RESHAPING THE FUTURE OF AIRCRAFT DESIGN

- Emiliano Costa
  Industrial design & CAE
  D’Appolonia SpA

RBF4AERO

D'APPOLONIA
consulting, design, operation & maintenance engineering

Outline

- RBF4AERO Overview
- Project contents
- Test cases results
- Conclusions

Project Overview

- The **RBF4AERO** project aims at developing the RBF4AERO **Benchmark Technology**, an integrated numerical platform and methodology to efficiently face the most demanding challenges of aircrafts design and optimization
- Project finished on 31st August 2016 after **3 years** (**FP7-AAT**)
- Total EC Funding of ≈ 2.4 M€ (global costs **≈ 3.5 M€**)

- The Consortium is composed by **9 partners from 5 countries** (Italy, Belgium, Greece, Slovenia and Turkey), of which 6 Industrial partners, 1 Research Establishments and 2 Universities
- **D'Appolonia SpA** is the **project coordinator**

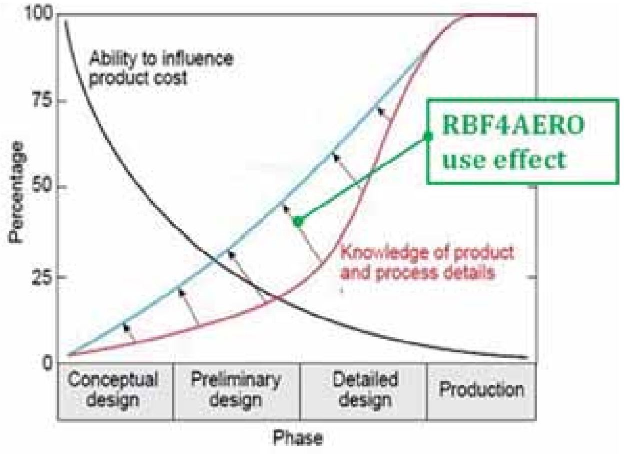
Project Overview

The numerical platform allows to carry out:

- multi-objective and multi-disciplinary optimization (MOO/MDO) using **EA** (evolutionary algorithms) with DoE sampling + metamodel;
- CFD optimization through **adjoint-morphing coupling**;
- **icing** simulation (constrained and on-the-fly);
- **FSI** (in EA-Opt two-way and mode-superposition).

The main purposes of the Project are:

- to reduce (**up to 80%** for specific applications) the aerodynamic design process duration;
- to make feasible some applications (e.g. FSI) even with high-fidelity models.

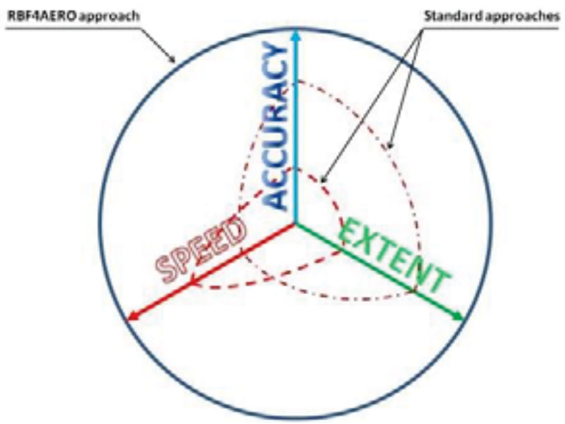


Project Overview

The tools and methodologies developed and used in RBF4AERO release the user from the compromise between the contrasting targets of **speed** (time required to complete computing), **accuracy** (high-fidelity numerical models) and **extent** (different configurations tested).

The basic idea is to make the **numerical model parametric** through the use of a shape optimization environment based on a **morphing technique** founded on radial basis functions (**RBF**) mathematical framework.

The whole project is based on the **integration** of pre-existing numerical tools developed by consortium partners.



RBF4AERO approach vs CAD-based approaches

Project Overview

RBF are a class of mathematical **interpolation functions**. In computer-aided engineering (**CAE**) applications, such functions can be used to drive morphing (smoothing) of computational mesh nodes applying predefined displacements to **source points**.

From mathematical point of view, the RBF fit is defined once the coefficients γi and βi are determined.

$$
\begin{cases}
s_x(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi\left(\left\|\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right\|\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\
s_y(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi\left(\left\|\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right\|\right) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\
s_z(\boldsymbol{x}) = \sum_{i=1}^{N} \gamma_i^z \varphi\left(\left\|\boldsymbol{x} - \boldsymbol{x}_{\boldsymbol{k}_i}\right\|\right) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z\,.
\end{cases}
$$

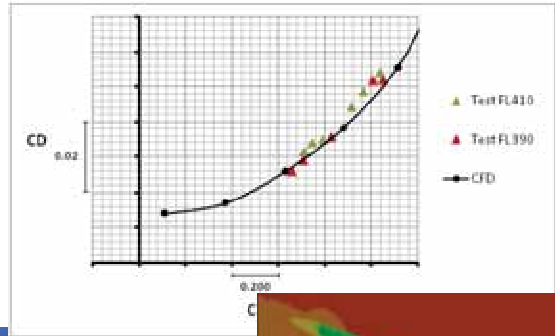
Project contents

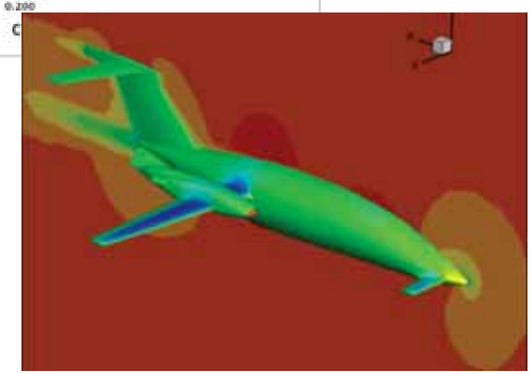
- RBF4AERO platform testing/validation/verification:
  - **Numericla testing**: 18 test cases ranging from NACA airfoil to real aircraft were studied and optimised through the developed numerical platform
  - **Numerical validation**: aero-elastic numerical procedures for static FSI were validated
  - **Experimental verification**: 3 specific numerical test cases (low-pressure turbine (**LPT**), turbine internal cooling and contra-rotating open rotors) were also verified by experiments

Winglet optimization

The aircraft selected to perform optimization activities: **Piaggio P180 Avanti EVO**, the fastest flying twin turboprop characterized by a very low fuel consumption.

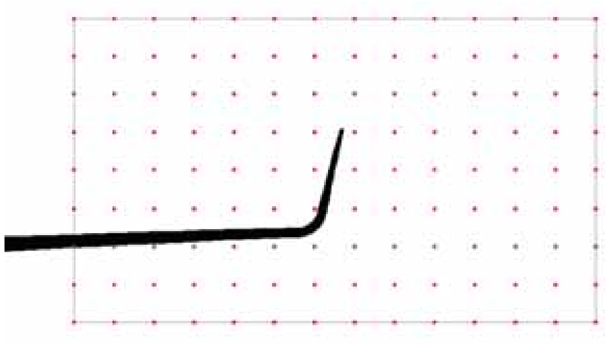
Morphing the winglet, an SOO was performed minimizing a **specific function** accounting fuel consumption.



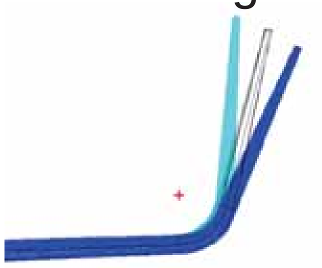


Winglet optimization

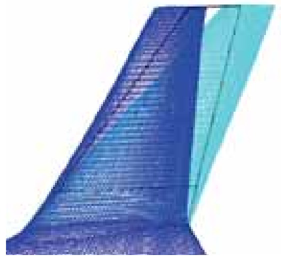
Morphing domain

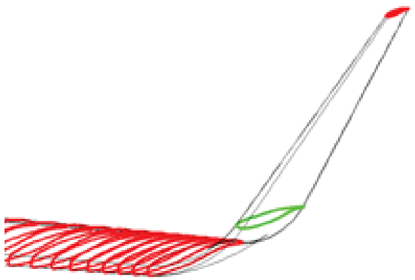


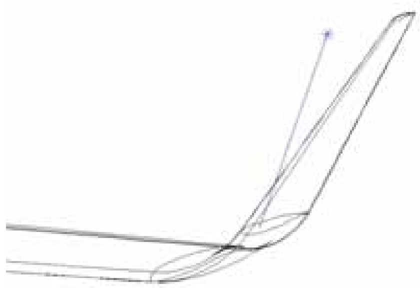
Cant angle



Sweep angle



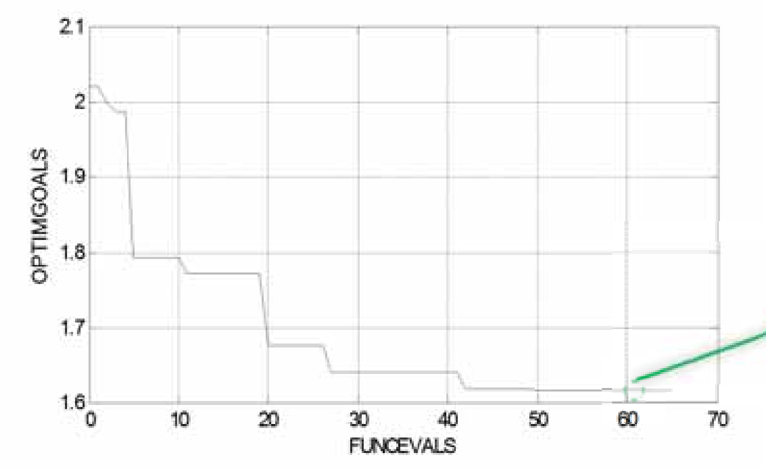




Root section angle of incidence

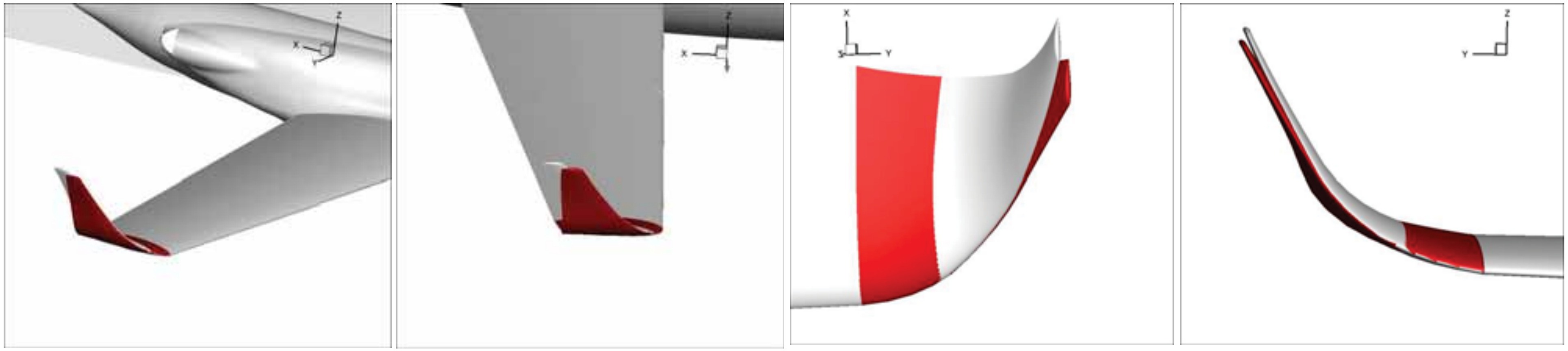
Tip section angle of incidence

Winglet optimization



Chosen design

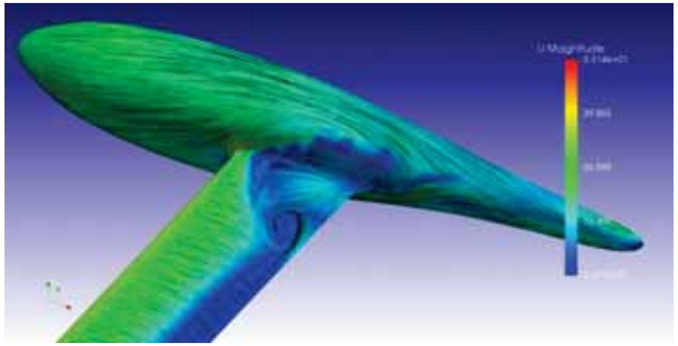
- **5 drag count reduction**
- **3% autonomy increase**
- **95% saved time** in pre-processing wrt a parametric CAD approach (hexa multi-block structured mesh)



Optimized (red) vs baseline (grey) configuration

Glider Optimization

- Solver: simpleFoam (OpenFOAM)
- Boundaries: Mach<0.1, Re=1.0 E+06, H=2000 m
- Modifications:
  - Fuselage surface modifications in a prescribed area near wing root
- Target:
  - Increase of aerodynamic efficiency (AE) by the reduction of flow separation
- Constraints:
  - Surface deformations limited to a determined area



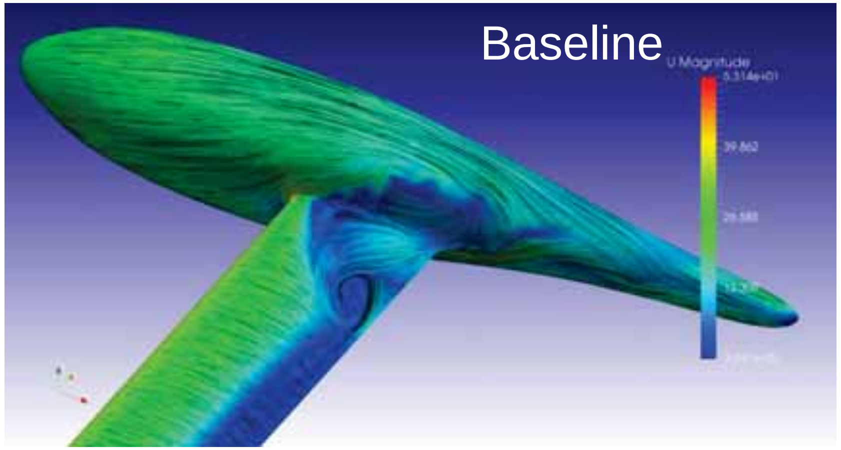
Glider Optimization

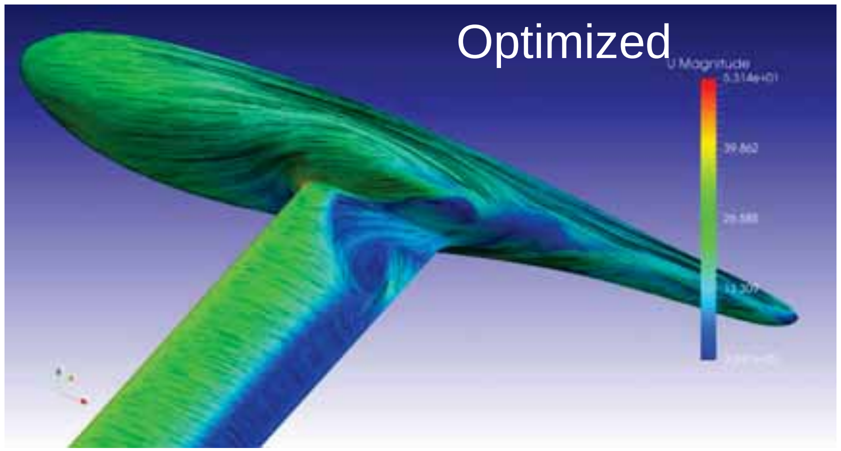
- Video of the glider EA-based optimization

glider-EA-optimization

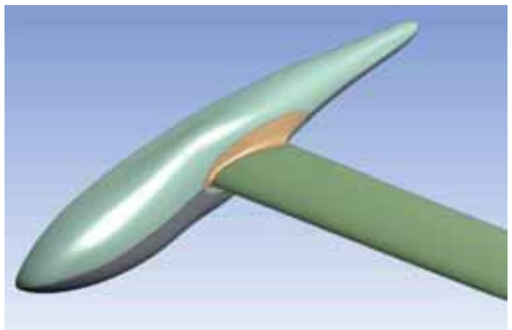
Glider Optimization

- **+19% AE** wrt the baseline configuration
- **70% time saved** in the pre-processing phase
- **66% time saved** for each design point (DP) analyzed in the solution phase
- **>90% time saved** in the post-processing phase (trial&error based on CAD)





Optimal CAD gained through the Back2CAD



FSI | validation

The HIRENASD model of the aero-elastic workshop prediction (**AeWP**) organized by NASA was selected (test #. 132 in steady state conditions) to accomplish the validation of **both FSI approaches**.

High-fidelity (extensively tested) models made available by the AeWP committee were used.

Parameter	Value	Units
Mach	0.8005	-
Reynolds	6.999999	-
Velocity	256.5	$m\ s^{-1}$
Density	1.22	$kg\ m^{-3}$
Static pressure	89289	Pa
Static temperature	246.9	K
AoA	1.5	-

FSI | validation

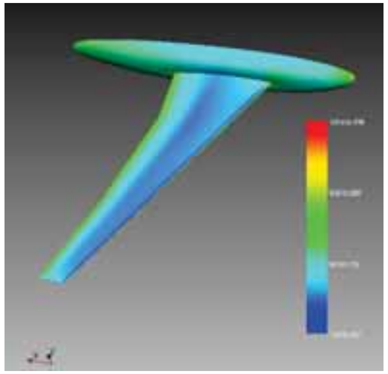
- CFD model:

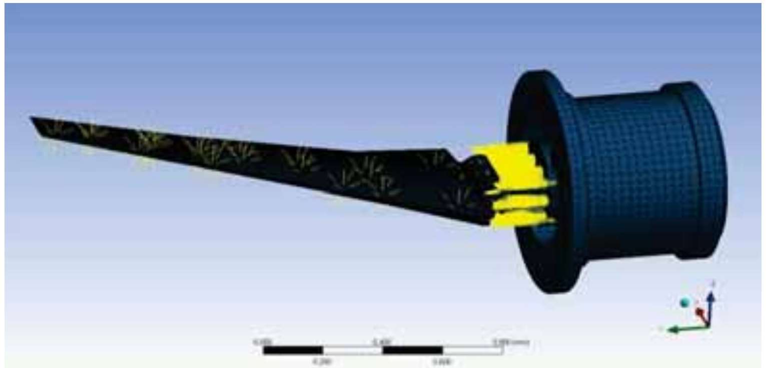
  The solvers adopted for CFD computing were **SU2** and **Fluent**. In particular, the empoyed mesh (SOLAR unstructured grid) is hybrid and has about 1.5 million of mixed cells.

- FEM model:

  The **ANSYS APDL** solver was used to calculate deformations (2W) and natural frequencies (MS) starting from the import of the FEM model in **NASTRAN** format. Such a model reproduces the wing, the balance and the wing-balance junction.

CFD Model



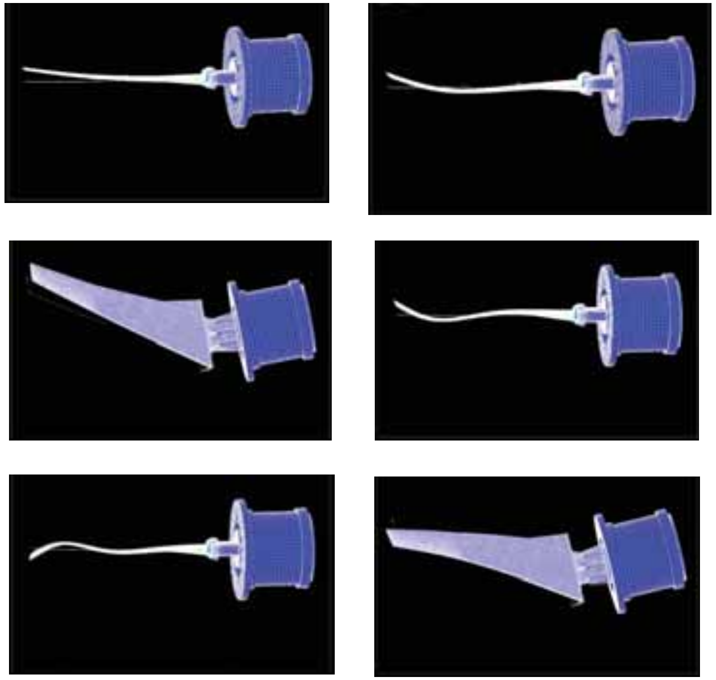


FEM Model

FSI | validation

- Mode-superposition (MS):

  Wing modes were extracted from the FEM model and used to prepare RBF shape modifications.



Wing modes (FEM)

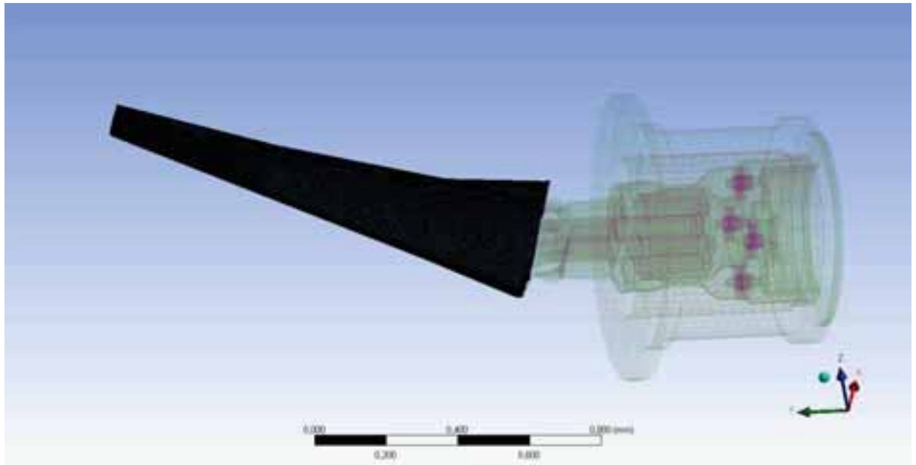
Preview of the source points before and after morphing (Mode 1)

Fixed and encap domain source points

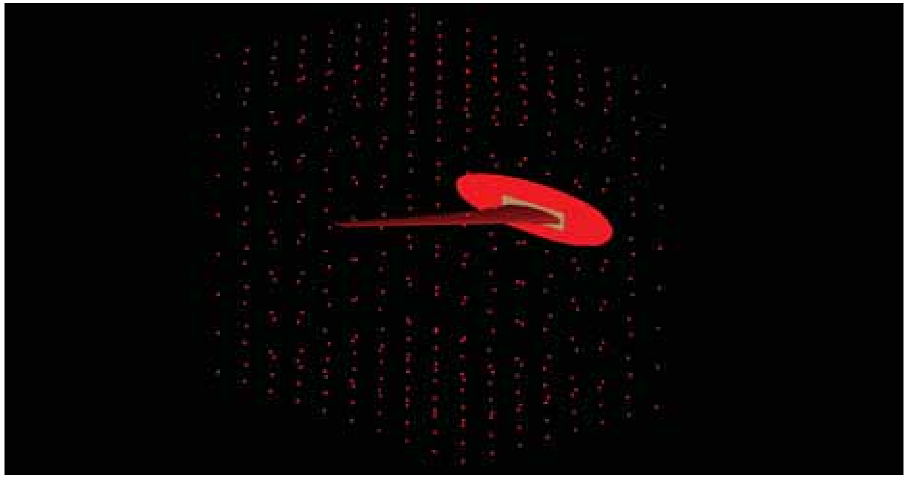
FSI | validation

- Two-way (2W):

  The FEM model was used to evaluate the deformed shape, and the RBF shape modification was accordingly set up by defining a '**fixed' RBF solution** in which the fixed surfaces of the structure, that has to be updated at each CFD iteration with displacement obtained with the FEM analysis, are defined.



Surface elements of the FEM model that host the CFD loads

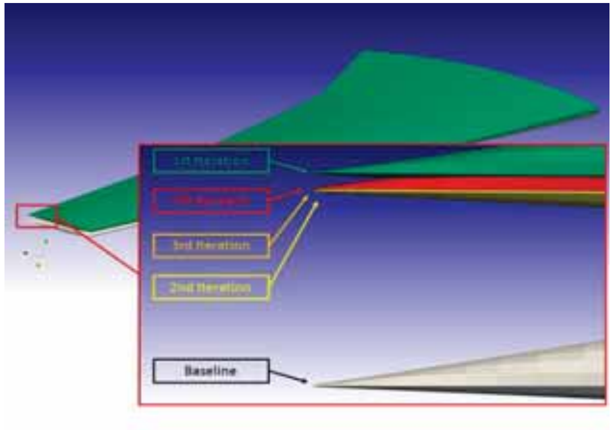


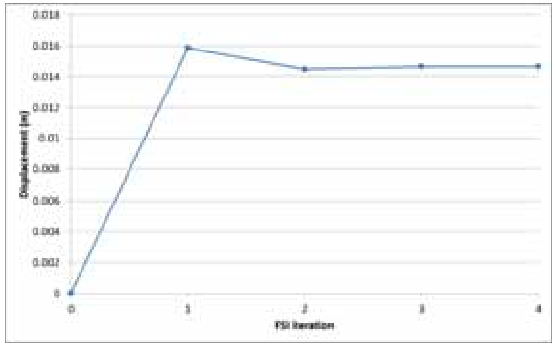
Source points of the constrained solution

FSI | validation

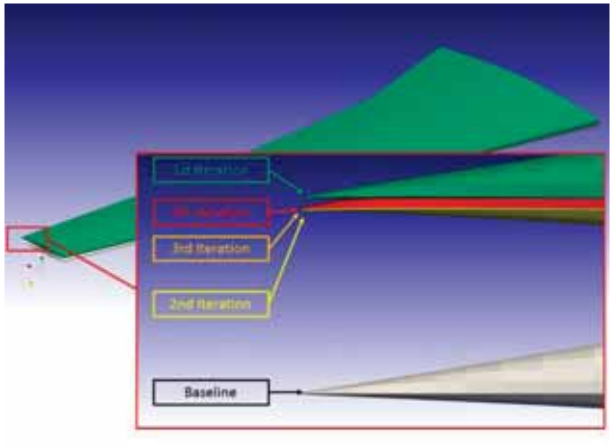
- Results:

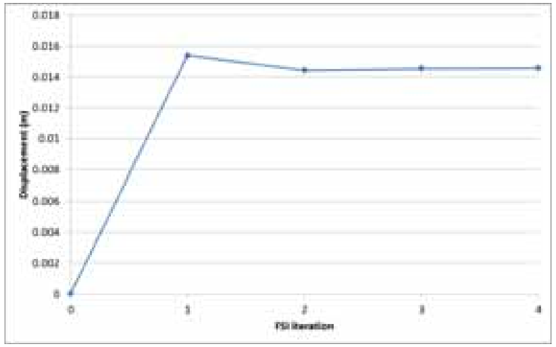
Mode-superposition





Two-way



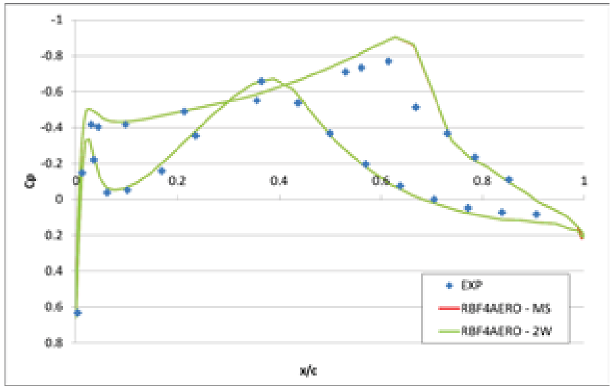


Wing displacement

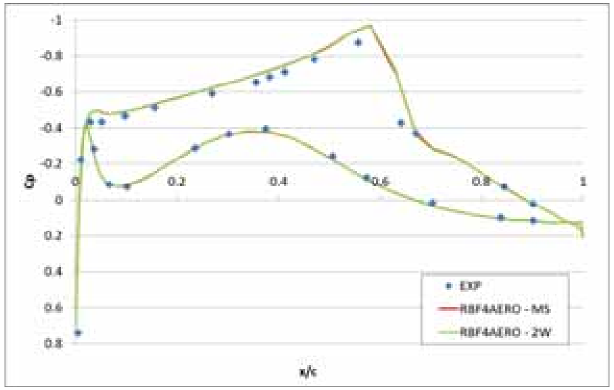
Profile of the vertical displacement of the monitoring point at FSI cycles

FSI | validation

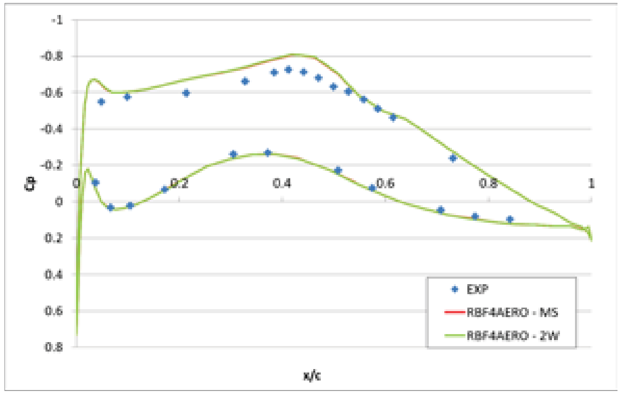
- Mode-superposition / two-way comparison:



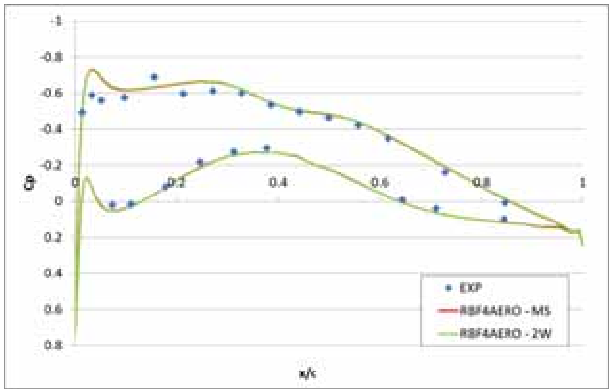
Section 1



Section 2



Section 6



Section 7

- **90% time saved** in the pre-processing phase wrt a parametric hexa-block approach
- **66% time saved** for each FSI cycle wrt a hybrid mesh approach

FSI | propeller

- WATTsUP propeller, D=1.6m
- FSI approach: mode-superposition
- FEM: **Abaqus** FEA
- CFD: **OpenFOAM**
    - MRF
    - incompressible
    - high-Re SA turbulence model
    - 1.6M cells

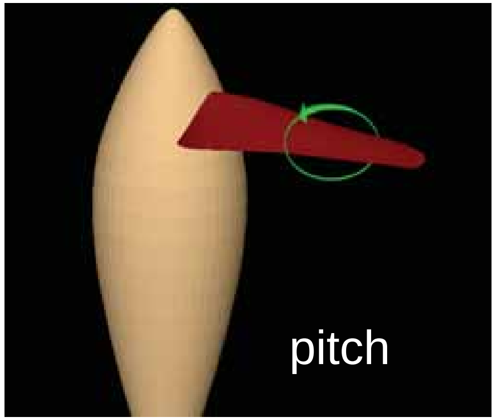
take off	cruise flight
2300RPM V_{INLET} = 30m/s ρ = 1.19kg/m^3	2550RPM V_{INLET} = 51.4m/s ρ = 1.11kg/m^3

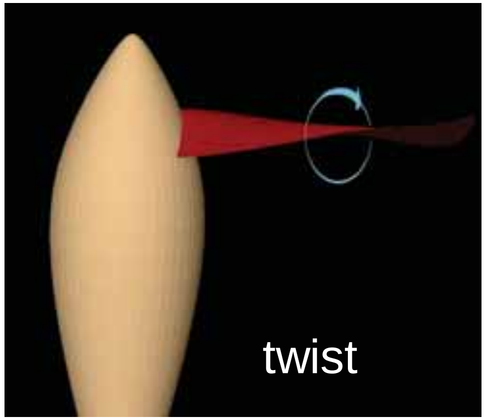
- EA-based optimization

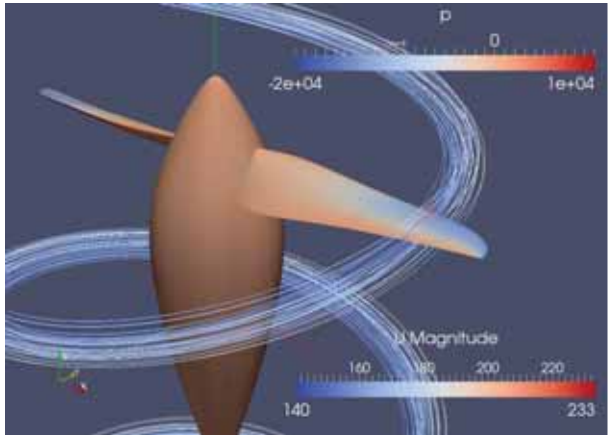
FSI | propeller

- EA-based + FSI (rbf4aeroFSI solver)
- 5 modes were accounted in MS
- shape modification: **pitch** and **twist**
- Propeller **efficiency** ν (thrust, velocity and power) **maximization** in cruise and take-off conditions (MOO)

$$\nu = \frac{TV}{P} \qquad F(t,p) = \frac{1}{2}\nu_{CRUISE} + \frac{1}{2}\nu_{TAKE-OFF}$$

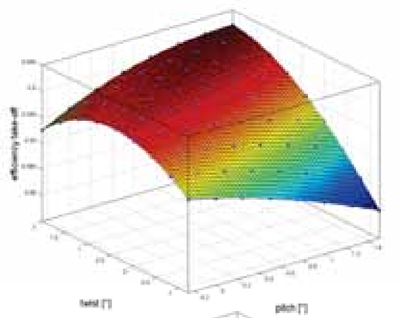




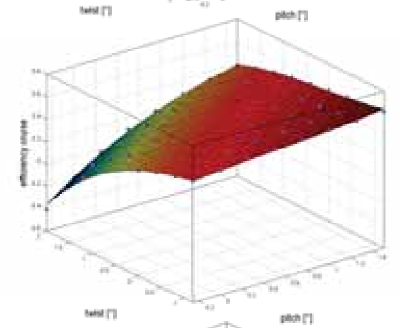


FSI | propeller

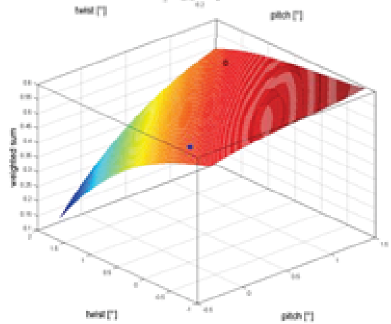
- EA-based + FSI



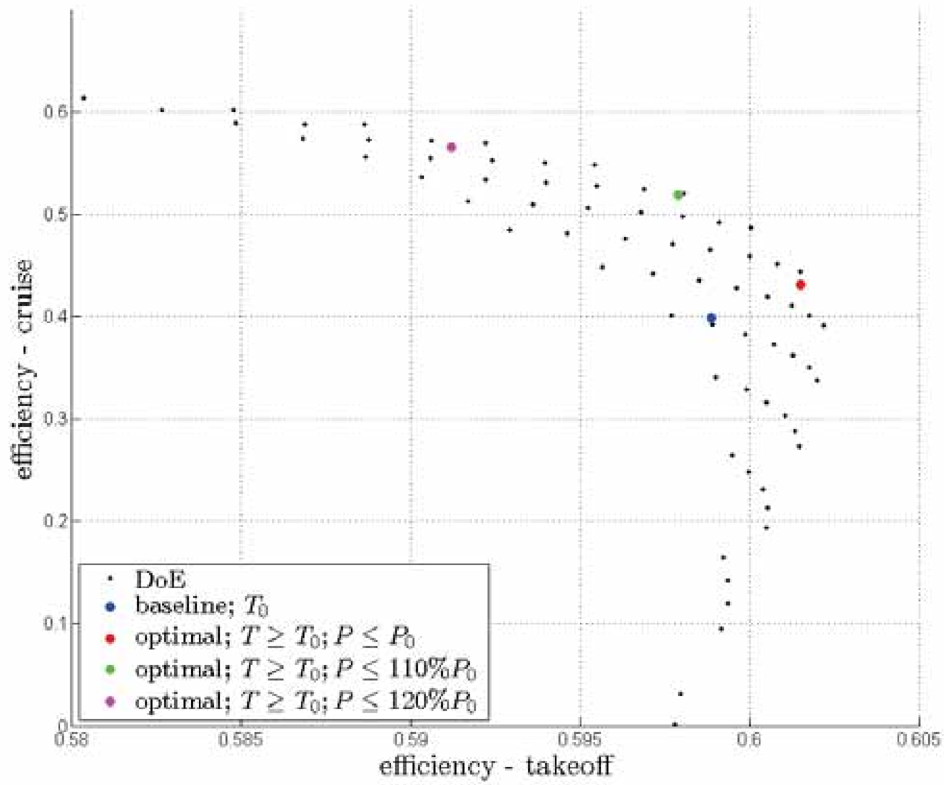
Take-off condition



Cruise condition



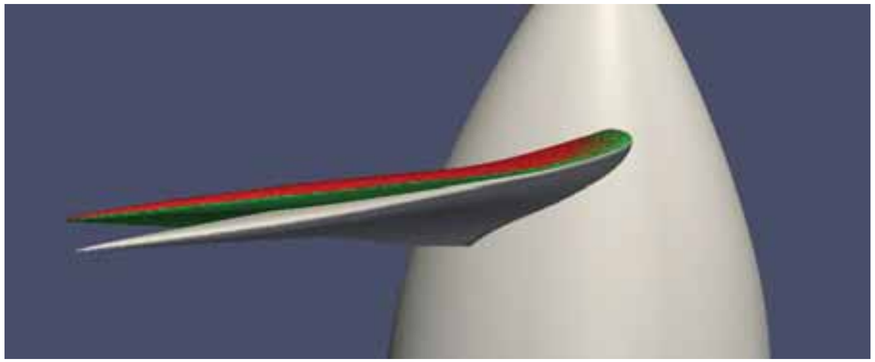
Surrogated model



DoE points with the baseline and optimal configurations on the Pareto front plot

FSI | propeller

- A procedure to include in the EA-based optimization **the effects of elasticity** of structures was successfully applied to an industrial test case (**2-3% efficiency increase**)
- The **RBF4AERO** approach required more time during the pre-processing phase (25% more) but allowed a substantial reduction of time needed to complete the solution phase (**80% less**) because manual geometry modification and remeshing the CFD model were avoided. Since many DPs were accounted, and then the large time was saved, the increase of the pre-processing time can be neglected

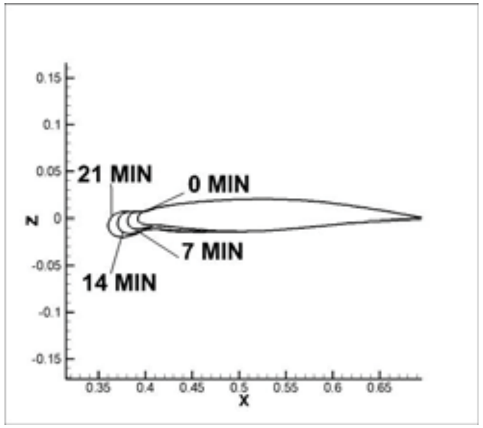


Optimized geometry:
Grey – baseline
Green – first FSI cycle
Red – fifth FSI cycle

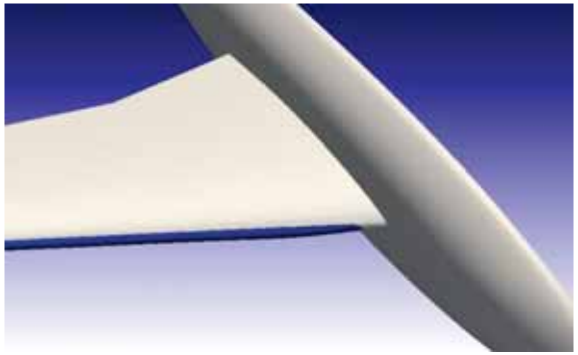
Icing | constrained

- Model: HIRENASD
- Mach = 0.5
- Re = $11.5 \cdot 10^6$
- Altitude = 4650 ft (1427.32 m)
- Solver = SU2

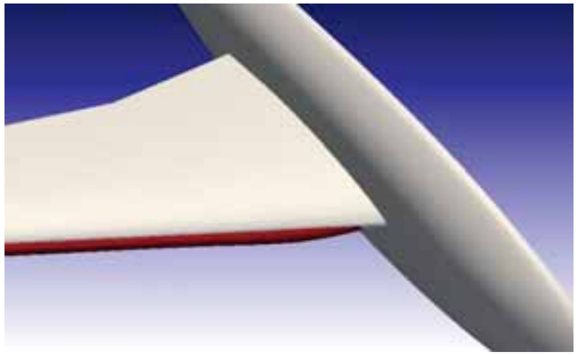
Generic wing section ice accretion profiles



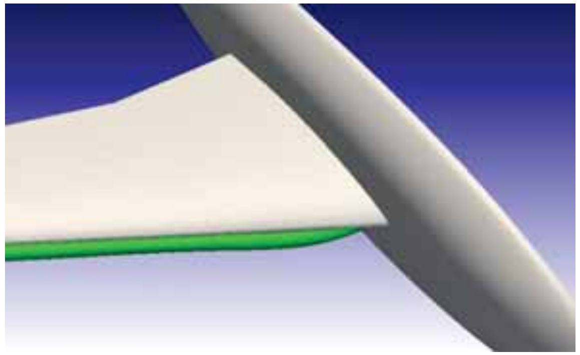
Accreted surfaces were generated using 2d icing profiles evaluated at specific wing sections through an in-house developed icing accretion model.



Ice surface at 7 min



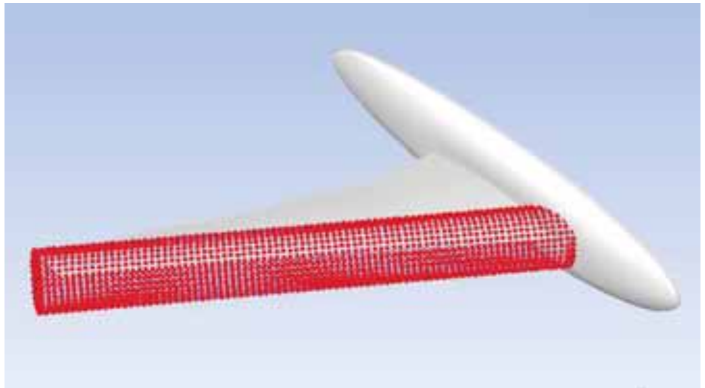
Ice surface at 14 min

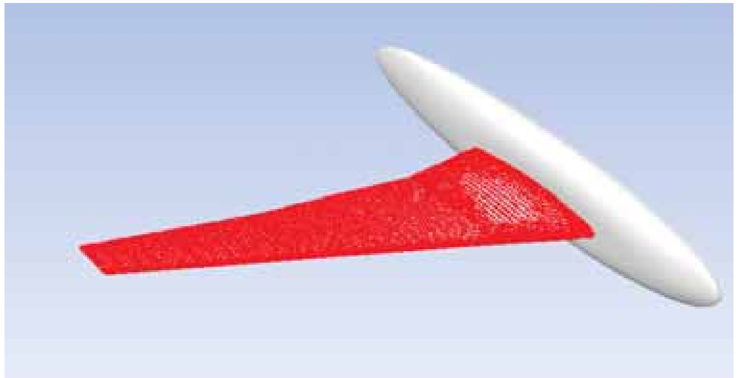


Ice surface at 21 min

Icing | constrained

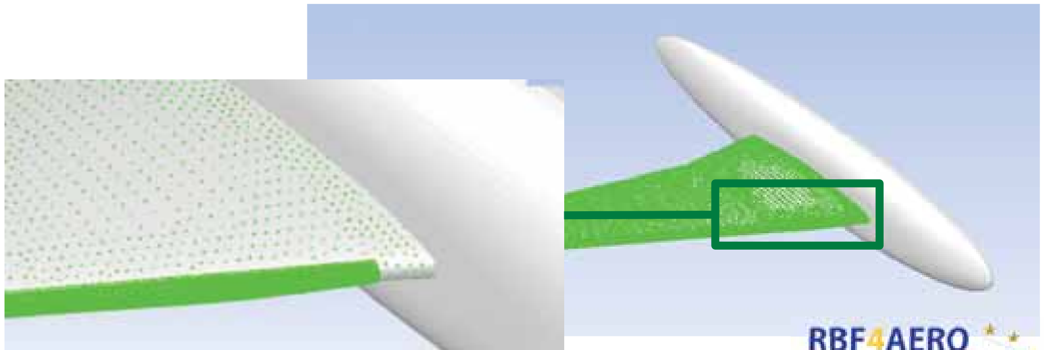
To generate the RBF solutions, the source points extracted from surface mesh were used to impose nodes displacements obtained through accreted surfaces. Domain encap to delimit the morphing action in the computational domain was set (two-step procedure of the MT).





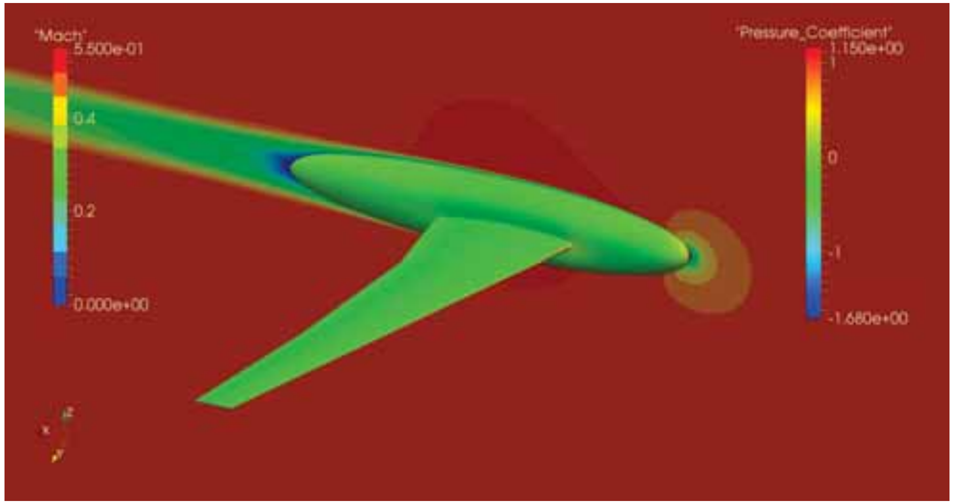
Source nodes on Domain encap

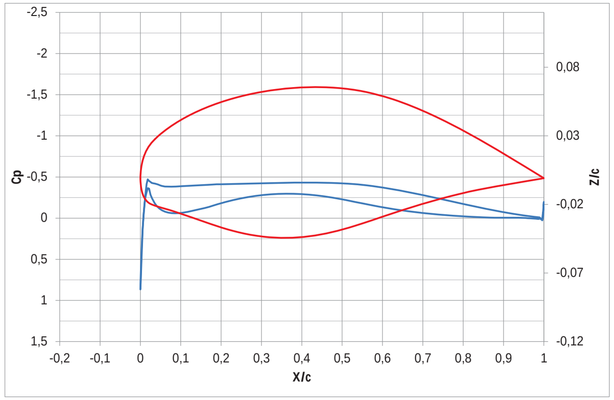
Source nodes position after morphing (7 min)



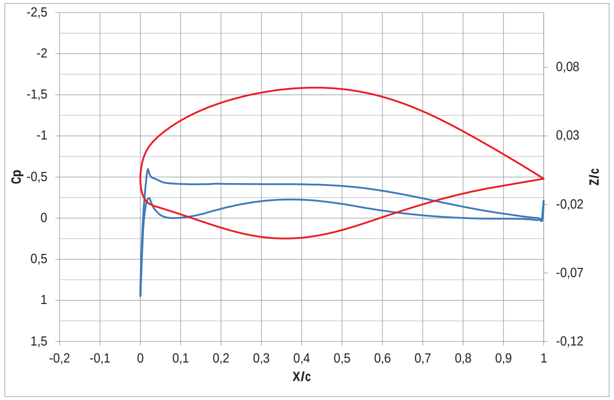
Icing | constrained

Cp profiles at different wing sections without ice accretion (baseline)

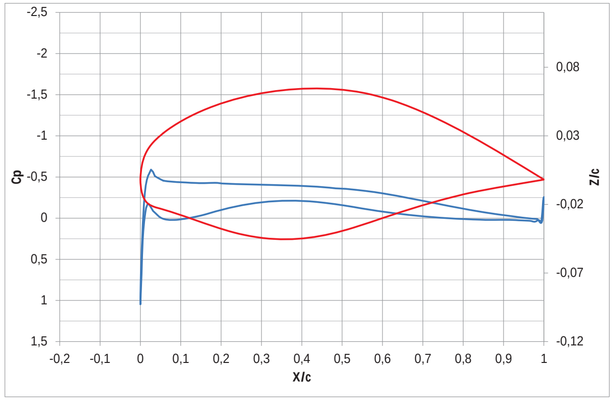




Cp and wing section profile at 30% monitoring station



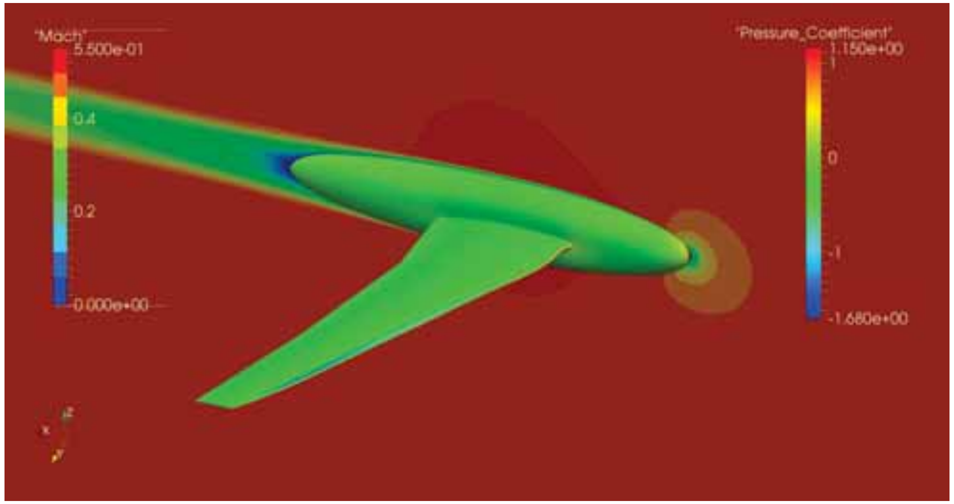
Cp and wing section profile at 60% monitoring station

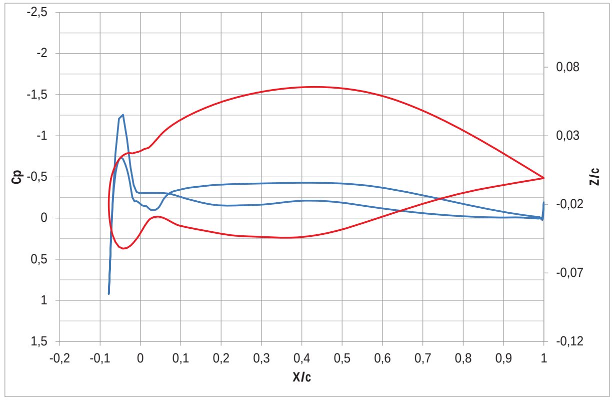


Cp and wing section profile at 90% monitoring station

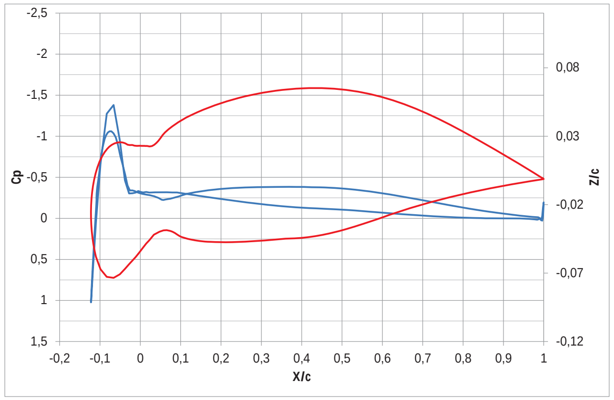
Icing | constrained

Cp profiles at different wing sections at accretion time t=21 min

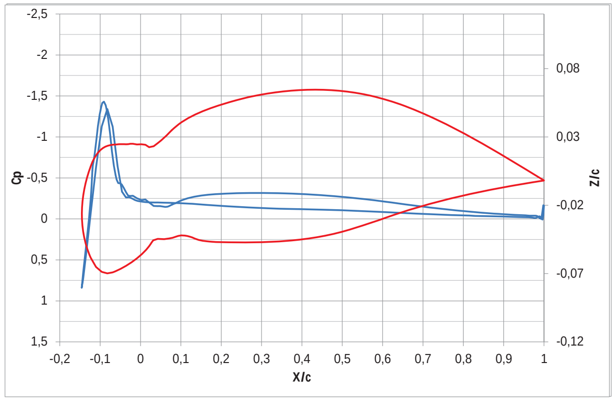




Cp and wing section profile at 30% monitoring station



Cp and wing section profile at 60% monitoring station



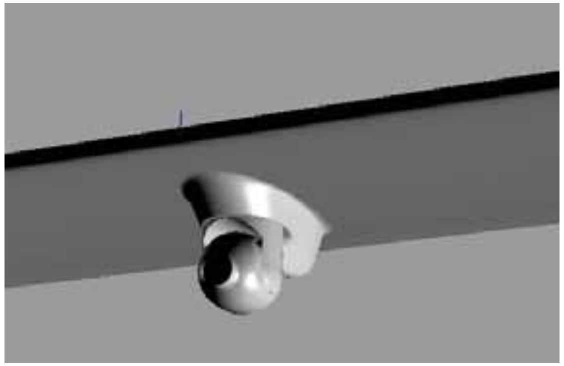
Cp and wing section profile at 90% monitoring station

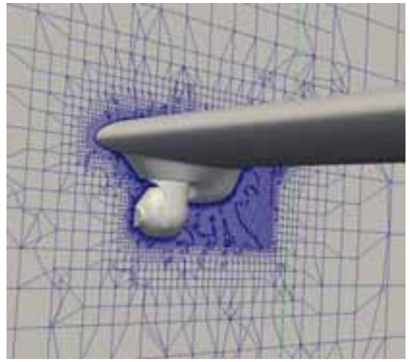
Icing | constrained

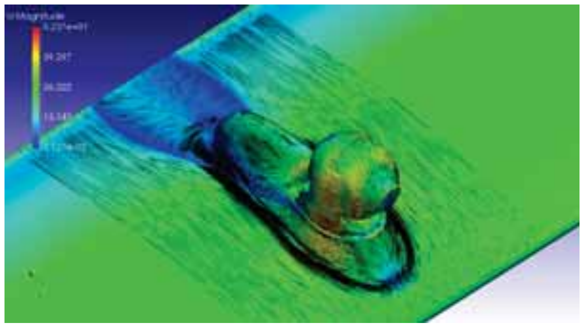
- The RBF mesh morphing based method and strategy, adopted to simulate icing growth on **2d and 3d models**, turned out to be effective and accurate
- **Precise control** of surface mesh was evidenced even for a **high-challenging 3d growths**
- CFD solvers implemented: OpenFOAM, Fluent, CFD++ and SU2
- Time saving estimated by End Users of the consortium:
  - 2d models: the time needed to perform icing on 2d models is **comparable** with that necessary to carry out CAD-based icing;
  - 3d models: the saved time (pre-processing stage) is around **90%** (just the mesh of the baseline model is needed).

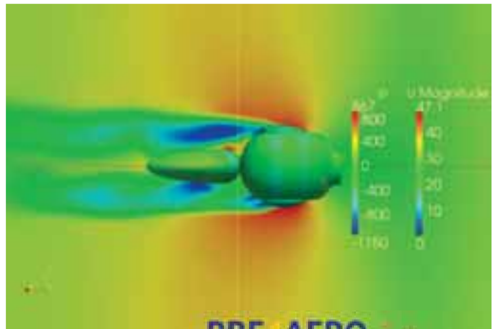
Adjoint-morphing coupling

- Gimball camera fairing
- Flow:
  - Loiter flight regime
  - RE = $1.8 \cdot 10^6$, Mach = 0.1
  - ISA @ 500m
  - AoA = 4°
- Mesh:
  - snappyHexMesh
  - $1.3 \cdot 10^6$ cells
- CFD:
  - simpleFoam
  - Spalart-Allmaras
- Objective:
  - C_D



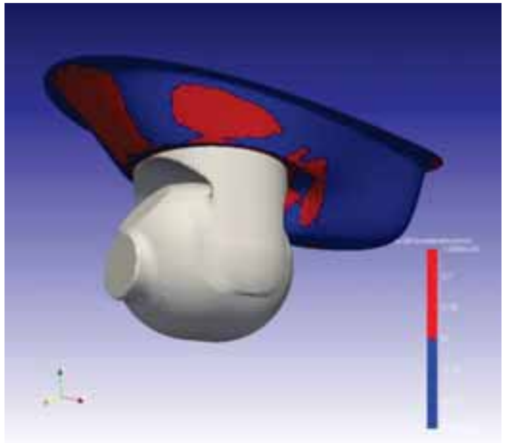




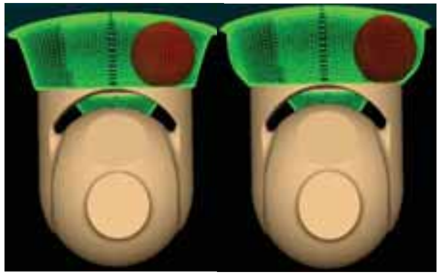


Adjoint-morphing coupling

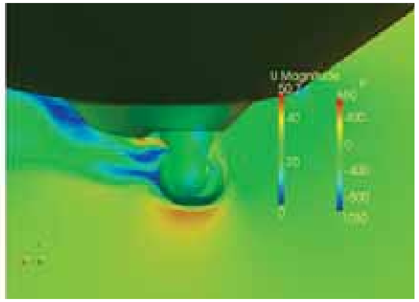
- Gimball camera fairing



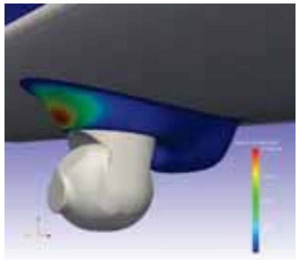
Sensitivity of the objective function to surface normal displacements

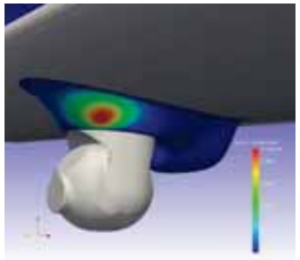


RBF solutions

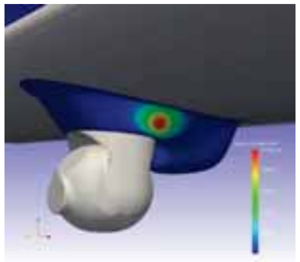


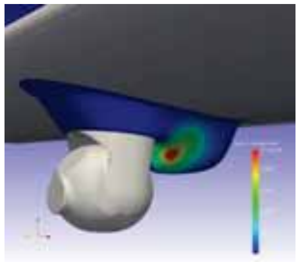
Pressure and velocity distribution

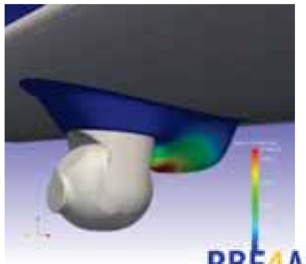




Shape modifications







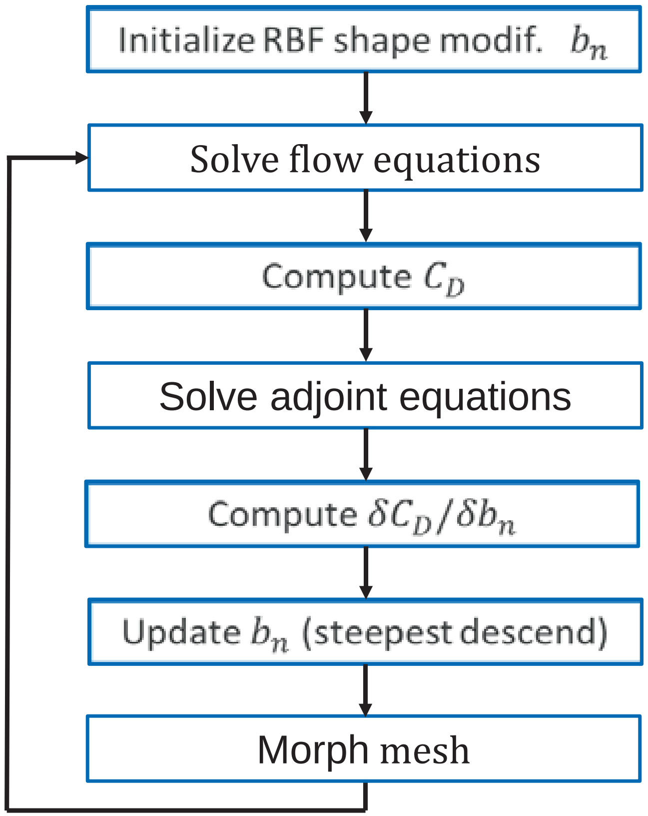
Amplifications of shape modifications

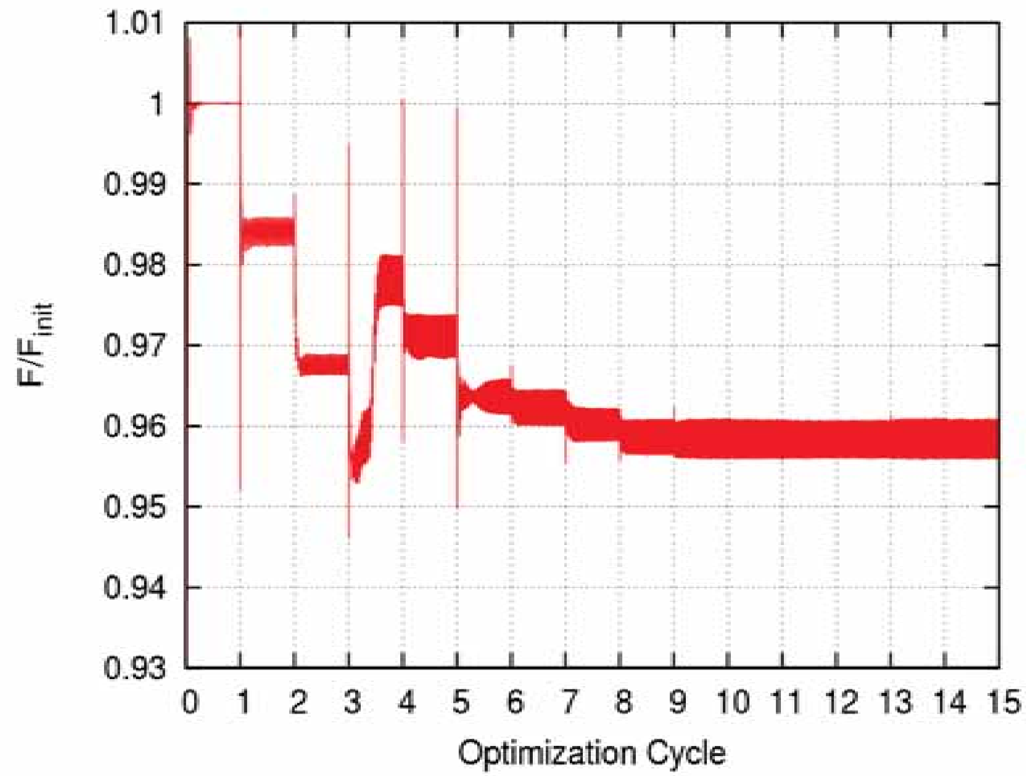
=

Optimization parameters

Adjoint-morphing coupling

- Gimball camera fairing





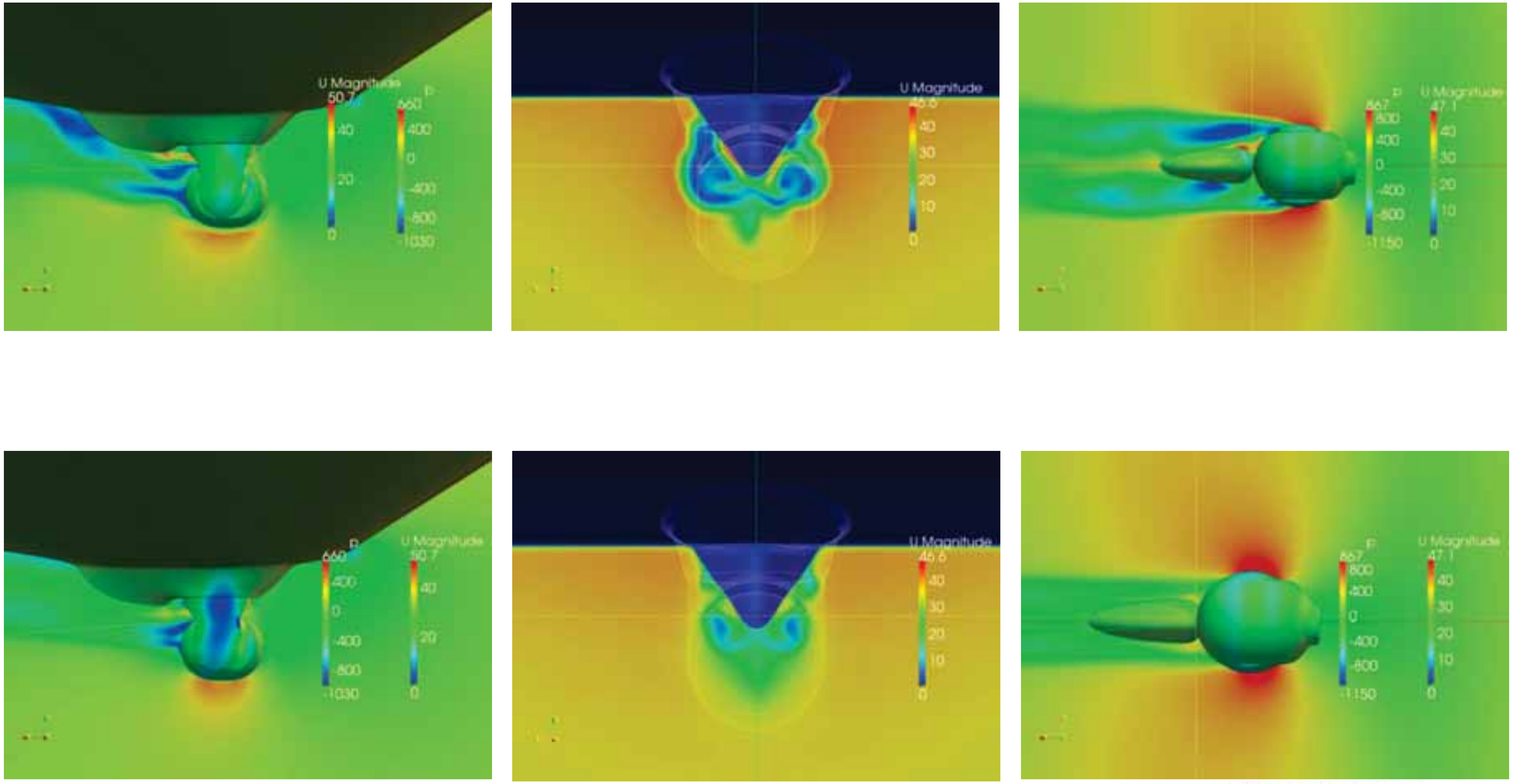
C_D	-4.2%

Adjoint-morphing coupling

- Gimball camera fairing

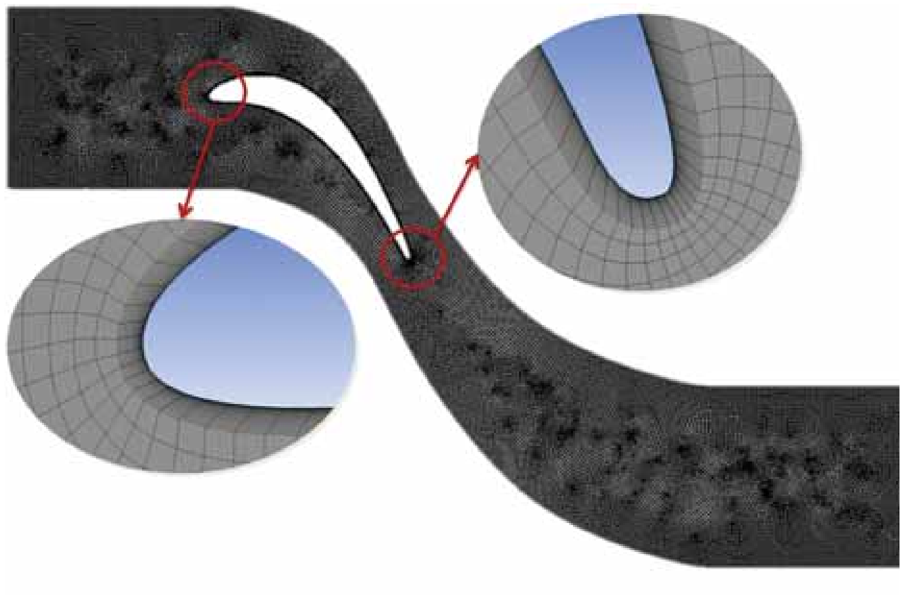
Baseline

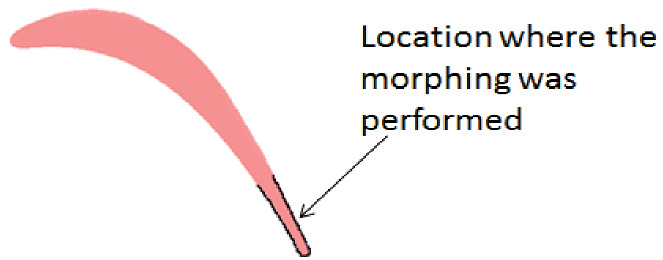
Optimal



Comparison of experimental and numerical performances of the LPT blades

- LPT test case (numerical)
- Flow regimes:
  - Inlet total temp. = 978 K
  - Inlet total press. = 180291 Pa
  - Outlet static press. = 97058 Pa
- Mesh:
  - 420000 nodes
- CFD:
  - ANSYS® Fluent®
  - 4 equation Transition SST
- Objective:
  - High performances: min C_D
  - Higher loading: max C_L



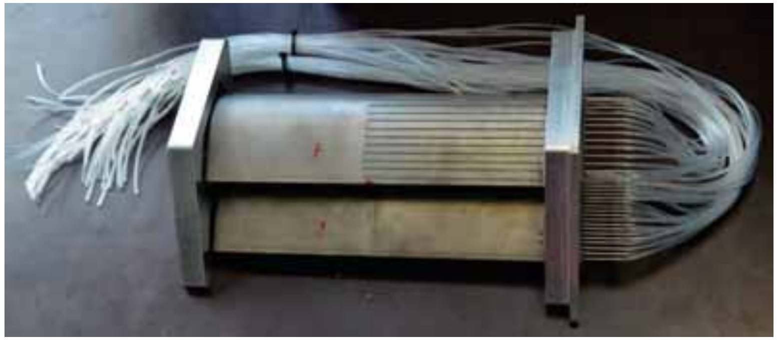


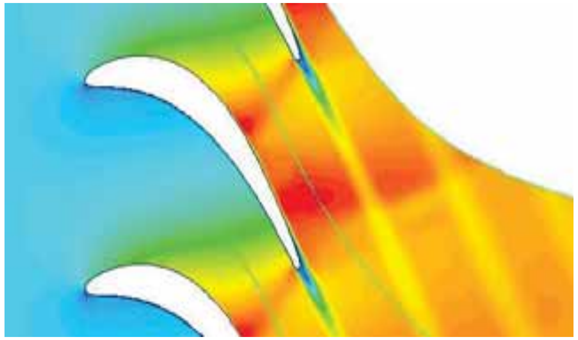
Comparison of experimental and numerical performances of the LPT blades

Experimental characterization ⟷ *Numerical predictions*

VKI S1 facility

Fluent ANSYS





Reynolds numbers : 70000 and 100000

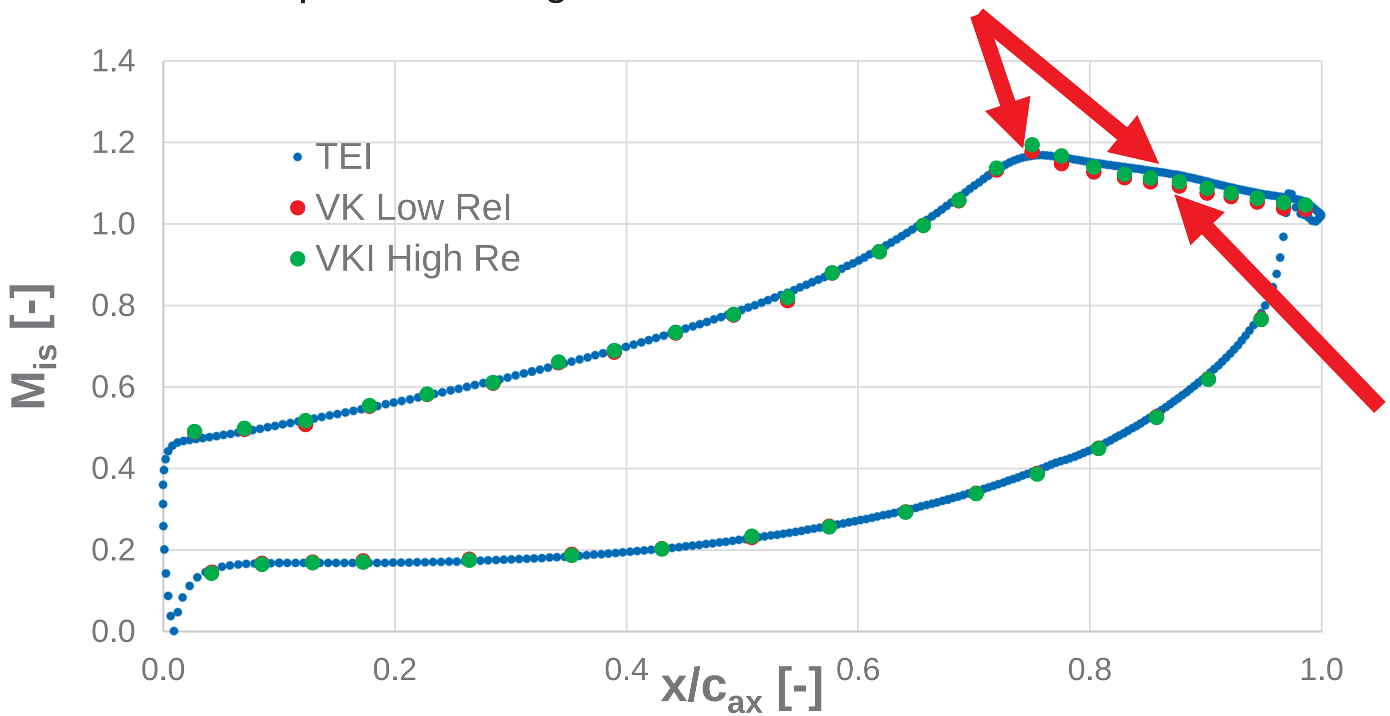
Reynolds numbers : 85000

Isentropic Mach number : 0.96

Comparison of experimental and numerical performances of the LPT blades

- Isentropic Mach number distribution along the blade surfaces.

  Experiments: High velocity peak, important deceleration and possible second peak => flow separation along suction side



Numerical results: monotone and slow deceleration on rear part of suction side => flow separation not predicted

Very high matching between prediction and measurements

Comparison of experimental and numerical performances of the LPT blades

- Extended experimental characterization of baseline and optimized geometry of LPT blades including effect of **Re** and **Mach** number
- Comparison of experimental and numerical performances of optimized geometry (**drag coefficient has been reduced approximately 4.5%**)
- Similar operating conditions – Reynolds and Mach numbers
- **Very good matching of isentropic Mach number** distribution along blade => validation of CFD tool for the predictions of LPT geometry

Conclusions

- The RBF4AERO platform was developed and successfully validated and tested, and it is now ready to be commercially exploited (**TRL7**)
- This week the consortium will have the **final review meeting** with the European Commission
- The consortium partners will undertake **exploitation joint-initiatives** to offer cloud-based CAE services
- Further information are available on the project website www.rbf4aero.eu

Any question?

- Corresponding author
  Emiliano Costa, PhD
  emiliano.costa@dappolonia.it