Towards High Fidelity Multidisciplinary Design of Aircraft Components

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And in collaboration with

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Politecnico di Milano, Italy

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Computer design of low emission aircraft components

- Objective:
  - Concept design of aircraft components based on accurate simulations
- Accurate simulations for:
  - Control of Laminar-to-Turbulent transition (BLE+PSE)
  - Control of flow separation (RANS)
  - Aeroelastic shape optimization (Euler/RANS+Modes/FEM)
- Concept design:
  - Large variations of the parameters
  - Large design space (many parameters)
- Proposed framework:
  - Gradient optimization whenever possible ! Instead of statistical methods (e.g. genetic algorithm, neural network)

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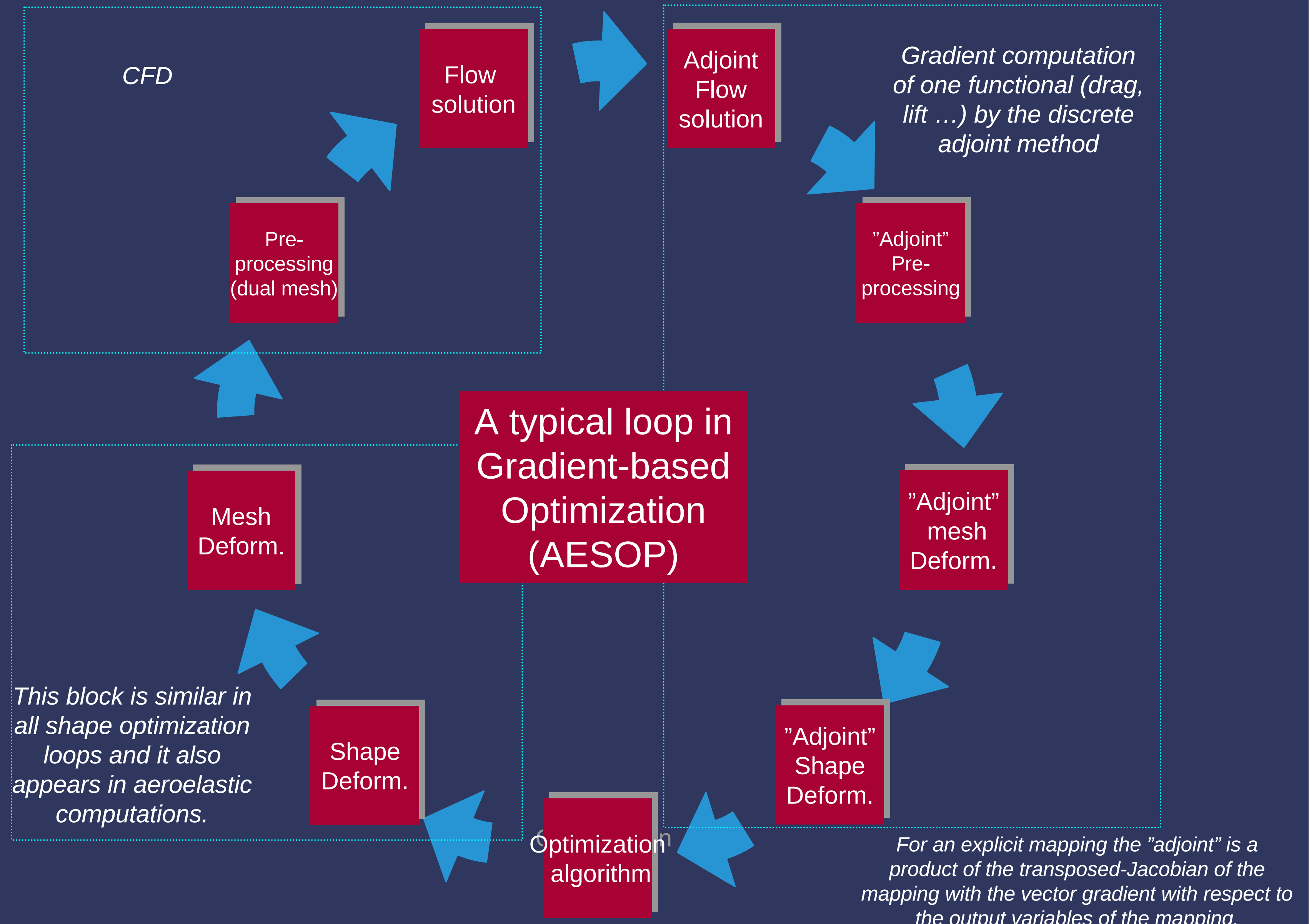
This presentation

- Large scale optimization based on flow simulation
- Control of transition
- RBF: parameterization for concept design and multidisciplinary applications
- Aerodynamic design in the New Aircraft Concept Research project NACRE
  - High Aspect Ratio Low Sweep aircraft (gradient method)
  - Flying wing (gradient method)
  - High lift system for forward swept wing aircraft (response surface)
- Possible improvements (topics for discussion)
  - Topology optimization for aerodynamic design ?
- Acknowledgements
- References (reports & articles)


CFD
Flow solution
Pre-processing (dual mesh)
Adjoint Flow solution
Gradient computation of one functional (drag, lift …) by the discrete adjoint method
"Adjoint" Pre-processing
A typical loop in Gradient-based Optimization (AESOP)
Mesh Deform.
"Adjoint" mesh Deform.
This block is similar in all shape optimization loops and it also appears in aeroelastic computations.
Shape Deform.
"Adjoint" Shape Deform.
Optimization algorithm
For an explicit mapping the "adjoint" is a product of the transposed-Jacobian of the mapping with the vector gradient with respect to the output variables of the mapping.

Large scale optimization based on flow simulations

- Large equations systems as constraints and many design parameters
  - Gradient algorithms are used for efficiency reasons (few function calls) and to handle problems with many design variables
  - Gradients are computed accurately and relatively fast solving “Adjoint” equation systems of the flow equations (flow equations=constraints)
- Current developments are focused on more accurate simulations
  - Unstructured CFD coupled to laminar boundary layer equation (BLE) and parabolized stability equations (PSE)
    - *...from 2D to 3D design*
  - RANS based shape optimization
    - *...from laminar to turbulent*
  - CFD-Structure coupling
    - *... fluid-modal structure shape optimization starts in 2008*

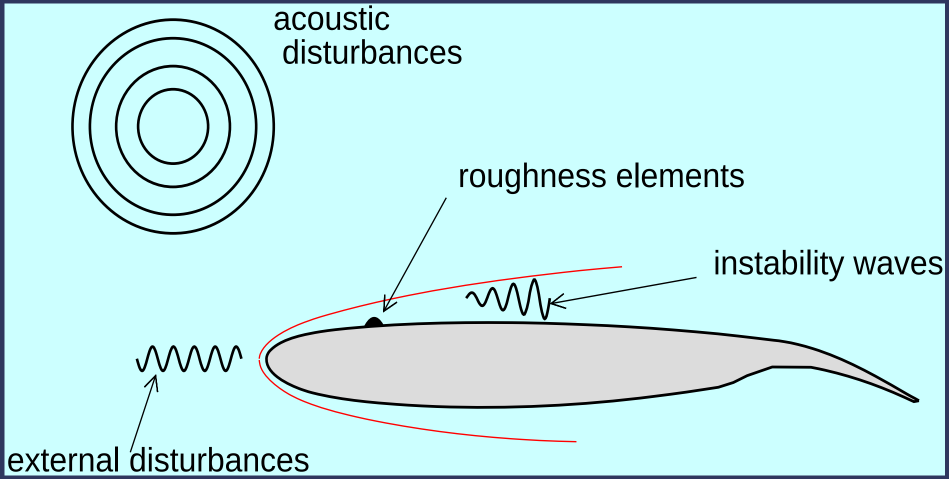
Control of the transition Laminar-to-Turbulent

in collaboration with KTH (Royal Institute of Technology, Stockholm)

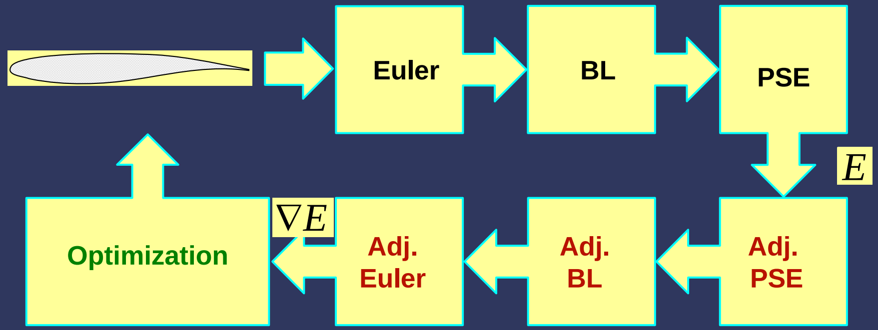
Transition is caused by breakdown of growing disturbances inside the boundary layer

↓

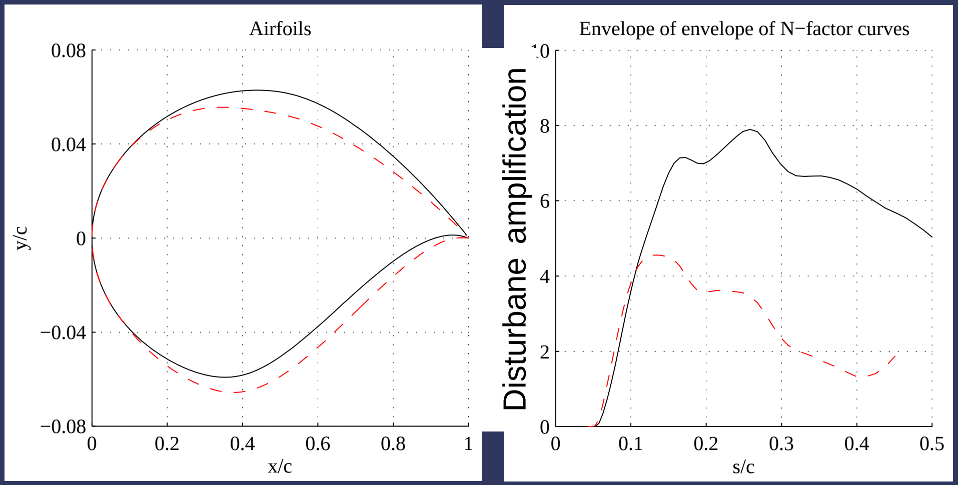
Prevent/delay transition by damping the growth of selected disturbances



Detail of the optimization loop for the minimization of the energy of one disturbance in the laminar part of the boundary layer



- E=energy (local or integrated) of a disturbance in the laminar boundary layer
- BL=Laminar boundary layer equations
- PSE=Parabolized Stability Equations (gives the growth in amplitude of the disturbance)
- Adj.=Adjoint



RAE 2822 (black solid) vs. optimized (red dash)
Amoignon et al, FOI, 2003

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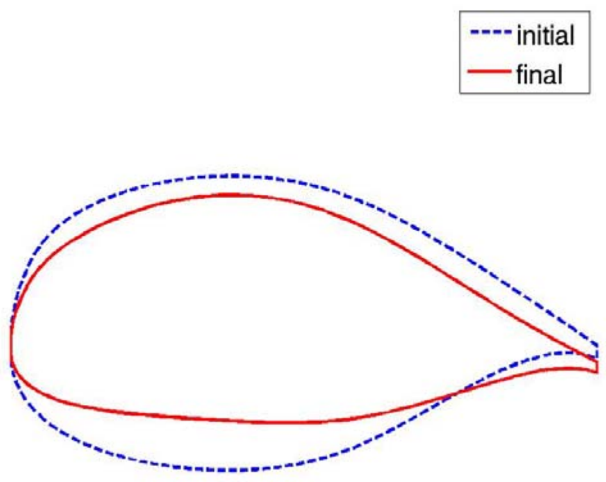
Natural Laminar Flow design of a tip airfoil at Mach=0.372, Re=12M (Euler + Boundary layer + Stability equations)

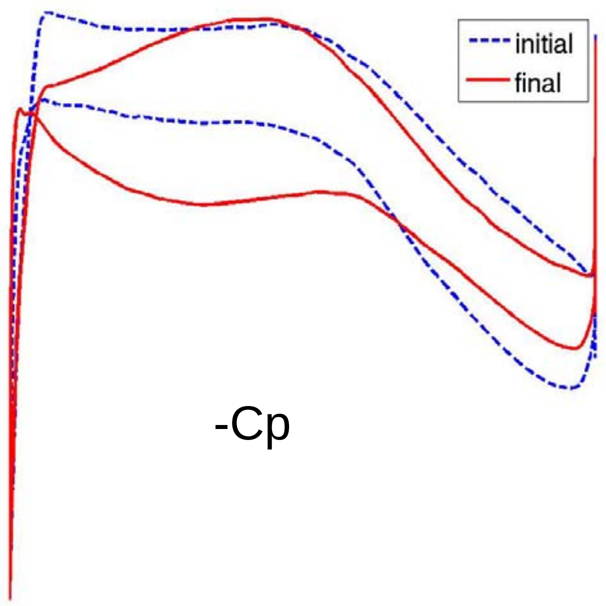
$$\min_{\Gamma} \quad J = \log(E) + 0.1\frac{C_D}{C_D^0} \quad , \quad \text{where } E = \int_{X_0}^{X_1}\int_0^{\infty} u^T u h_1 dx^1 dx^3$$

$$\text{subject to} \begin{cases} C_L \geq C_L^0 \\ C_M \geq C_M^0 \\ t \geq t^0 \quad \text{(thickness constraint smaller than baseline)} \end{cases}$$

E is the energy of one selected disturbance on the upper surface of the airfoil



CESAR (EU) project



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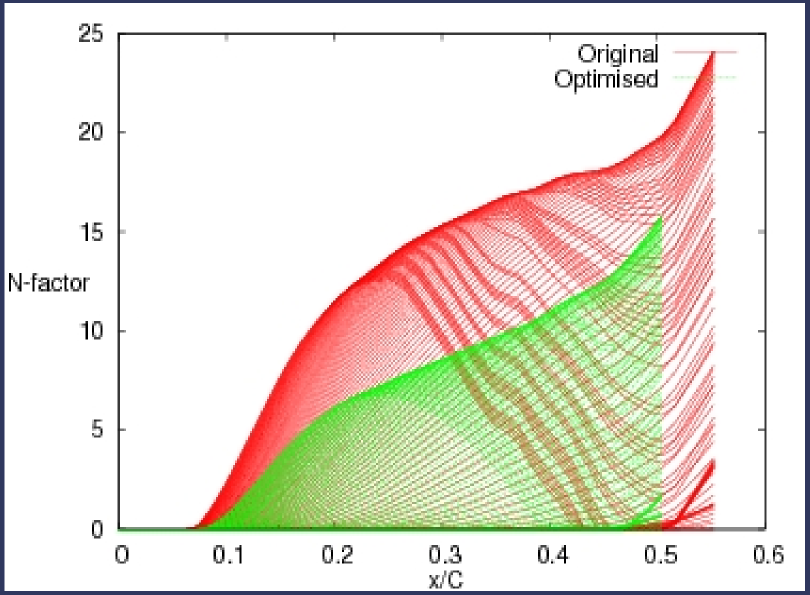
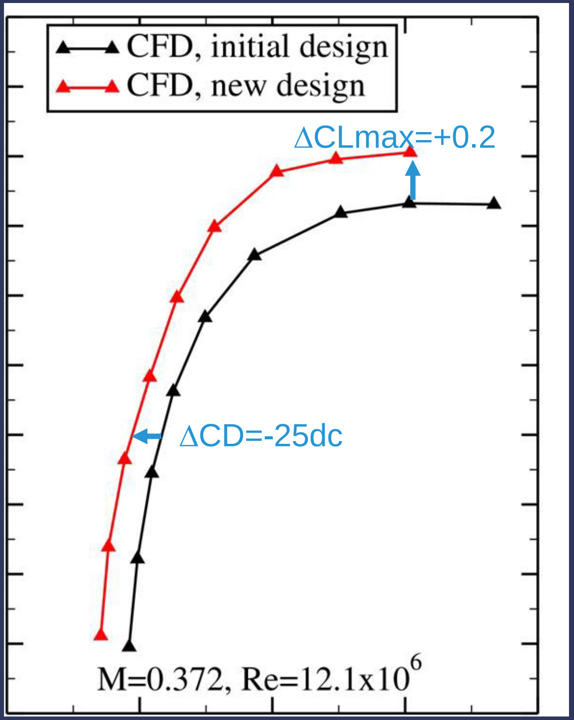
…interpretation of the results from the previous slide

Natural Laminar Flow design of a tip airfoil



N-factor curves indicate the energy growth of disturbances in the laminar boundary layer. If transition occurs at N-factor=9, it starts at 15%c on the upper surface of the original design and at more than 30%c on the upper surface of the optimized airfoil.

CL

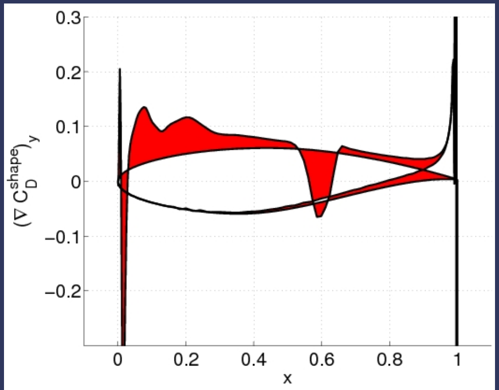


CD

Analysis with RANS + transition at N=9

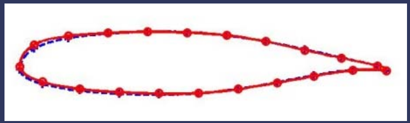
Radial Basis Functions are used here for Shape parameterization and Multidisciplinary applications

- RBF are widely used for:
  - Unstructured data interpolation (the connectivity between the data locations is not needed)
  - Regularization of data (e.g. ‘noisy’ experimental data)
  - Extrapolation (e.g. reconstruction of missing data in image analysis or in repairing CAD models)
- Parameterization: shape_deformations=RBF expansion
  - Interpolation or approximation (regularization) of control points displacements (the RBF need not be fitted to the baseline geometry)
- Multidisciplinary applications
  - Coupling of 3D unstructured CFD with boundary layer stability analysis
  - Aeroelastic coupling (*Implementation in Edge, Cavagna, Polimi, 2008*)
  - Fast mesh deformation scheme (*Jakobsson & Amoignon, 2007*)

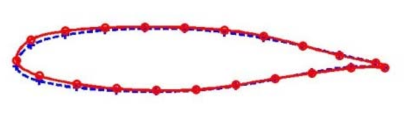


The shape gradient of the inviscid drag at transonic speed plotted on the shape.

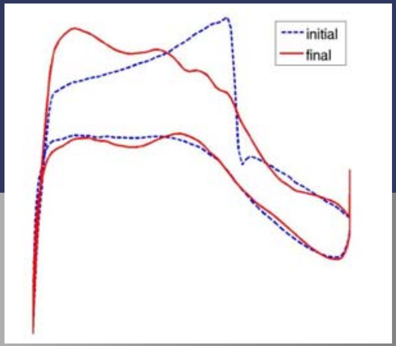
The lack of regularity of the gradients can cause wiggles when using interpolation in shape parameterization. Approximation of control points displacements, instead of interpolation, can resolve this problem (see figures below).

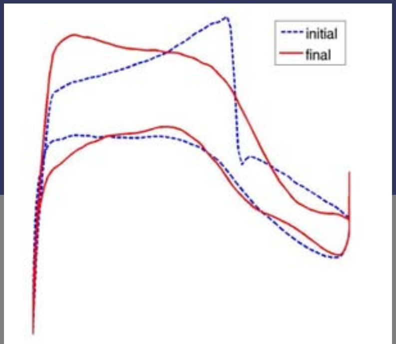


RBF interpolation



RBF approximation





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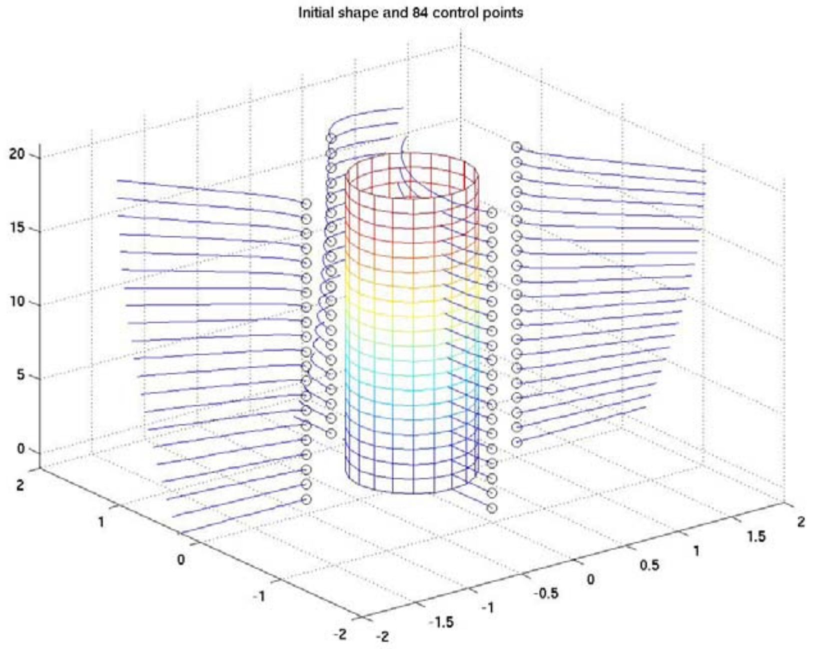
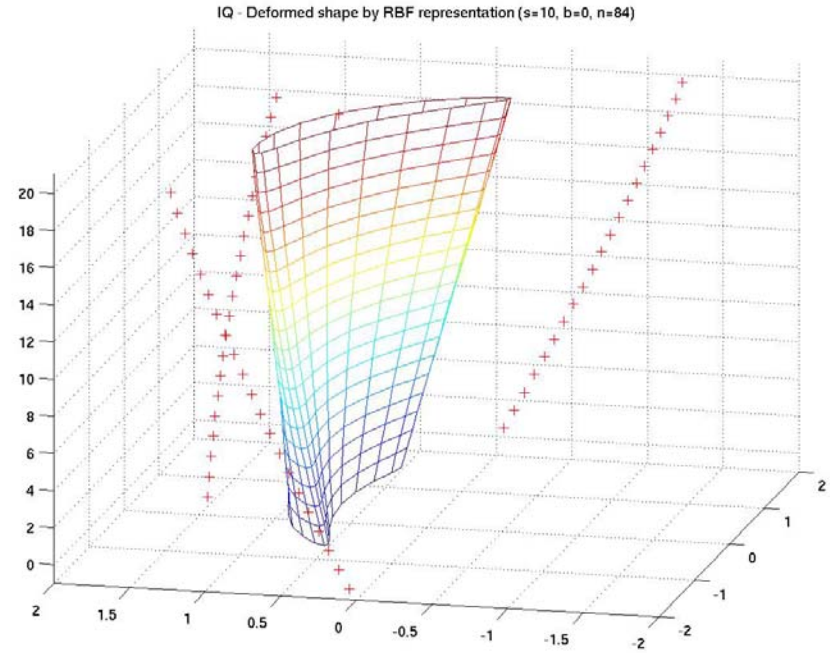
Shape deformations parameterized by RBF (IQ: inverse quadric)





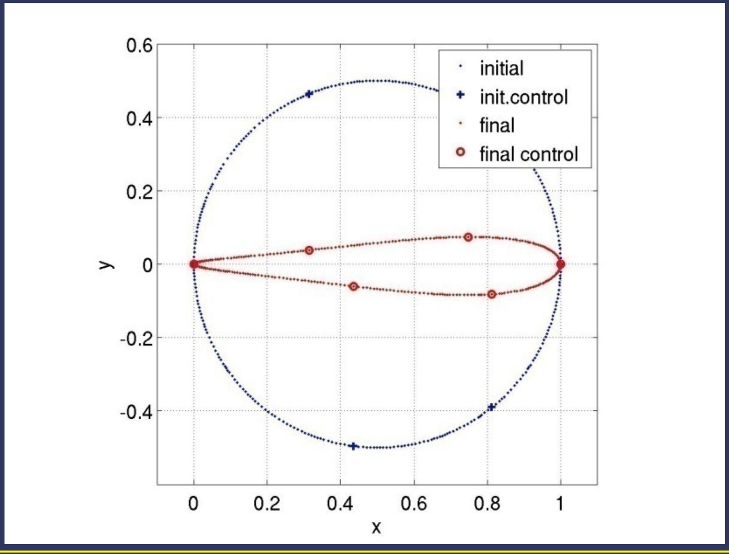
The displacements of the control points (indicated by the lines in the left picture) are extrapolated to all the nodes on the shape of the cylinder

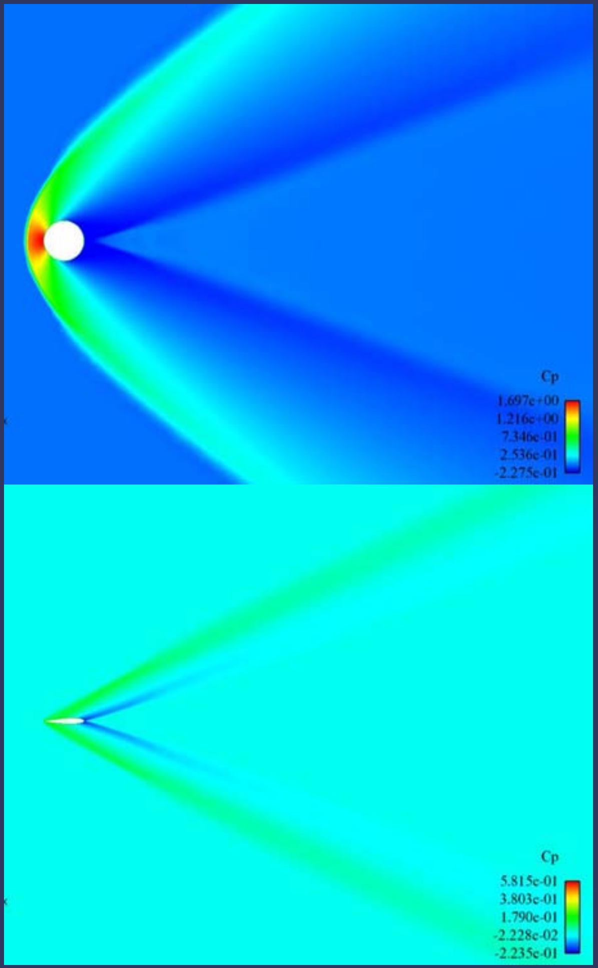
Example of RBF parameterization: a supersonic airfoil (sharp leading edge) obtained by deformation of a smooth baseline geometry (circle)

$$\min_{\Gamma} \quad J = \frac{C_D}{C_D^0} + C_L^2 + C_m^2 \quad \text{subject to } \textit{thickness} \geq 15\%$$

At Mach $= 2.5$, C_D reduced from 1.38 to 0.05

with 6 or 23 control points (no differences).





These are preliminary results. A minimum sampling distance is given to select the position of control points on the geometry but, because of the problem symmetry two control points were pre-selected (leading and trailing edge). The mesh is deformed along the optimization in order to fit the changes of the geometry. The most influencing parameters in these tests, as in other tests on the RBF parameterization, were the 'shape factor' and the type of RBF (Gauss, MQ …)

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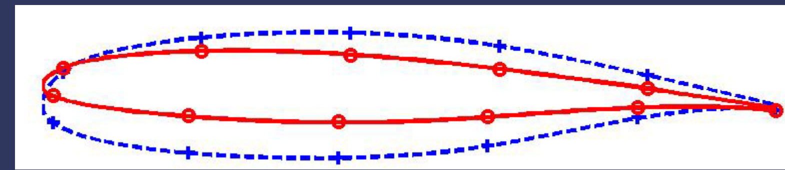
Multipoint optimization of an airfoil at Mach=0.716 (Euler)



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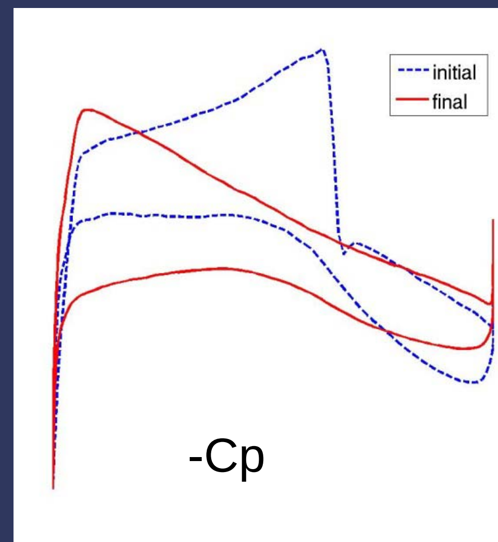
$$\min_{\Gamma} \quad J = \frac{C_{D1}}{C_{D1}^{0}} \quad \text{subject to} \begin{cases} C_{L1} \geq C_{L1}^{0} \\ C_{L2} \geq C_{L2}^{0} \\ C_{M1} \geq C_{M1}^{0} \\ C_{M2} \geq C_{M2}^{0} \\ C_{D2} \leq C_{D2}^{0} \\ thickness \geq t^{0} \end{cases}$$

C_{D1} reduced of 70 dc

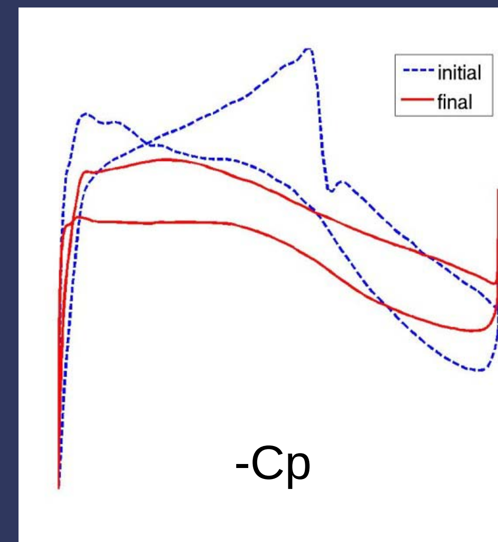
C_{D2} reduced of 12 dc

C_{L1} constant

C_{L2}, C_{M1}, C_{M2} increased



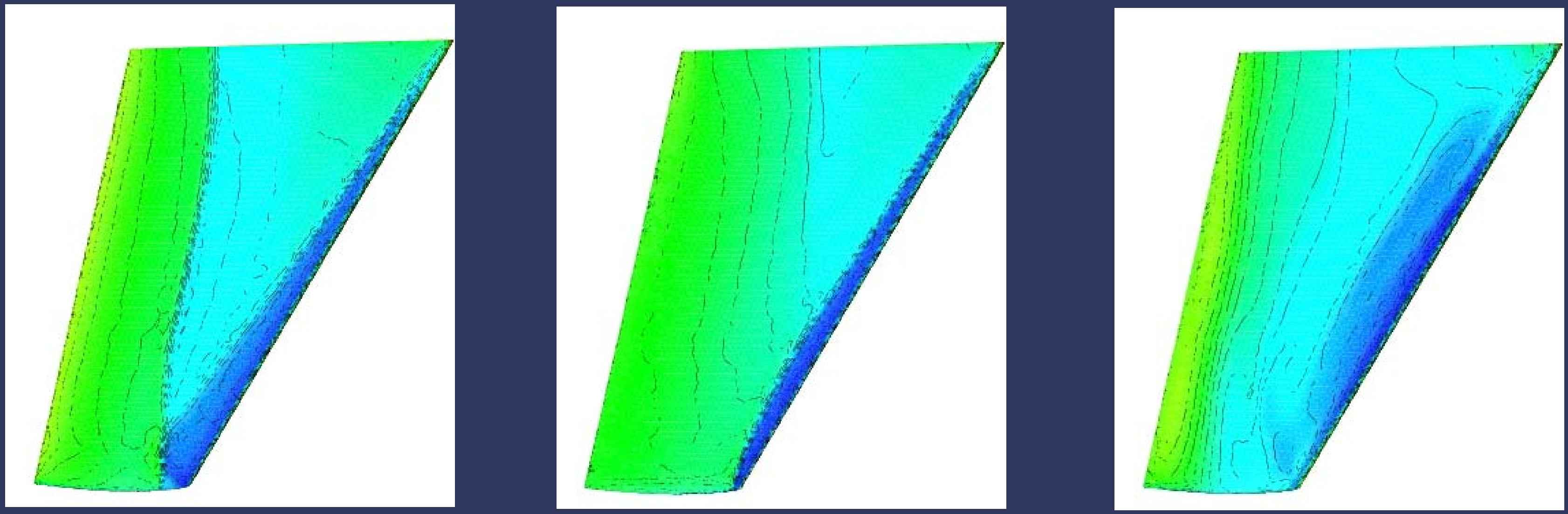
Design point 1



Design point 2

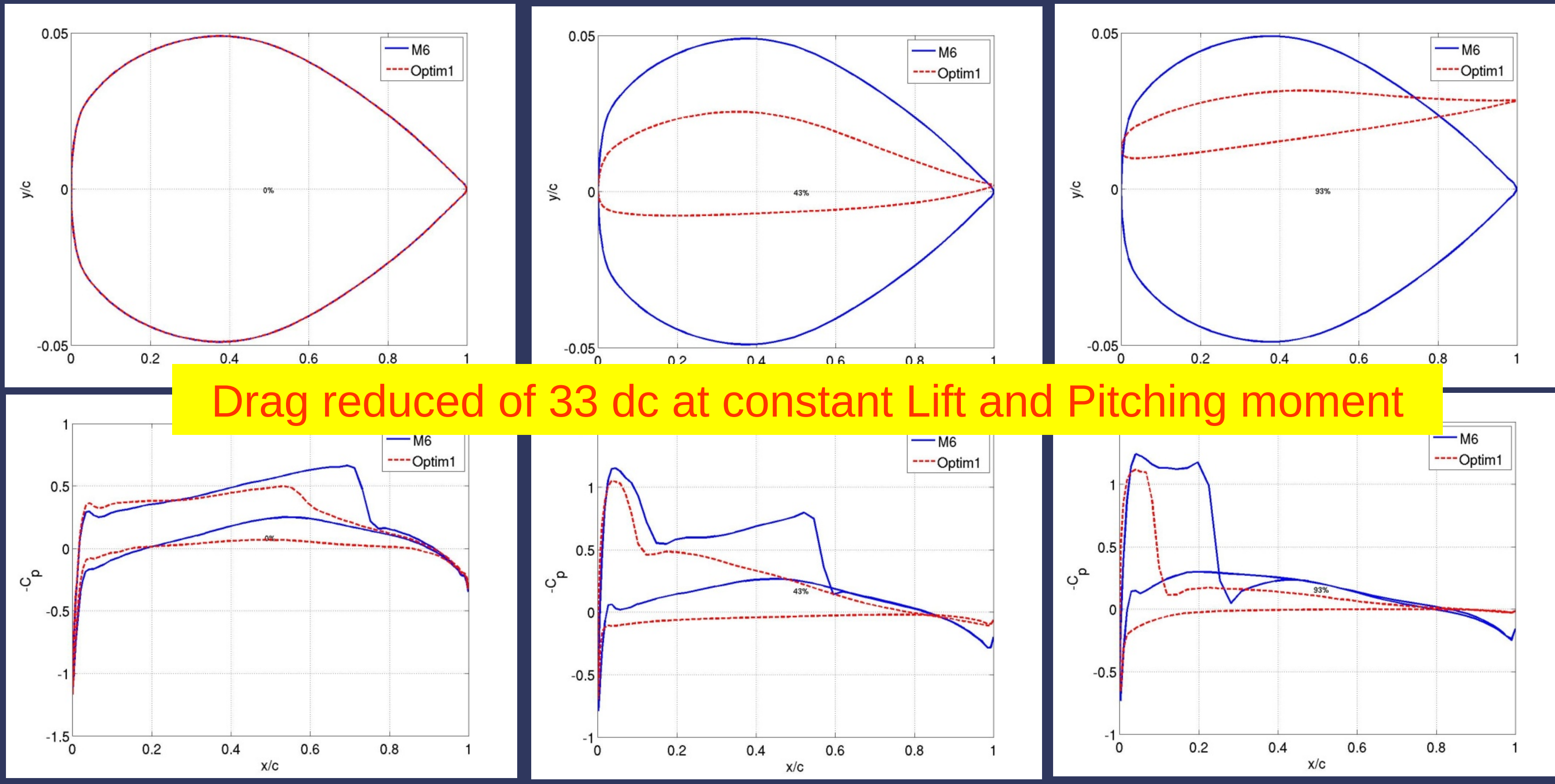
Note: The optimization results obtained by inviscid flow analysis (Euler) were cross-checked using RANS.

Example of 3D transonic inviscid optimization using RBF parameterizations
M6 wing optimization at Mach=0.84 , angle of attack=3 deg



Cp: left (M6) – middle (7 parameters, no thickness constraints) – right (50 parameters + thickness constraint)

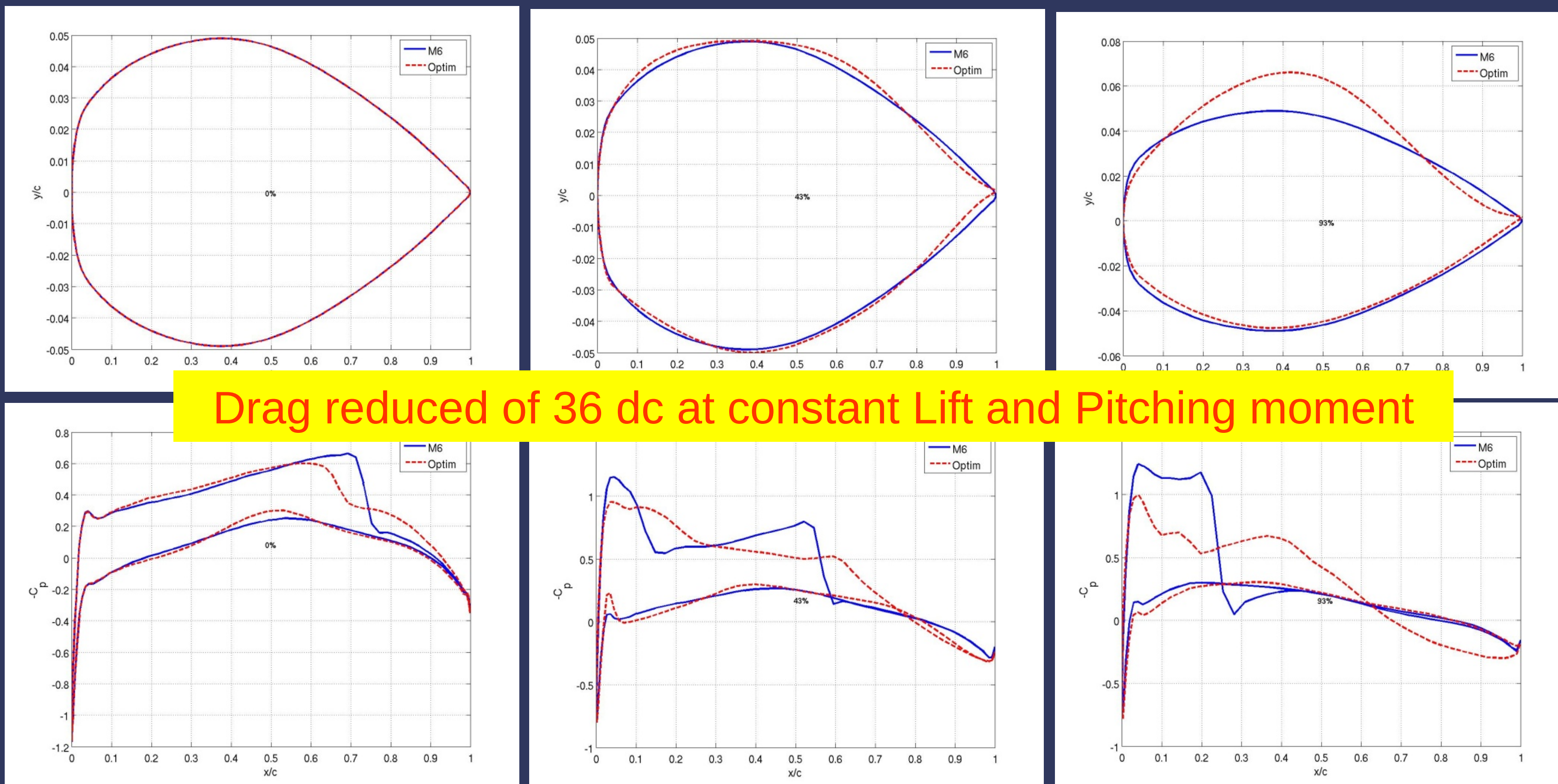
M6 wing optimization: large profile changes obtained by RBF parameterization (Gauss) with 7 parameters and NO constraint on the thickness of the airfoils (unless the fixed root)



Drag reduced of 33 dc at constant Lift and Pitching moment

Streamwise cuts at 0 – 43 – 93 % of span (from left to right)

M6 wing optimization with a RBF parameterization (Gauss) 50 parameters + airfoils thickness constraints at # spanwise positions

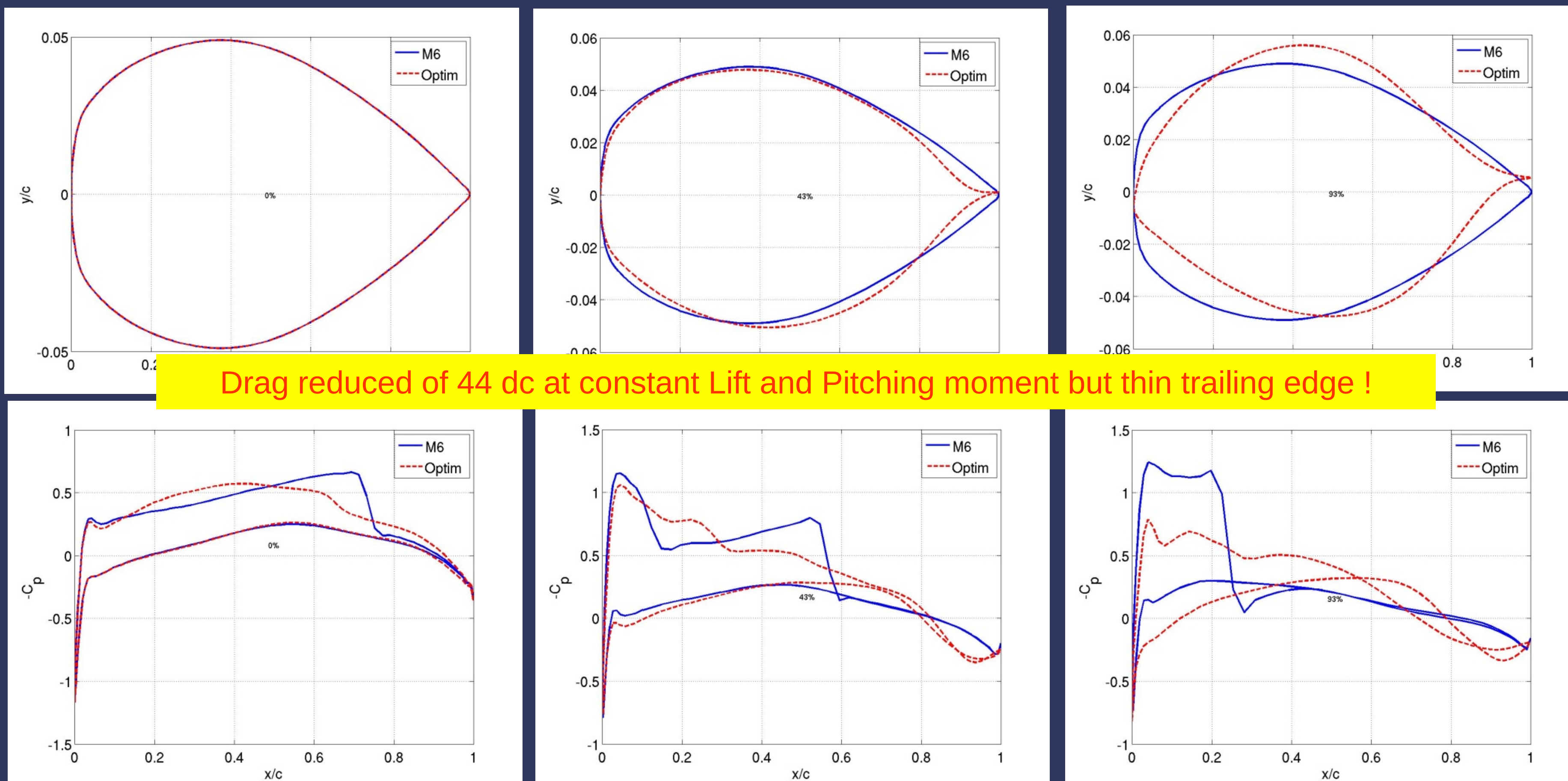


Drag reduced of 36 dc at constant Lift and Pitching moment

Streamwise cuts at 0 – 43 – 93 % of span (from left to right)

FOI

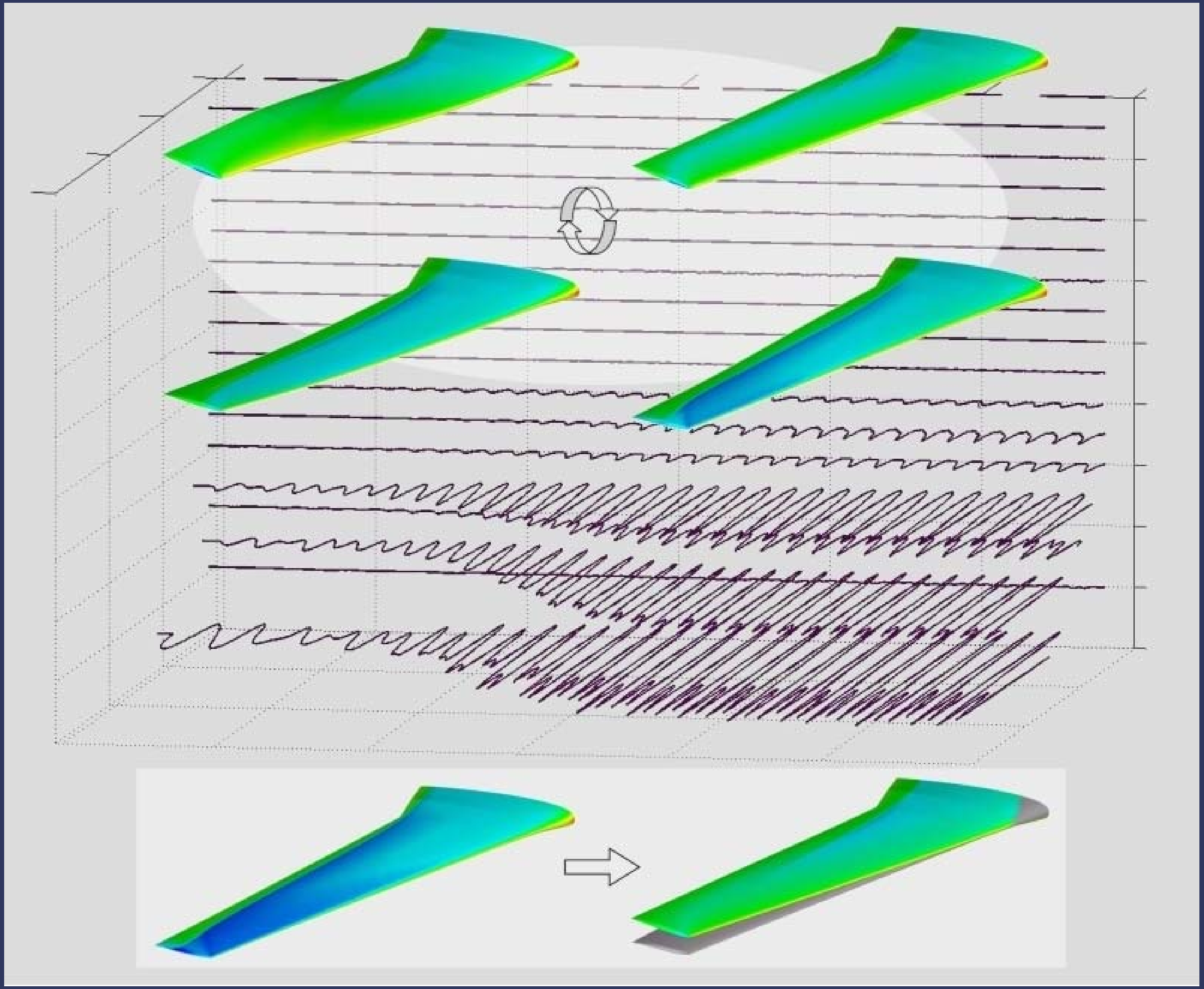
M6 wing optimization with a RBF parameterization (Wendland) 50 parameters + airfoils thickness constraints at # spanwise positions.



Drag reduced of 44 dc at constant Lift and Pitching moment but thin trailing edge !

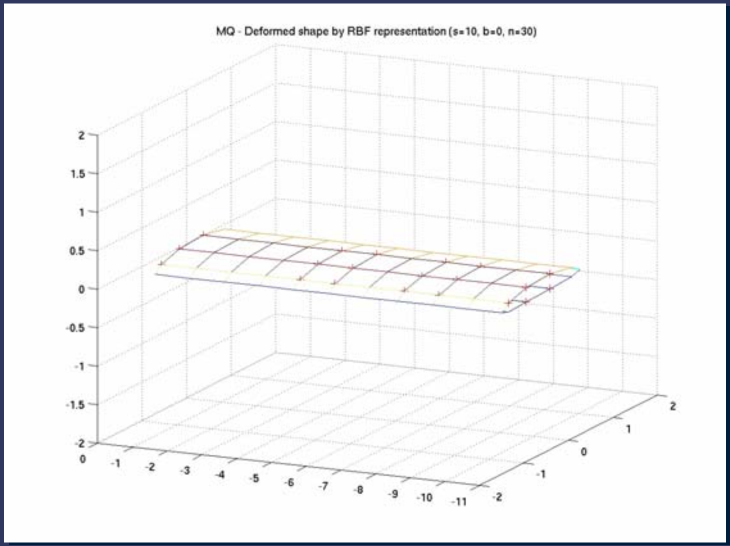
Streamwise cuts at 0 – 43 – 93 % of span (from left to right)

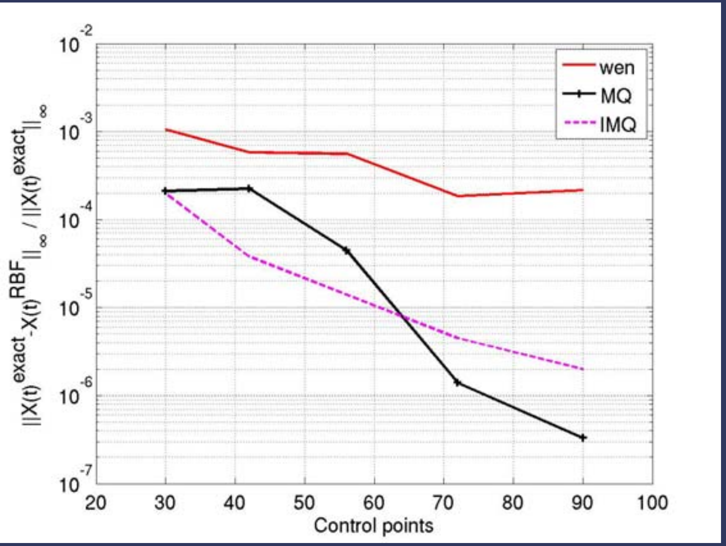
Towards aeroelastic optimization with Edge



Towards aeroelastic optimization

- Coupling algorithms:
  - Transfer matrix based on Moving Least-squares and RBF (Cavagna, Politecnico di Milano)
  - Shape parameterization based on RBF
  - Online mesh deformation
- Coupled equations
  - Adjoint CFD-Modal Structure equations under development in Edge





Figures: Influence of the number of control points and type of RBF on the accuracy of the dynamic coupling between two meshes.
In the 'toy' problem used to assess the accuracy of the RBF the meshes coincide - the forced oscillations of the 'structure' are transferred to the 'fluid' mesh via RBF interpolation of the displacements of the structure at a number of control points. The difference between the position of the two meshes is due to the interpolation error. The figure on the right indicates the max norm of the difference vector over a time period of oscillation and in space.

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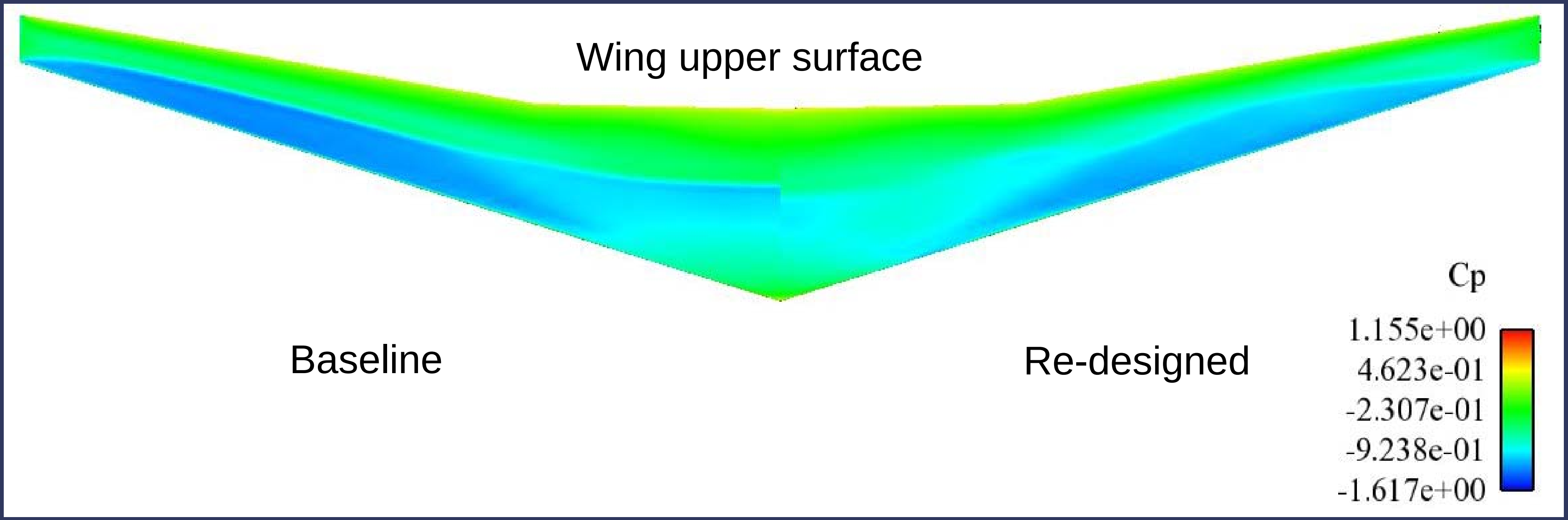
NACRE – High Aspect Ratio Low Sweep (HARLS) wing shape optimization at cruise (M=0.74)

$$\min_{\Gamma} \quad J = \frac{C_D}{C_D^0} \quad ,$$

$$\text{subject to} \begin{cases} C_L \geq C_L^0 \\ C_M \geq C_M^0 \\ t_k \geq t_k^0 \quad 1 \leq k \leq n \;\; (thickness) \end{cases}$$



Note: The optimized shapes were obtained by inviscid flow simulations (Euler) and the improvement in performance cross-checked using RANS.

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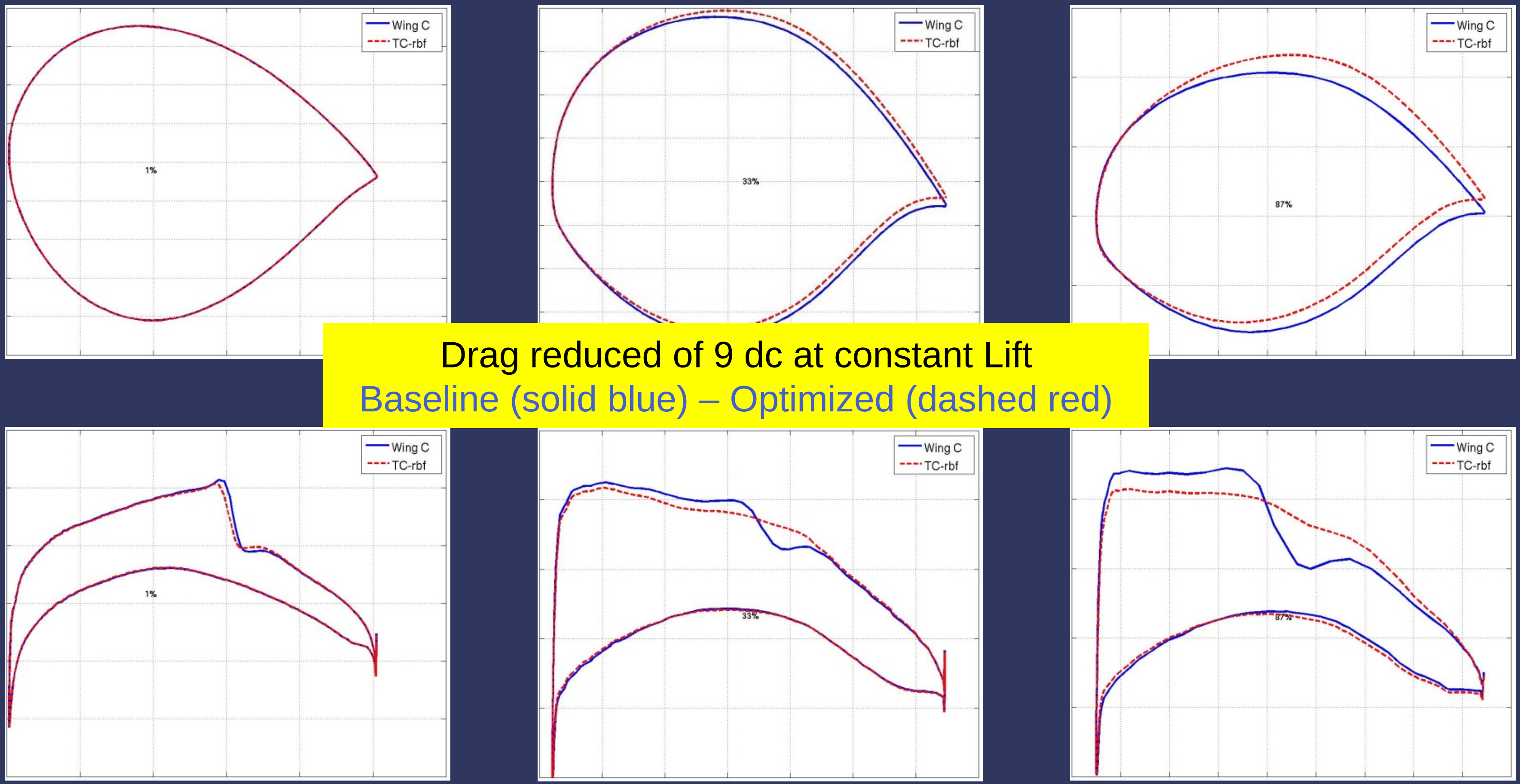
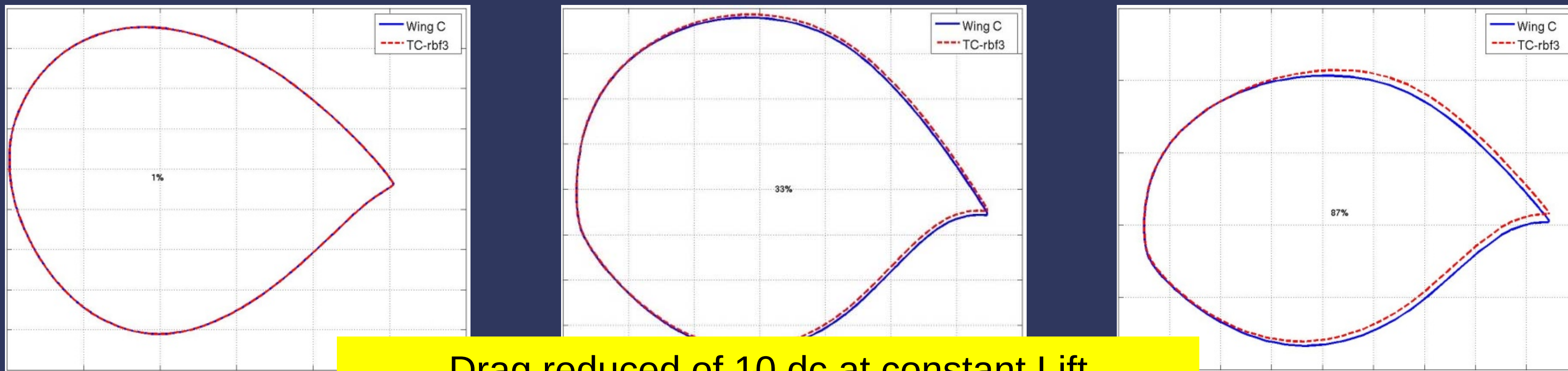
64 parameters (twist + camber + RBF representation of deformations in z-dir.)
Total cost = 97 flow equivalent solutions (flow+adjoints)



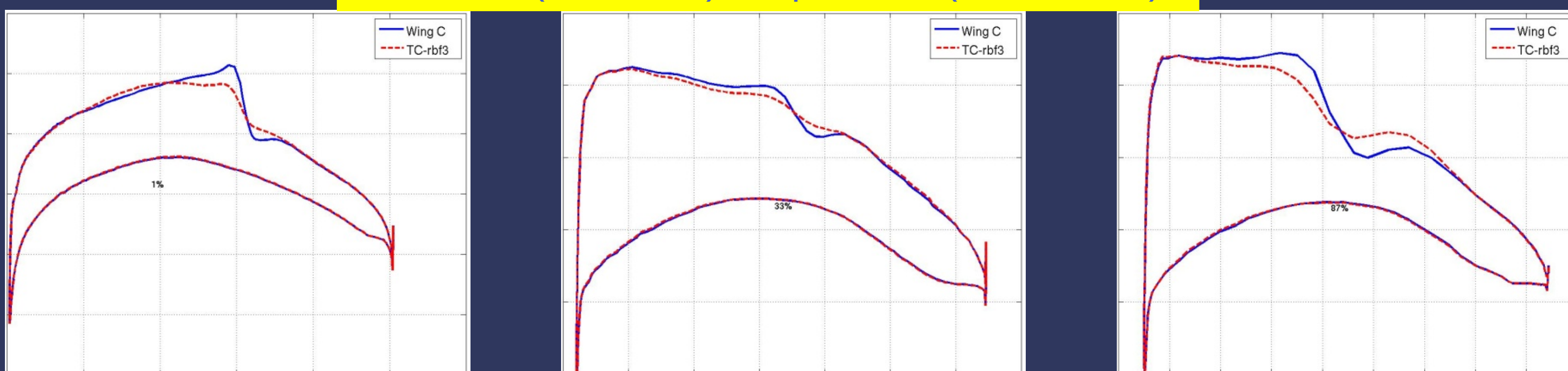
Drag reduced of 9 dc at constant Lift
Baseline (solid blue) – Optimized (dashed red)

Streamwise cuts at 1 – 33 – 87 % of span (from left to right)

170 parameters (twist + camber + RBF representation of deformations in z-dir.)
Total cost = 68 flow equivalent solutions (flow+adjoints)



Drag reduced of 10 dc at constant Lift
Baseline (solid blue) – Optimized (dashed red)



Streamwise cuts at 1 – 33 – 87 % of span (from left to right)

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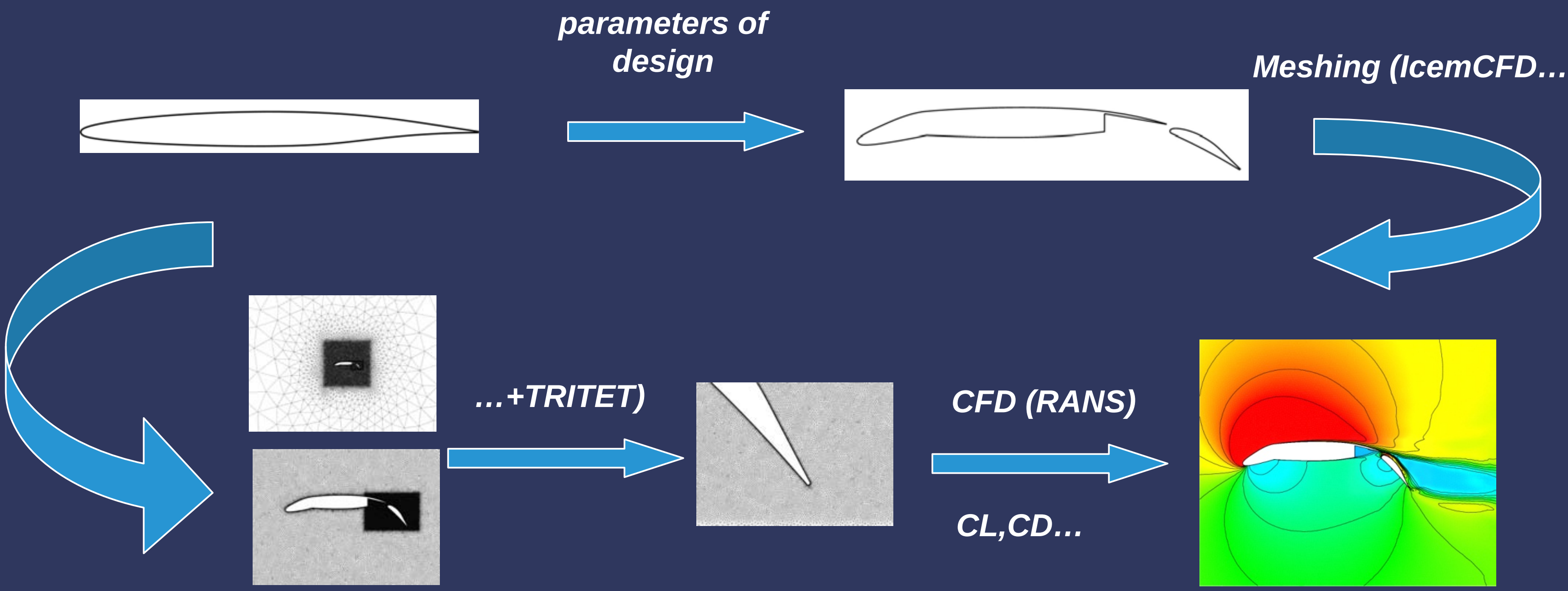
Derivatives free optimization

NACRE - High Lift design for Forward Swept Wing A/C by a Response Surface Method



Geometry and mesh are generated for each high lift design (12 parameters: length of flap, shape and position of flap, length and deflection of droop nose device, deflection of spoiler)

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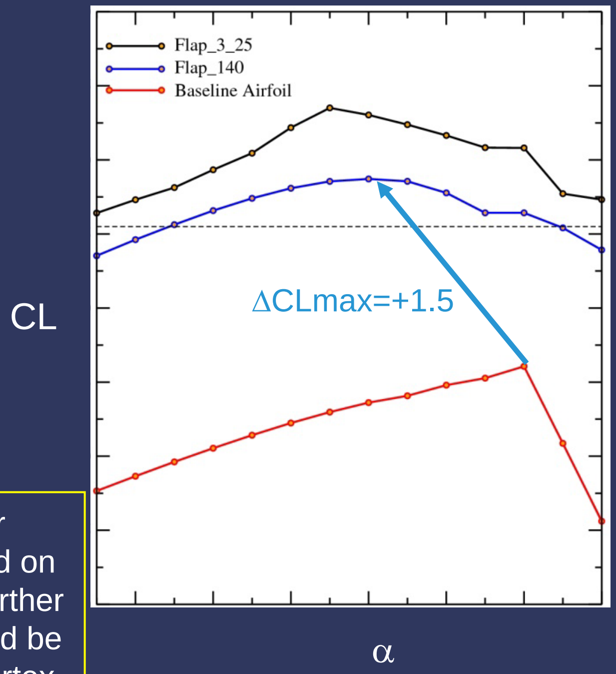
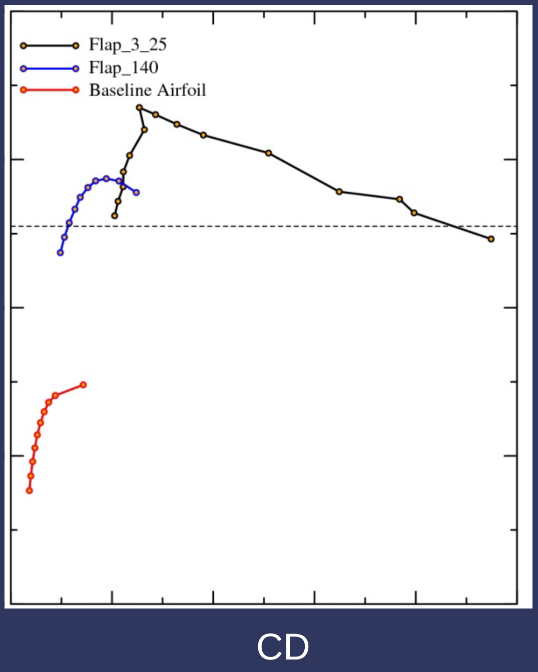
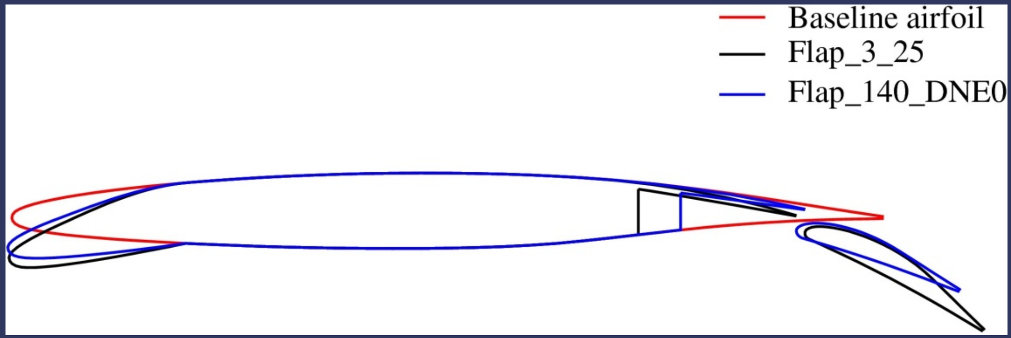
High lift design by Response Surface Method at Mach=0.16, Re=21M 12 design parameters





The behavior of the polar curve (right) for Flap_3_25 is due to the flow being separated on the flap around the angle of maximum lift. Further simulations showed that flow separation could be avoided, and the lift improved, by placing Vortex Generators on the flap at a position that does not affect the aerodynamic at cruise.



Possible improvements in aerodynamic shape optimization and flow control

- Optimization of non-linear dynamic systems:
  - Reduce Order Modeling (ROM) could be a good candidate to perform optimal flow control based on even more accurate flow simulations like Large Eddy Simulations (LES)
- The use of commercial software (CAD, Meshing) in optimization loops is limited:
  - The sensitivities are missing (for gradient-based optimization)
  - The software are developed for being user friendly instead of being modular
  - Consequence: nearly all optimizations are ‘CAD-free’ which requires to transfer the optimized shapes back to some CAD format. A time consuming operation (‘by hand’) that can also be inaccurate.

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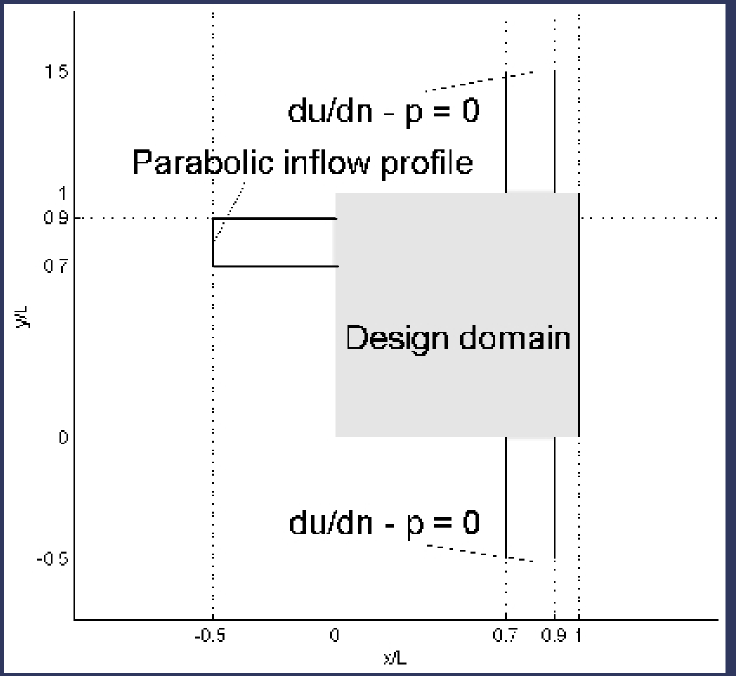
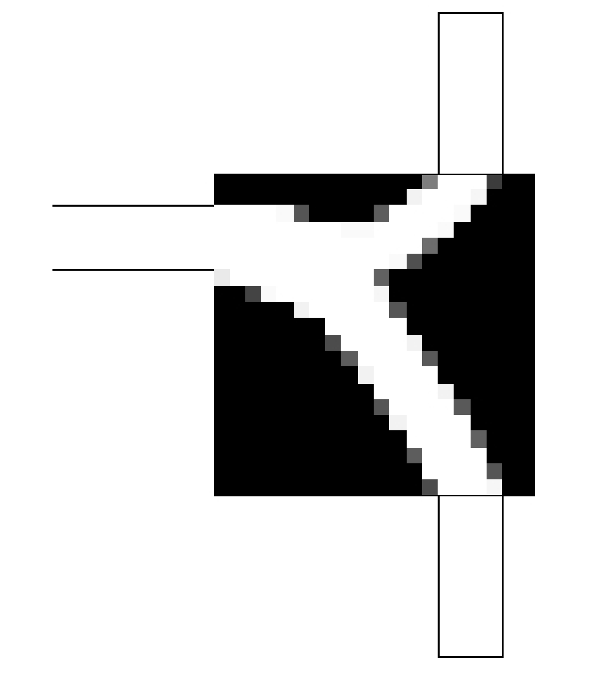
Future technology - Topology optimization for high speed flow ?

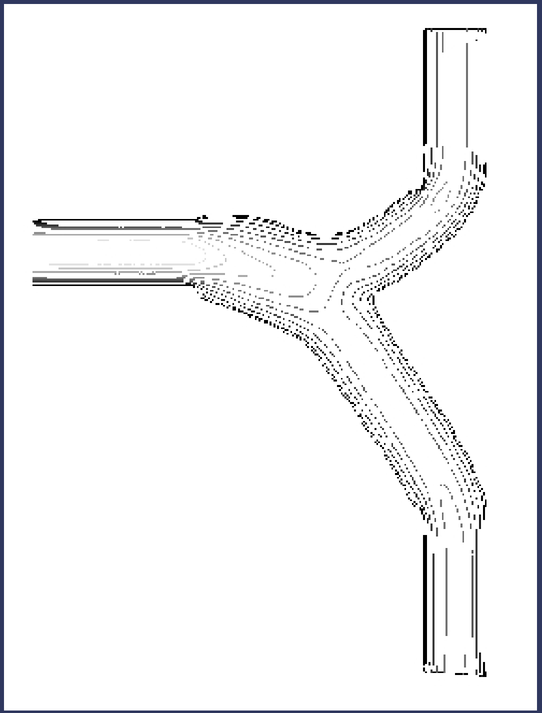
Topology optimization in Stokes Flow

Gersborg-Hansen, Berggren**, Dammann*, 2006*

Find the material distribution that minimizes the rate of energy dissipation subject to constraints (fluid volume, ... Stokes equations)







Boundary conditions – Result of topology optimization – Post-processed geometry

* Technical University of Denmark
**Umeå University, Sweden

Acknowledgements

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NACRE is a consortium of 35 partners

- 4 major aircraft manufacturers (**Airbus, Alenia, Dassault Aviation, Piaggio**)
- 4 major engine manufacturers (**R-R plc, R-R Deutschland, Snecma Moteurs, MTU Aero Engines**)
- 2 key suppliers (**Hurel-Hispano, Messier-Dowty**)
- 9 Research Centres (**ARA, CIRA, DLR, EADS CRC-G, FOI, INTA, NLR, ONERA, VZLU**)
- 7 Universities (**TCD, Univ. Greenwich, TU München, Univ. Stuttgart, KTH, Warsaw Univ. Technology, ISVR**)
- 4 small and medium enterprises (**IBK, INASCO, PEDECE, ARTTIC**)

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