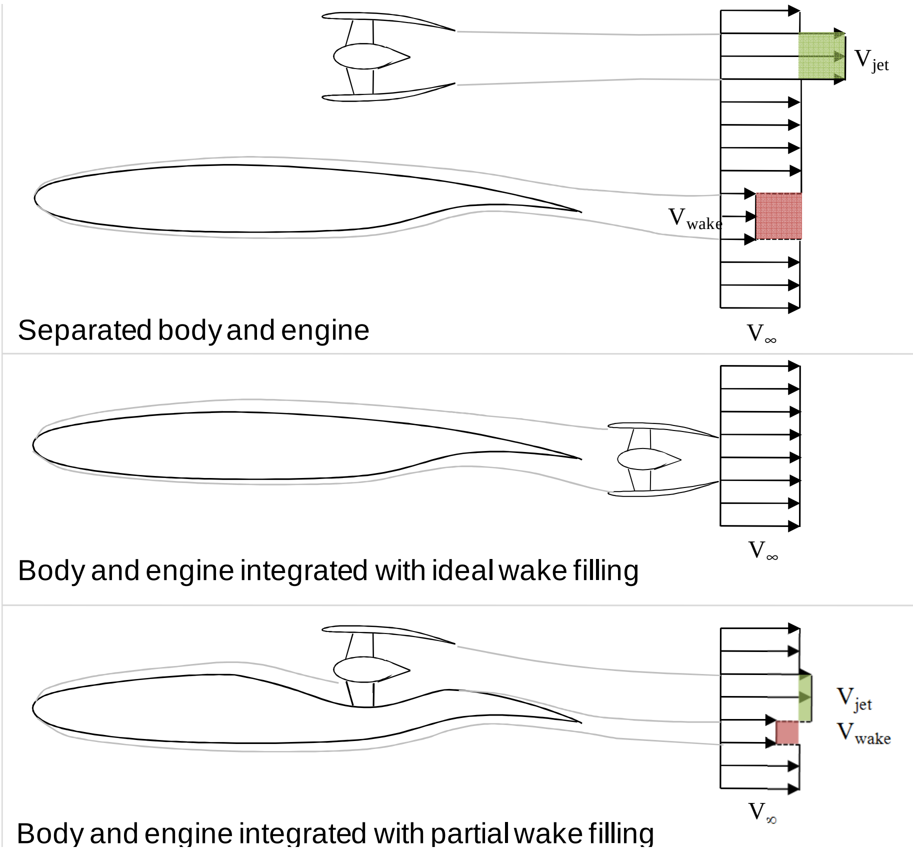
$$Range = c\,M\,\frac{L}{D}\,\frac{1}{g.TSFC}\,\ln\left(\frac{W_{empty}+W_{fuel}}{W_{empty}}\right)$$

Improve engine and airframe aerodynamics separately

Use airframe/prop. interactions to further improve aeropropulsive efficiency

Introduction to the BLI concept

Boundary layer ingestion and wake filling



Wake analysis: any deviation from uniform velocity distribution involve efficiency losses

Filling the BL wake (velocity deficit) with the engine jet (velocity excess)

$$\eta = \frac{2V_\infty}{V_{jet} + V_\infty} \rightarrow 1 \quad as\ V_{jet} \rightarrow V_\infty$$

$$T \propto \Delta V \rightarrow 0$$

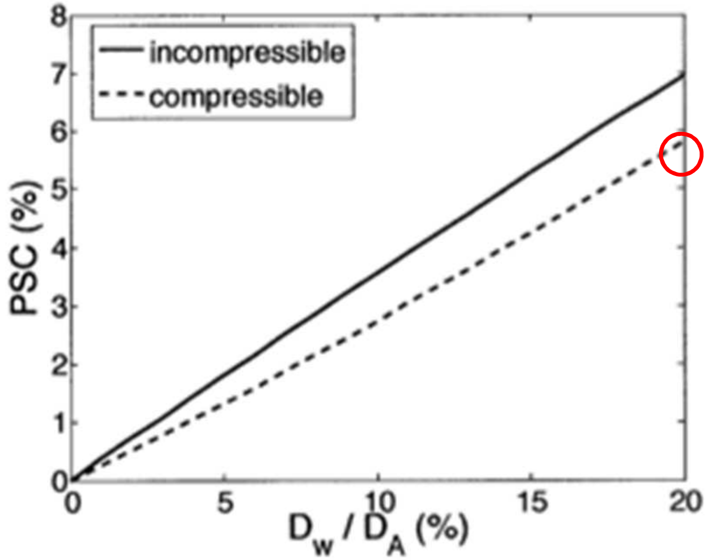
Potential benefits of BLI in term of aeropropulsive efficiency

Definitions:

Power Saving Coefficient = $\dfrac{Power^{NoBLI} - Power^{BLI}}{Power^{NoBLI}}$ (@ Thrust=Drag equilibrium)

Ingested BL fraction = D_w/D_A : ratio of ingested drag to total A/C drag

Results from simple theoretical studies:



(source: A. Plas, MIT)

~6 % gains achievable (for 20% of A/C BL ingested) are reported in literature

But many aspects are not considered in such studies (several simplifying assumptions…)

➔ Need for further studies to consolidate the expected benefits of BLI

DGAC project RAPRO-2

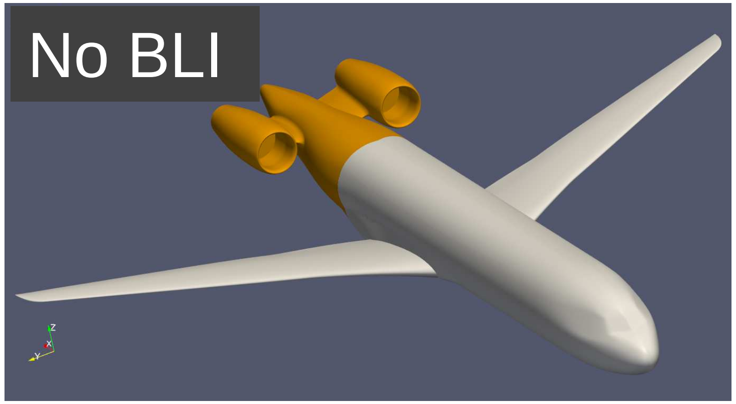
Introduction

The RAPRO2 project

- RAPRO2 (RAdical PROpulsion) project
  - Period: 2010-2013
  - Funded by the French governmental agency DGAC
  - Conducted in close collaboration with Airbus (and Safran)

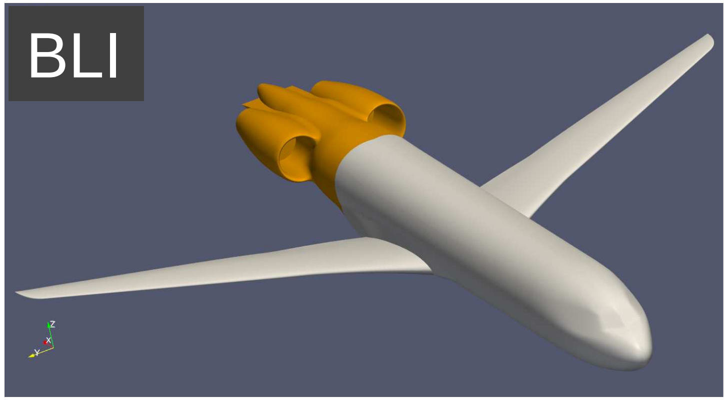
- Objectives:
  - Develop a simulation-based methodology allowing to evaluate and understand the aeropropulsive benefits of BLI
  - Validate this methodology through wind-tunnel experiments

- Questions to be answered:



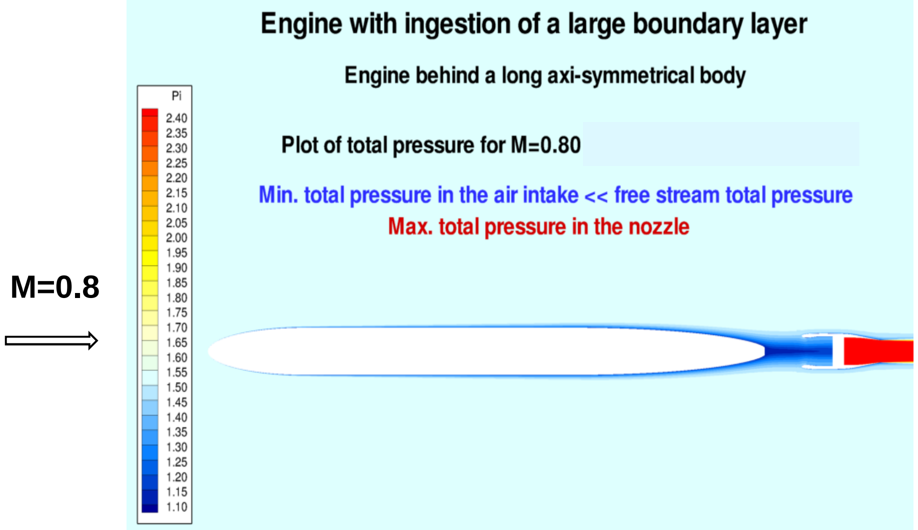
Benefits ?

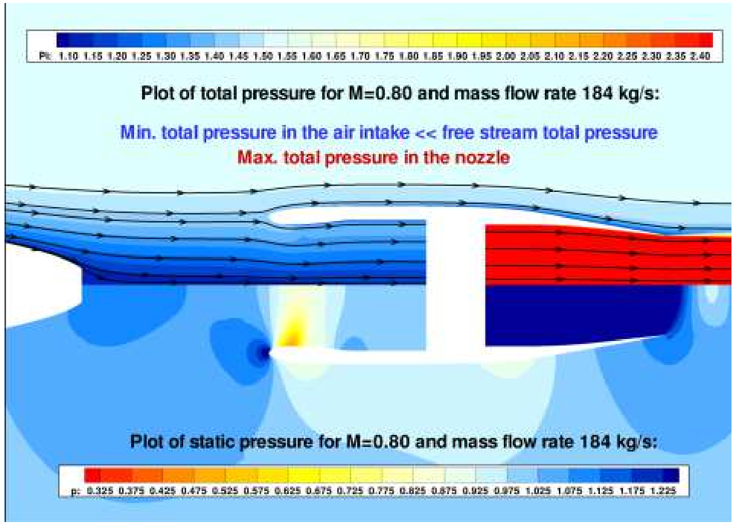
How, where do we gain?



From first numerical studies to the definition of an experimental WT tests (1/3)

- First concept of a simplified, axisymmetrical, 2-bodies, BLI configuration
- Numerical investigations using RANS calculations with elsA software (@M=0.8):
    - Engine modeled by boundary conditions (specified mass flow and specified Ti/Pi)





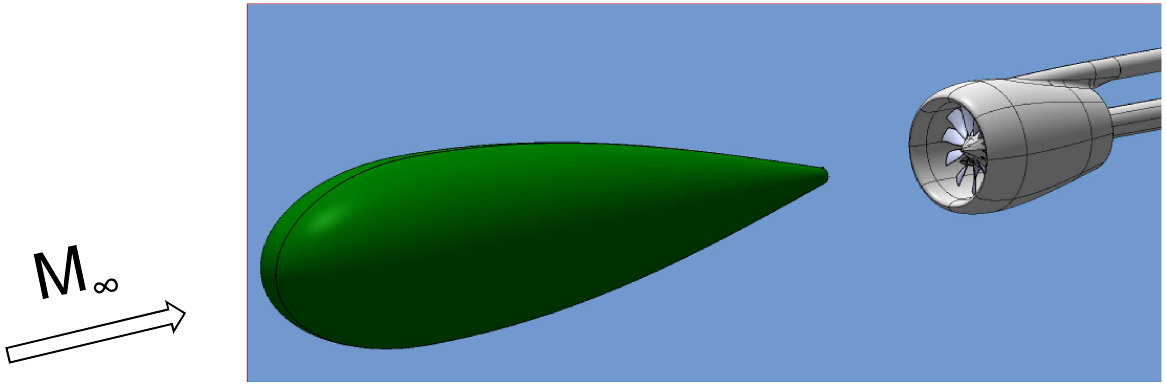
- Outcomes:
    - Benefits of BLI confirmed
    - Methodological challenges identified:
        - To model the engine in the simulation (and its interaction with the BL)
        - To analyse, in a meaningful way, the numerical results and evaluate the BLI interests

From first numerical studies to the definition of an experimental WT tests (2/3)

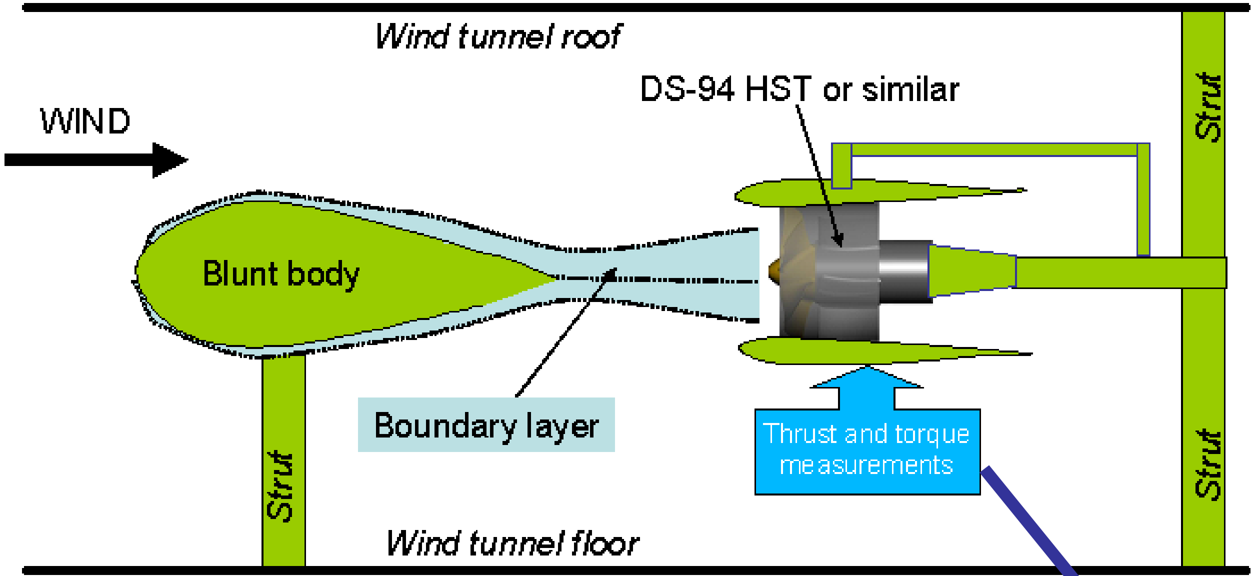
- Several approaches have been proposed and investigated for the evaluation of BLI efficiency:
  - Modified Froude efficiency: $\eta_{Froude\ \ \mathrm{mod}ified} = \frac{Pu}{\Delta Ecw} = \frac{Thrust.V_0}{\Delta Ecw} = \frac{2V_0}{Vj + Vw}$
  - Enthalpy based efficiency: $\eta = \frac{Pu}{\Delta Hi} = \frac{Thrust.V_0}{\Delta Hi}$

➡ Need for accurate and detailed experimental data to validate numerical methods for BLI efficiency evaluation

- Proposed WT test concept:

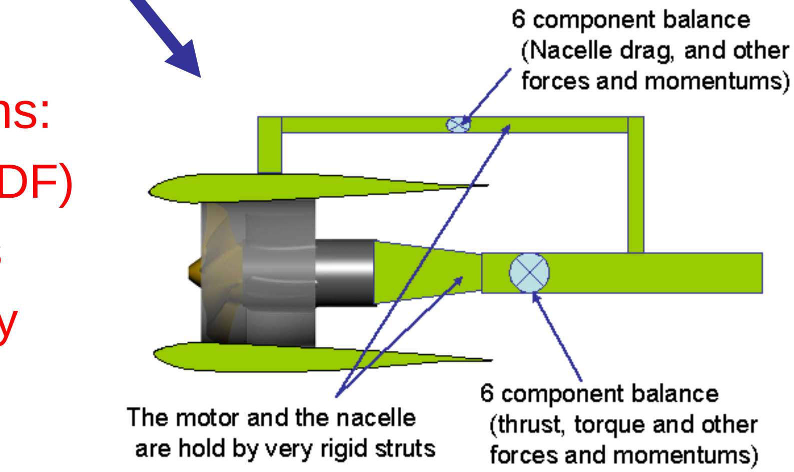


From first numerical studies to the definition of an experimental WT tests (3/3)



ONERA test-rig concept for BLI investigations:

- Electric powered nacelle (using Schübeler® EDF)
- Forces/torques measured on the three bodies
- Engine power measur. ➔ propulsive efficiency



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Experimental BLI investigation in ONERA-L1 WT (1/4)

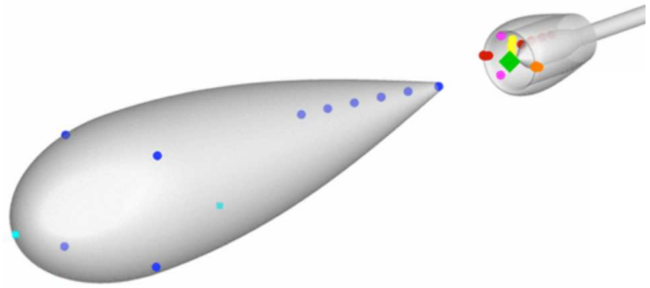
- Objectives of the RAPRO2 L1-WT tests:
  - to acquire accurate and detailed aerodynamic data for validation of CFD-based BLI evaluation methodology
  - to confirm BLI concept potential (Mach 0.2)

RAPRO2 test in ONERA L1 WT (Mach 0.2)

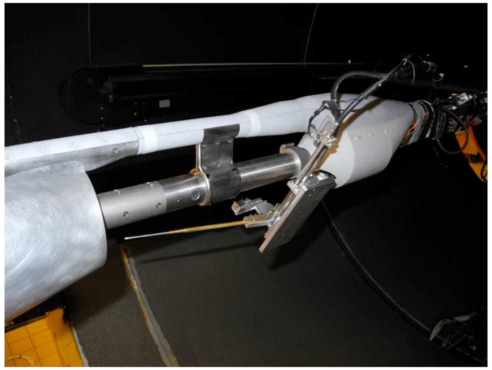
Electric powered nacelle (Schübeler EDF)

Experimental BLI investigation in ONERA-L1 WT (2/4)

- Measurements:
  - Pressures (static) on fuselage(s) and nacelle



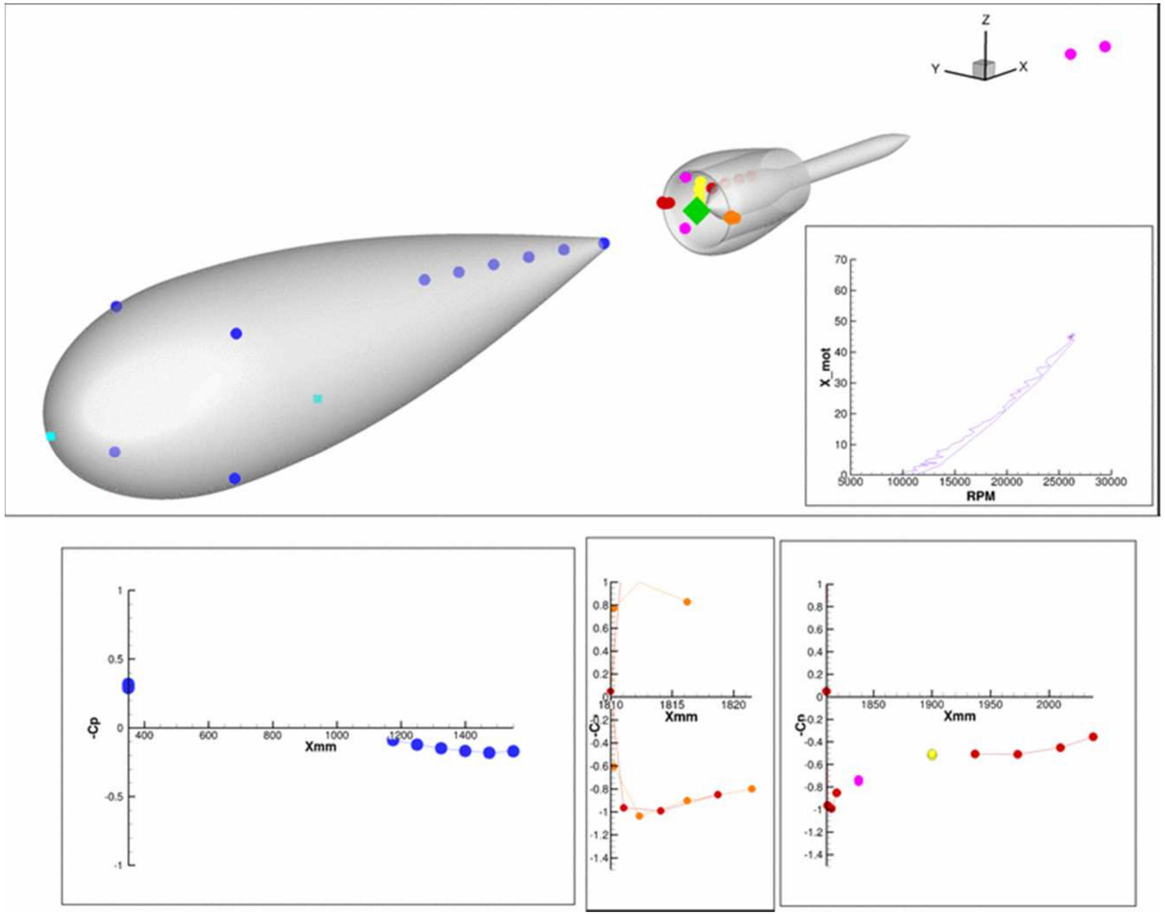
  - Separate force/torque measurements on fuselage/nacelle/engine
  - Electrical power to the engine, RPM
  - Wake survey behind fuselage(s) and the nacelle (5-hole probe)



- Investigated BLI parameters:
  - Two fuselages: 1 m and 1.5 m long
  - With/wo stator vanes in the nacelle
  - Different positions of the nacelle behind the fuselages (ΔX, ΔR)
  - Engine power/thrust
  - Freestream Mach number (0.1 to 0.2)

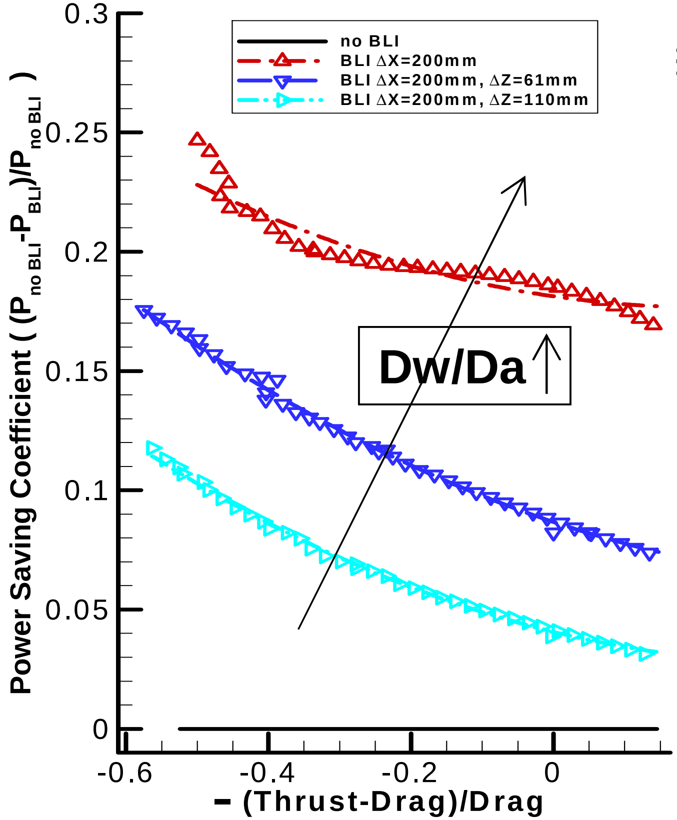
Experimental BLI investigation in ONERA-L1 WT (3/4)

Detailed aerodynamic data measurements for CFD validation :

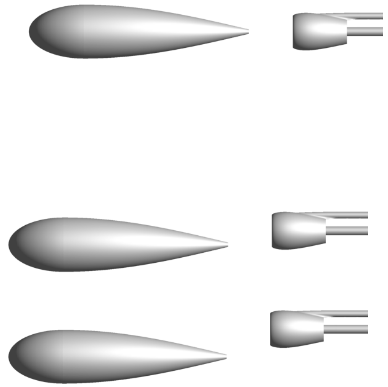


Static pressure measurements on fuselage and nacelle

Analysis of the BLI efficiency: PSC as a function of thrust excess



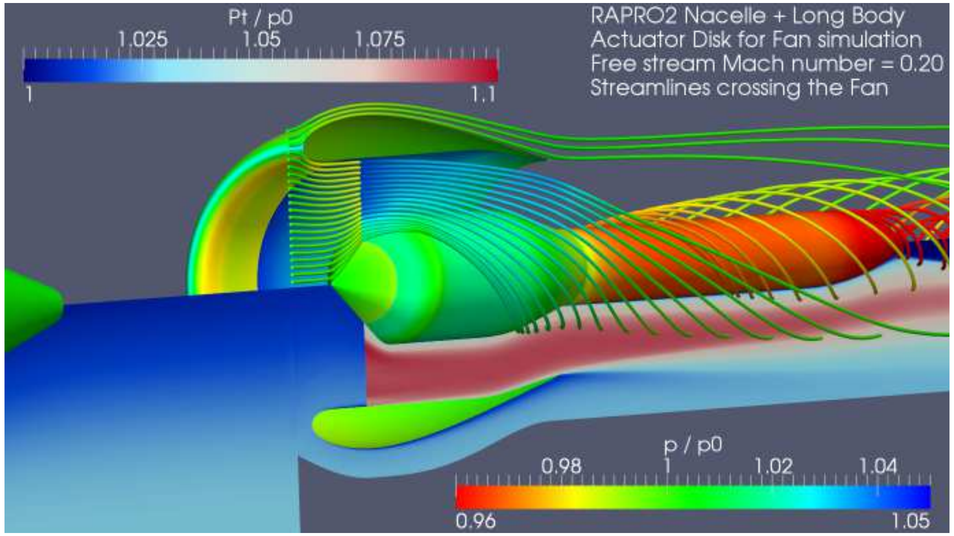
ve efficiency improvement
s confirmed
y @ M 0.2 : ~ 20% (D_W/D_A =1)



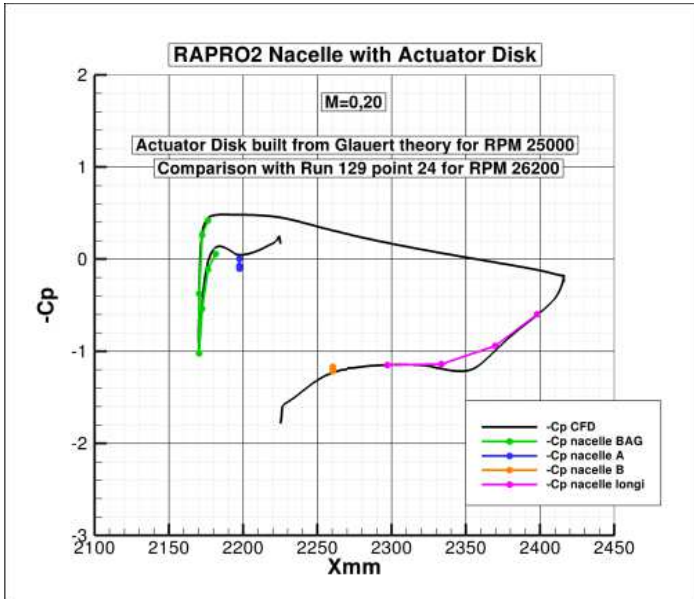
Validation of numerical methods for BLI investigations (1/2)

Modeling of the engine fan by an Actuator Disk boundary condition:

- Actuator Disk data based on the real fan geometry

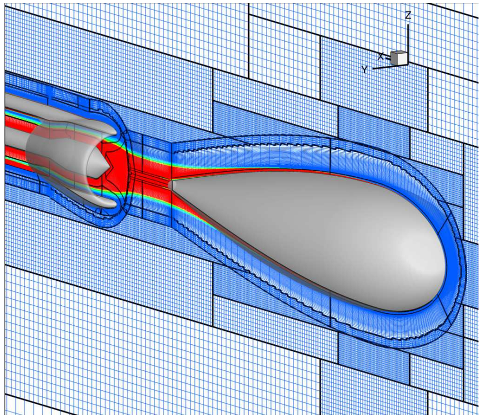


elsA CFD calculation with AD model

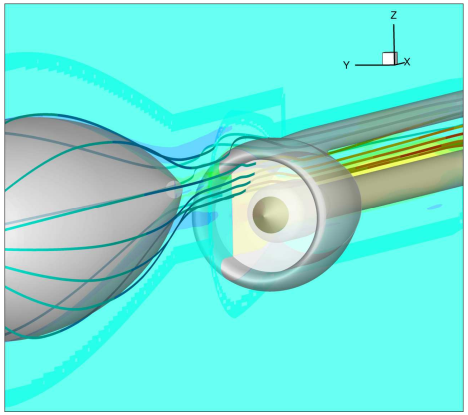


Comparison of the numerical and expe. nacelle pressure distributions

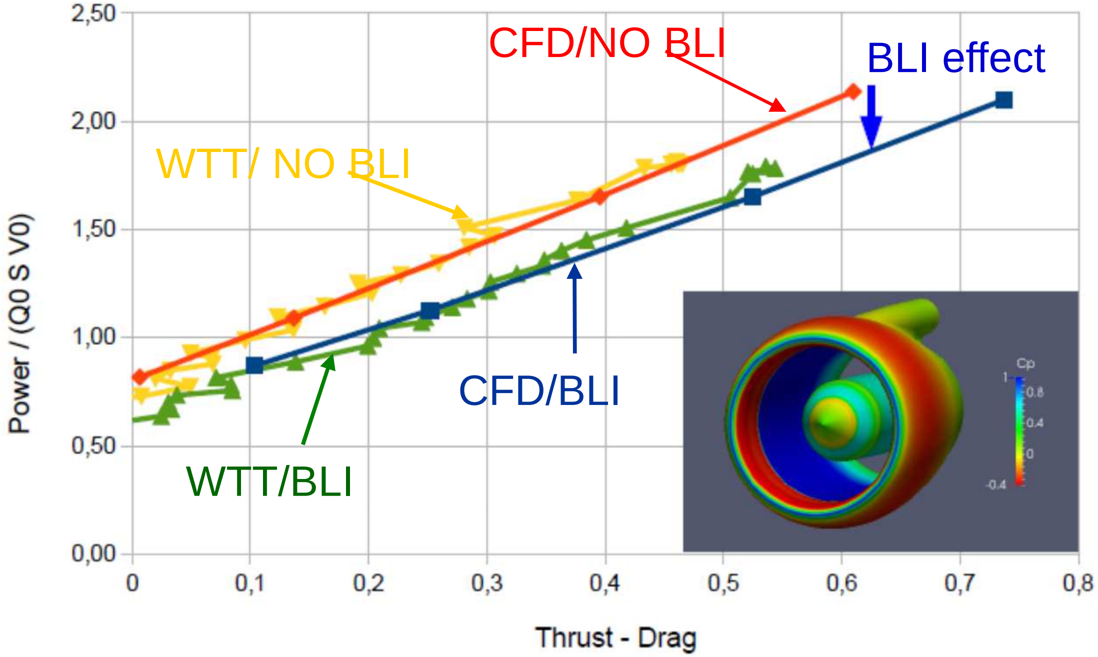
Validation of numerical methods for BLI investigations (2/2)



Use of overset and Cartesian grids techniques (elsA)



CFD simulation of the powered nacelle using Actuator Disk (elsA)



- 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

DisPURSAL

Distributed Propulsion and Ultra-high By-pass Rotor Study at Aircraft Level (DisPURSAL)

Objective:

Explore the efficiency potentials of distributed propulsion and propulsive fuselage concepts, associated to boundary layer ingestion by the engine (BLI), for transport aircraft through multi-disciplinary analysis and global assessment at aircraft level

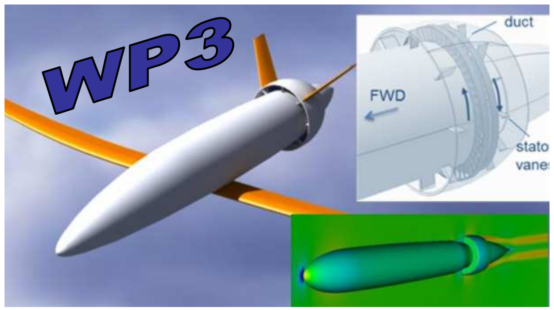
Partners:* *Bauhaus Lufthart, CIAM, Airbus Innovation, ONERA

Planning:* *24 months (February 2013 to January 2015)

Effort:* *68 Man-Months

Example of concepts:

Blended wing body with distributed propulsion (NASA)

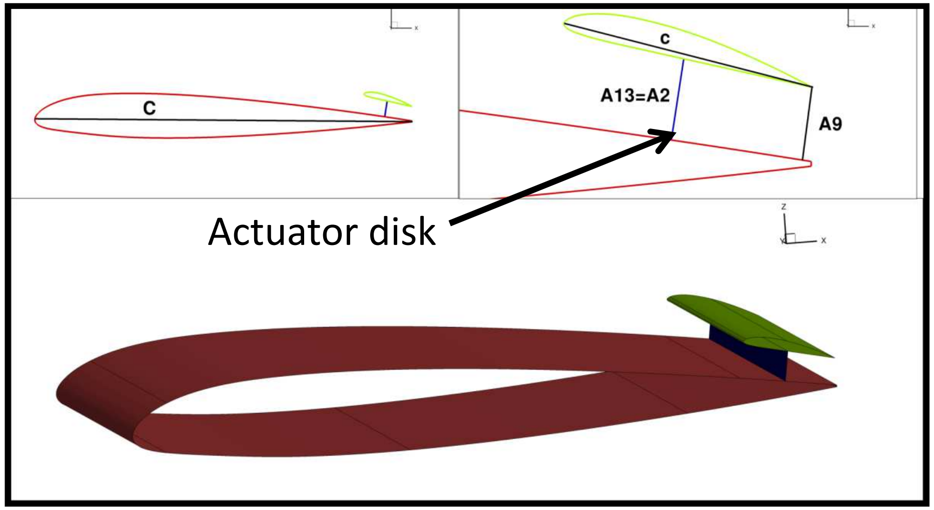


Propulsive fuselage (BHL)

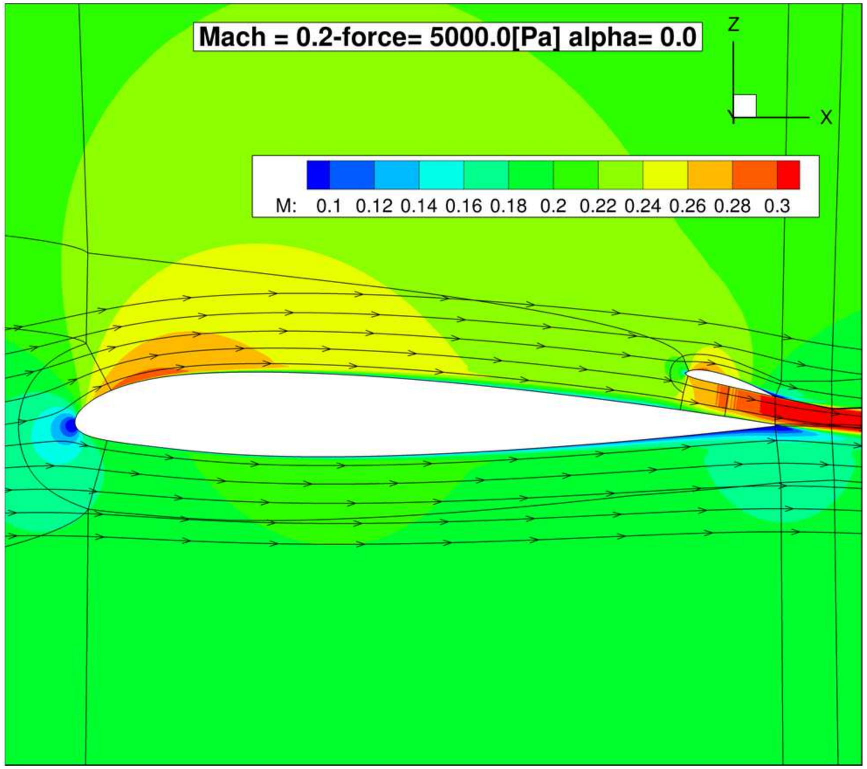
Objective: evaluate the influence of distributed propulsion on the aerodynamic performance

Definition of a 2D model

- Computations of a wing and an integrated nacelle
- Influence of engine speed on CL^{max}
- Geometrical driving parameters:
  - Engine diameter
  - Engine position

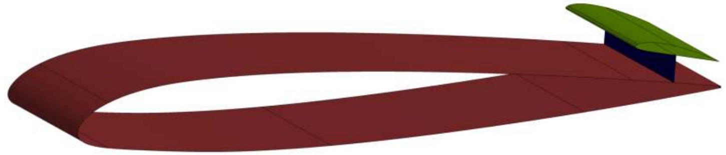


Results



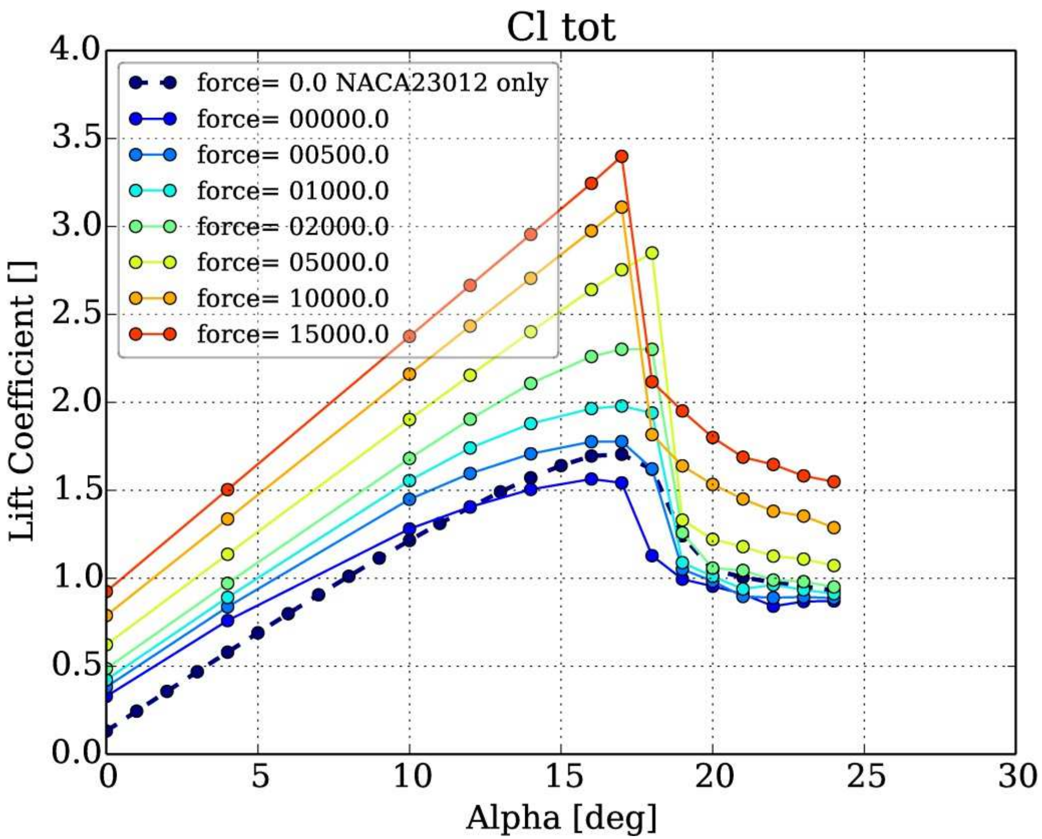
- Stall starts at leading edge
- In post-stall engine does not work properly

WP2 : Distributed propulsion



Aerodynamic performance

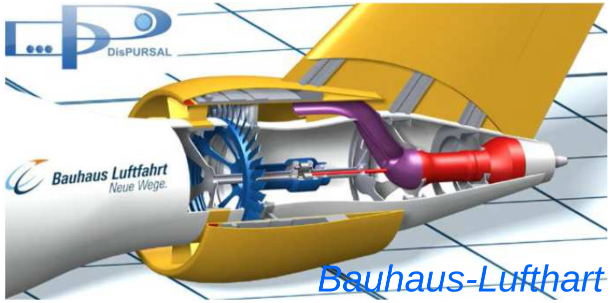
Influence on lift coefficient



Results

- $CL^{max} = 2\ CL^{ref}$
- CL_0 increases
- Stall occurs approximately at the same angle of attack
- Slight loss of performance in CL^{max} without thrust

WP3: Propulsive fuselage



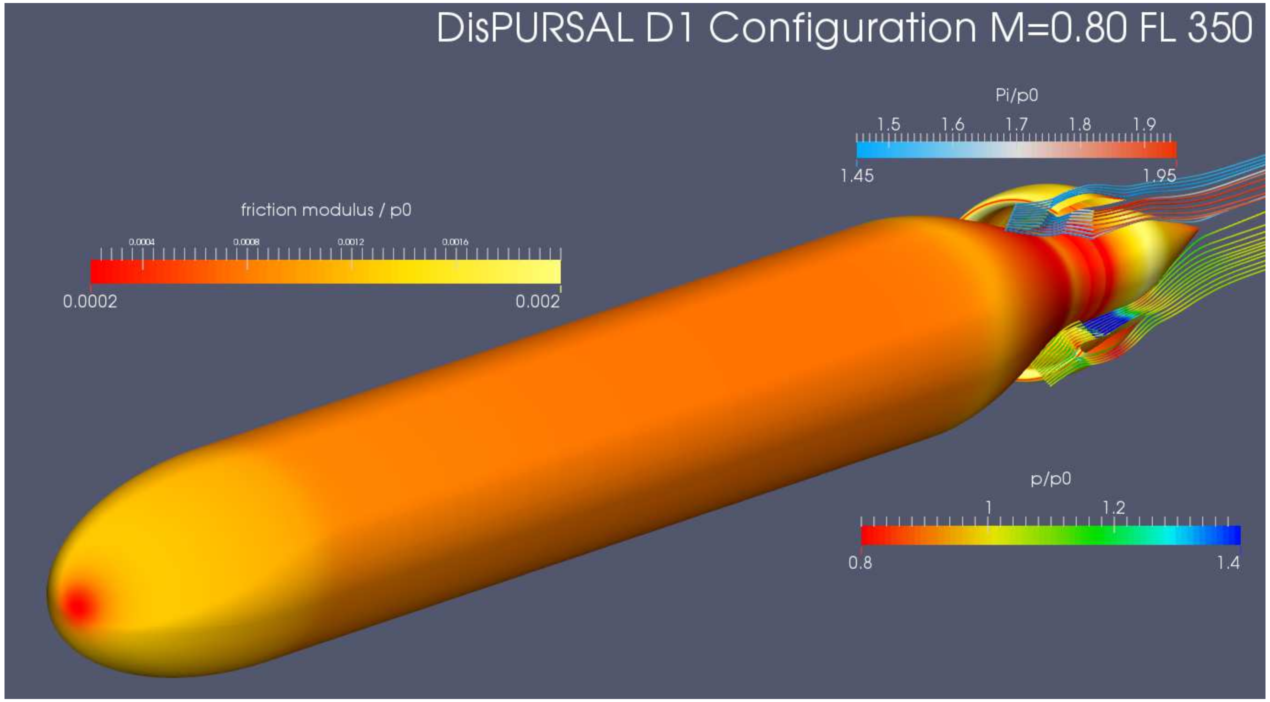
Purpose

Evaluate the power saving of a configuration ingesting the overall fuselage boundary layer

Characteristics

Configuration equipped with circumferential fan

Numerical assessment performed using AD to model the fan



WP3: Propulsive fuselage

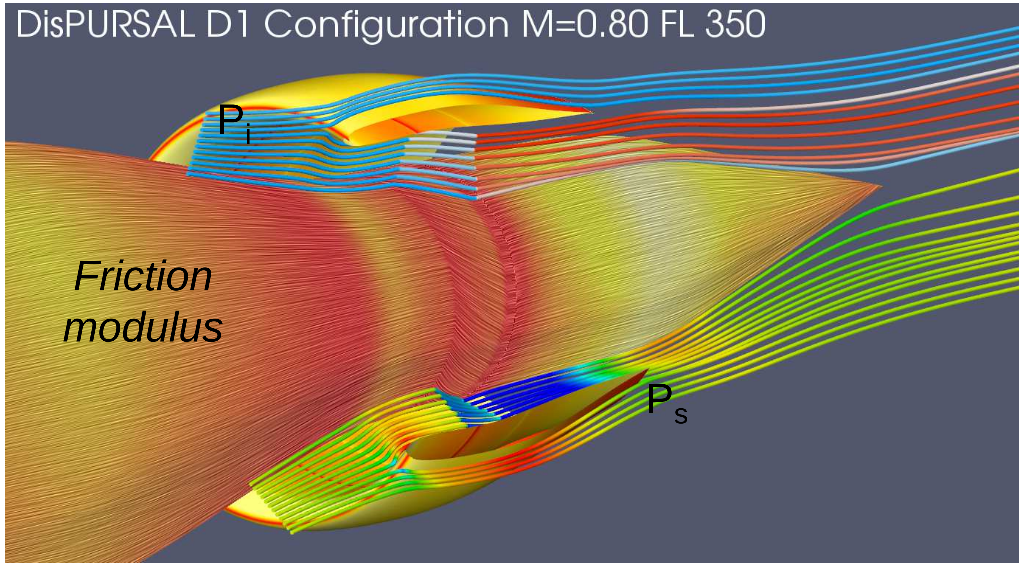
Analysis of the internal flow

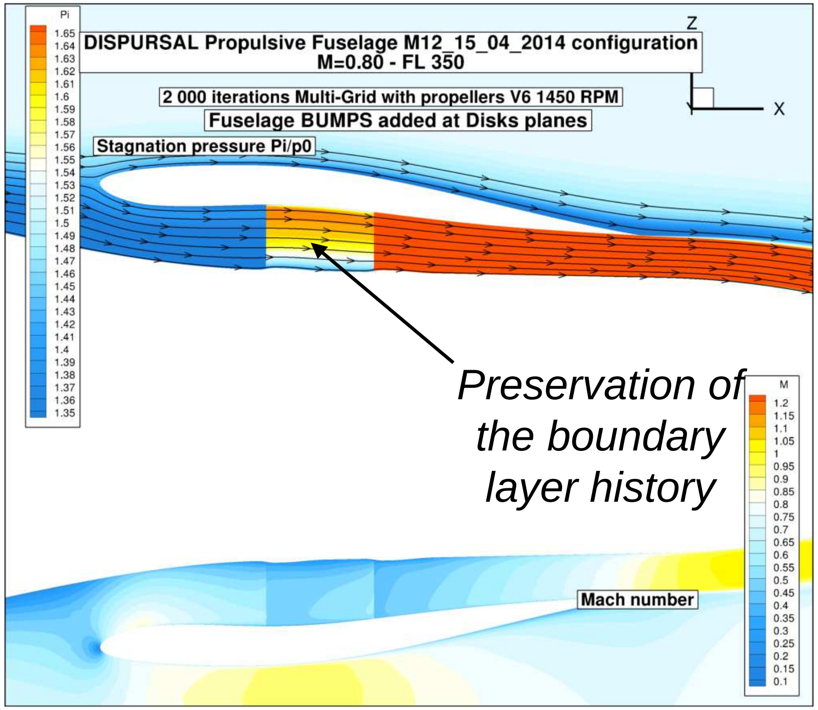
BLI correctly modeled by AD:

- Visible deviation of friction lines through the fan

- Boundary correctly re-energized by AD

Overall power saving observed and estimated numerically with AD

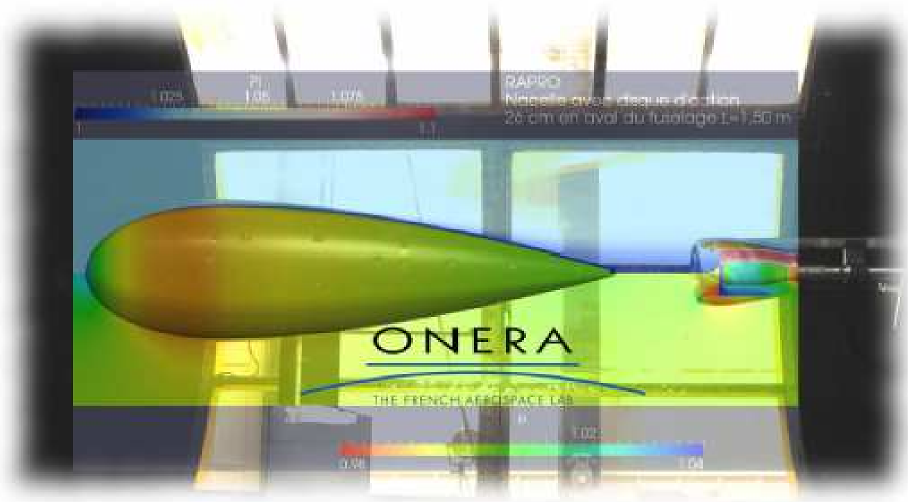




Conclusions

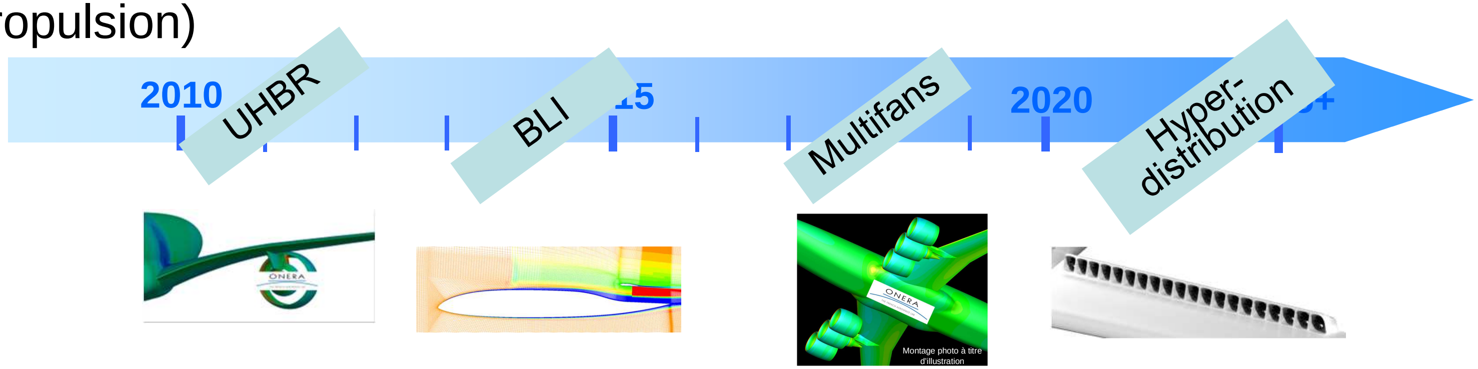
- Experimental low-speed confirmation of the aero-propulsive efficiency benefits of BLI in RAPRO-2 project
  - Intensive use of numerical simulation to define/prepare the WT tests
  - Application of innovative WT test techniques: electrical powered nacelle
  - High quality/rich experimental database
- Numerical methodologies have been proposed and validated to assess the benefits of BLI
- Numerical evaluation of the distributed propulsion benefits in terms of CL^{max}

Numerical restitution of the RAPRO2 wind tunnel test (L1- Lille)



Perspectives

- *BLI concept:*
  - Experimental transonic BLI validation with coupled inlet and fan models
  - Design of fan robust to distortion
- *Distributed propulsion concept:*
  - Experimental validation of low-speed benefits
  - Definition of new control system taking advantage of distributed propulsion
  - Hybridation of power sources
- *BLI together with distributed propulsion*
  - Design of innovative engine integration concepts (BLI, multi-fans, distributed propulsion)



  - Design of radical new aircraft configurations benefiting from both concepts (Strut-braced, box-wing, blended wing body)


Thanks for your attention.
Any question?
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