DLR - German Aerospace Center

State of the art at DLR in solving aerodynamic shape optimization problems using the discrete viscous adjoint method

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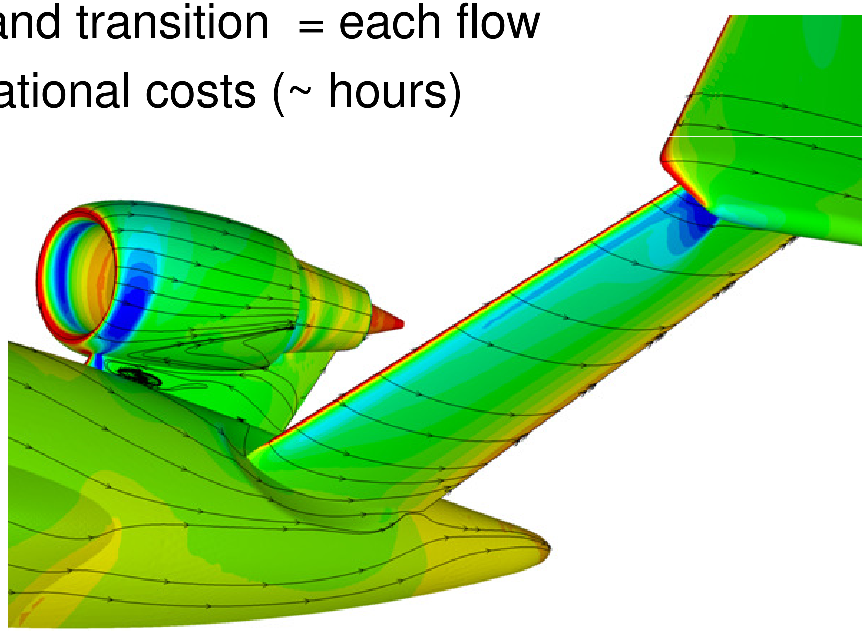
DLR

Motivation: Design of a Future Aviation

- Design of commercial transport aircraft is driven more and more by demands for substantial reduced emissions (ACARE 2020, Flightpath 2050)
- Design based on high fidelity methods promise helping to find new innovative shapes capable to fulfill stringent constraints
- Moderate to highly complex geometry under compressible Navier-Stokes equations with models for turbulence and transition = each flow computation suffers from high computational costs (~ hours)
- Detailed design with large number of design variables (~ 10 to 100 design variables)
- Need to consider physical constraints (lift, pitching moment, ..)
- Geometrical constraints
- Multipoint design



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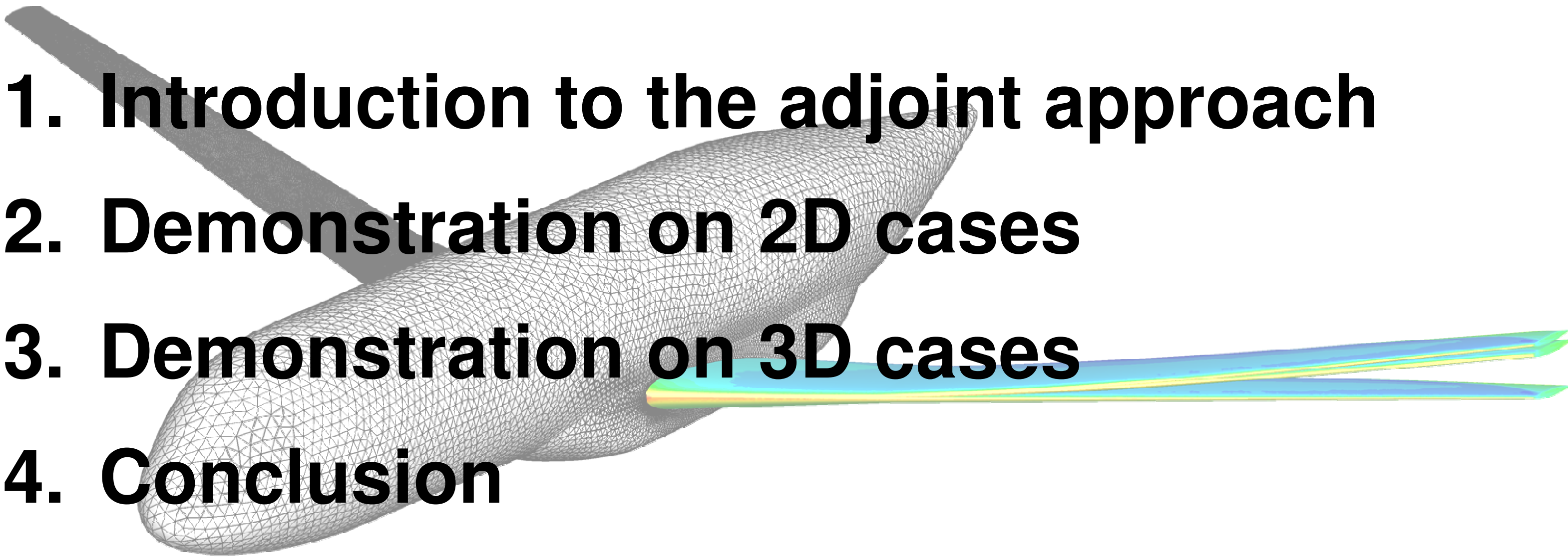
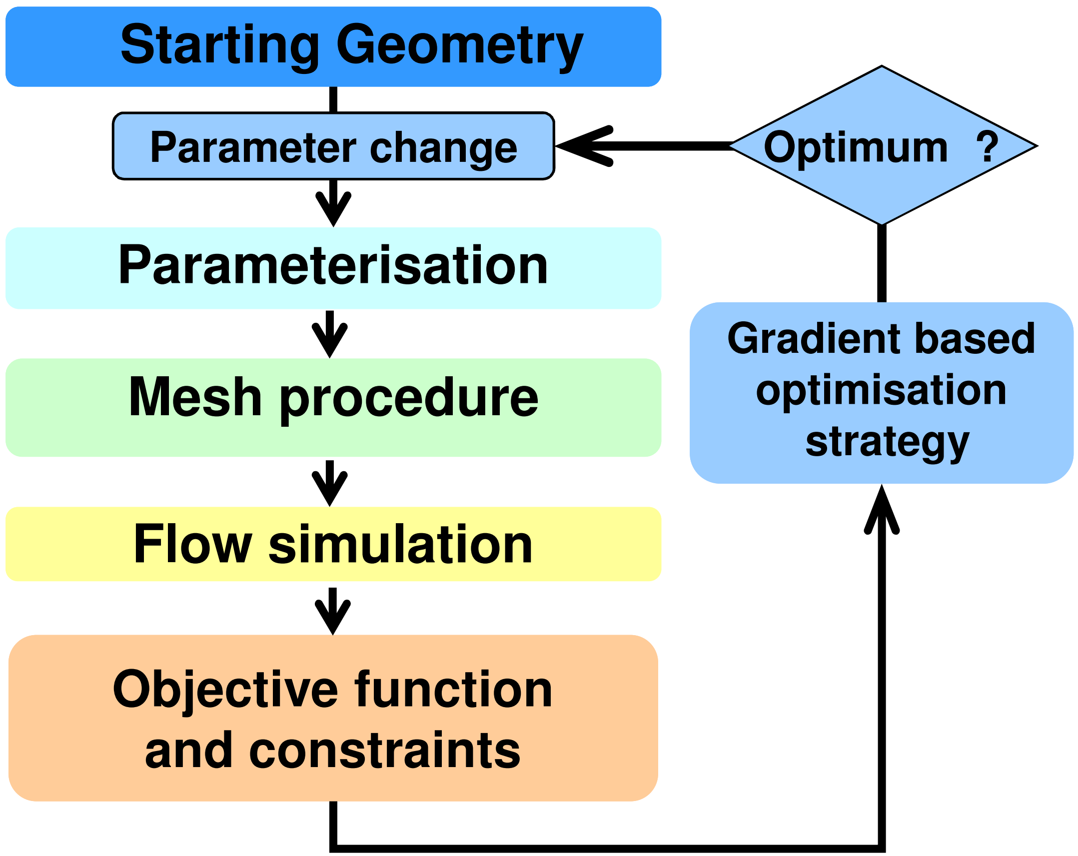
Gradient based optimisation strategy

Outline



1. Introduction to the adjoint approach
2. Demonstration on 2D cases
3. Demonstration on 3D cases
4. Conclusion

Introduction to the adjoint approach



Gradient based optimiser requires

- **the objective function and the constraints**
- **the corresponding gradients !**

How to compute the gradient:

- **with finite differences**

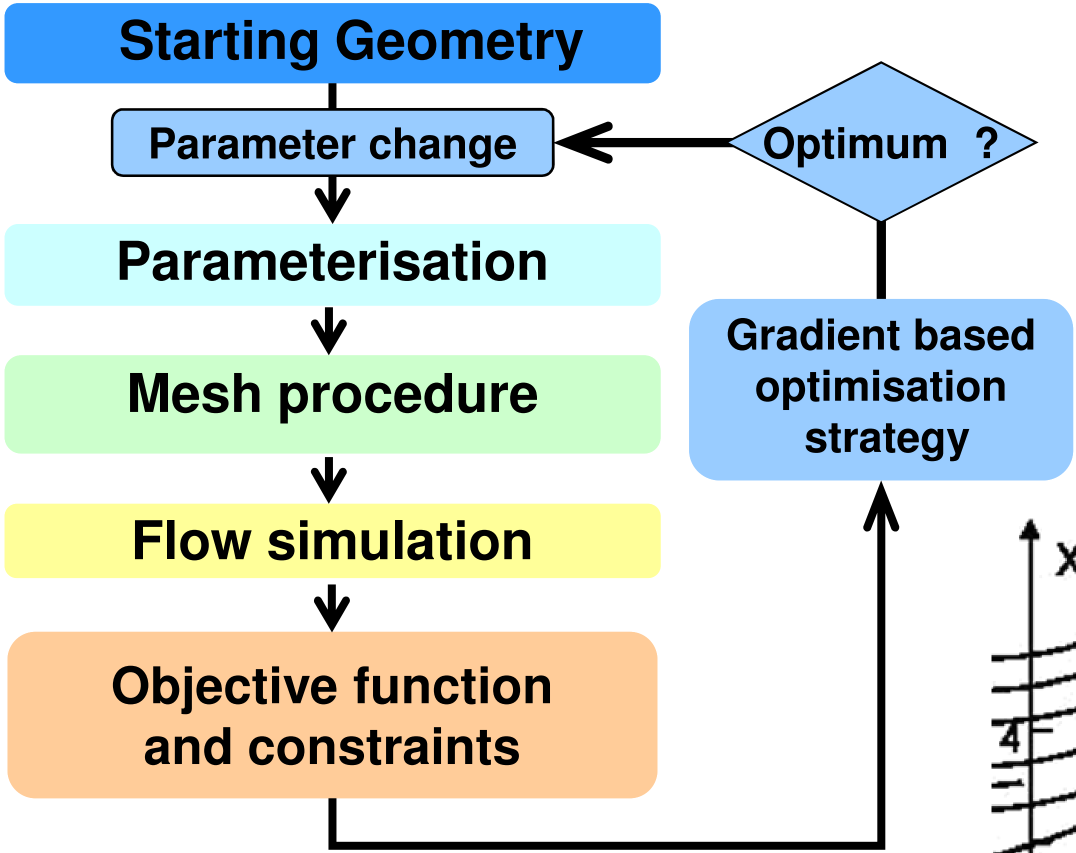
$$\frac{dI}{dD} \approx \frac{I(D+\Delta D) - I(D)}{\Delta D}$$

with

I the function of interest

D the shape design variable

Introduction to the adjoint approach



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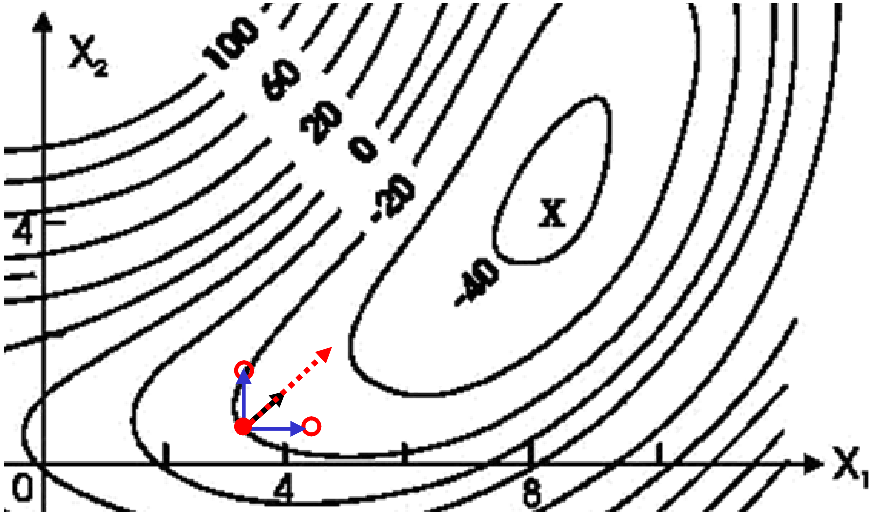
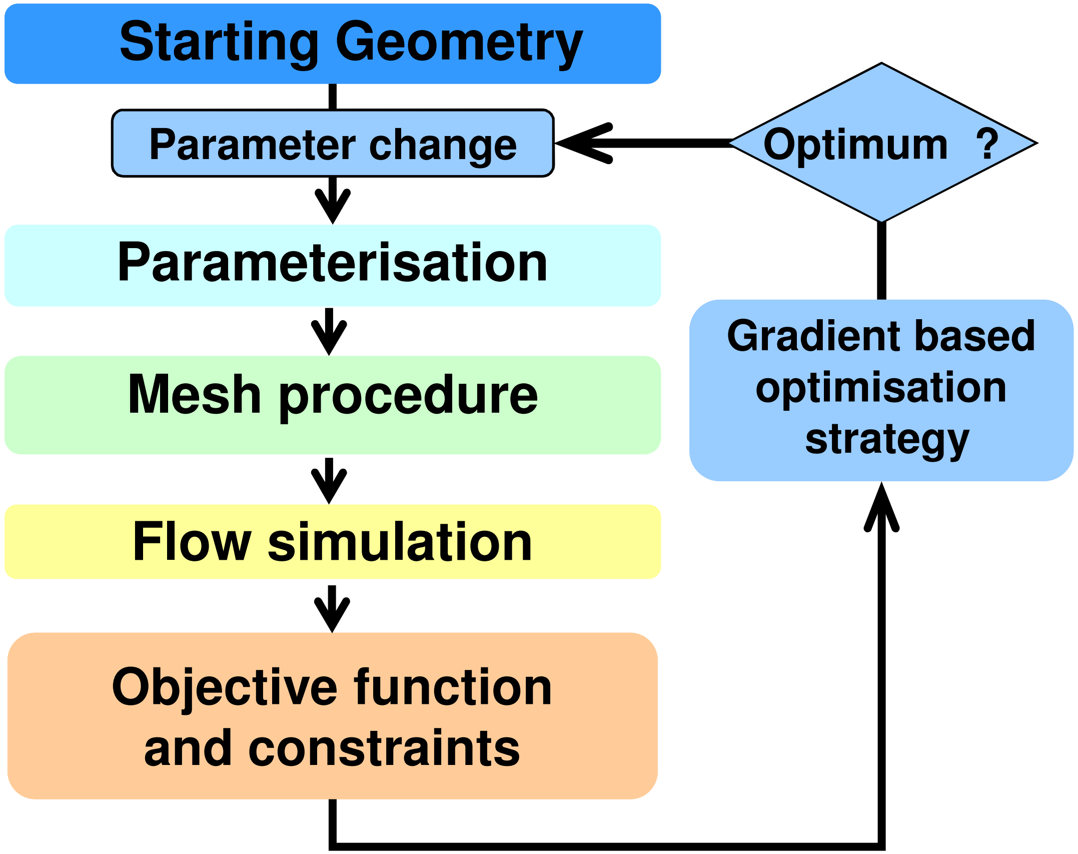


Introduction to the adjoint approach



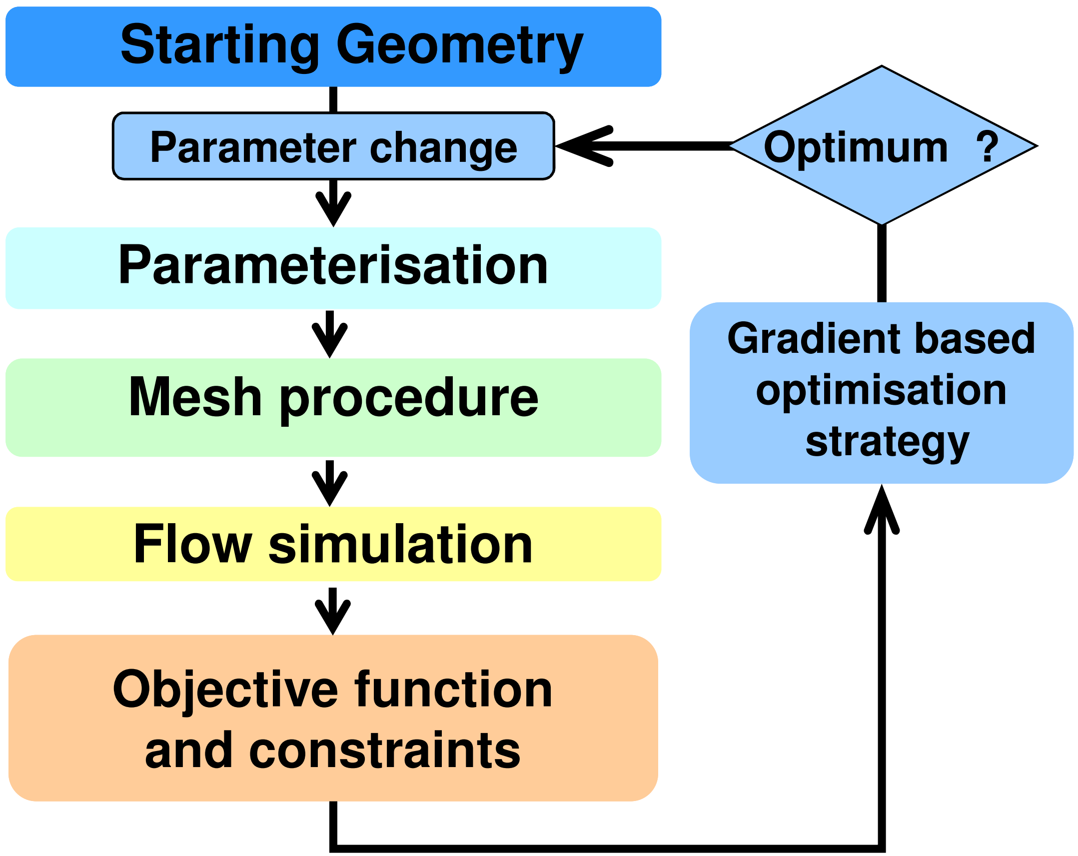
Gradient based optimiser requires

- the objective function and the constraints
- the corresponding gradients !

How to compute the gradient:

- with finite differences
  - straight forward
  - parallel evaluation
  - n evaluations required
  - accuracy not guaranteed

Introduction to the adjoint approach



Gradient based optimiser requires

- the objective function and the constraints
- the corresponding gradients !

How to compute the gradient:

- with finite differences
- with adjoint approach

Introduction to the adjoint approach

$\boldsymbol{I}$	the function of interest
$\boldsymbol{D}$	the design vector
$\boldsymbol{W}$	the flow variables
$\boldsymbol{R}$	the RANS residual
$\boldsymbol{X}$	the mesh
$\boldsymbol{\Lambda}$	the flow adjoint vector

If the flow residual is converged,

$$R(W, X, D) = 0$$

and after solving the flow adjoint equation of the function I

$$\frac{\partial I}{\partial W} + \Lambda^T \frac{\partial R}{\partial W} = 0$$

Adjoint equation independent to the design variable D

the derivatives of I with respect to the shape design vector D becomes

$$\frac{dI}{dD} = \underbrace{\frac{\partial I}{\partial X}\frac{\partial X}{\partial D}} + \Lambda^T \underbrace{\frac{\partial R}{\partial X}\frac{\partial X}{\partial D}}$$

Metrics terms, independent to W

Variation of the function I w.r.t. the shape parameter D by W constant

Variation of the RANS residual R w.r.t. the shape parameter D by W constant

Introduction to the adjoint approach

$$\frac{\partial I}{\partial W} + \Lambda^T \frac{\partial R}{\partial W} = 0$$

Computation of the discrete adjoint flow in DLR-Tau code

- Linearization of the cost function:
  - CD, CL, Cm including pressure and viscous comp.; Target Cp
- Linearization of the residuum
  - for Euler flow
  - for Navier-Stokes with SA and k-ω models
- Resolution of the flow adjoint equation with
  - PETSC in 2D and 3D (with or without frozen turbulence)
  - FACEMAT in 2D or 3D (but conv. guarantee only for frozen turbulence)
  - AMG solver with Krylov solver for stabilization (currently under test)

Computation of the continuous adjoint flow in Tau

- Inviscid formulation in central version available
- Cost function: CD, CL, Cm

Computation of the metric terms

$$\frac{dI}{dD} = \frac{\partial I}{\partial X}\frac{\partial X}{\partial D} + \Lambda^T \frac{\partial R}{\partial X}\frac{\partial X}{\partial D}$$

Strategy 1: with finite differences

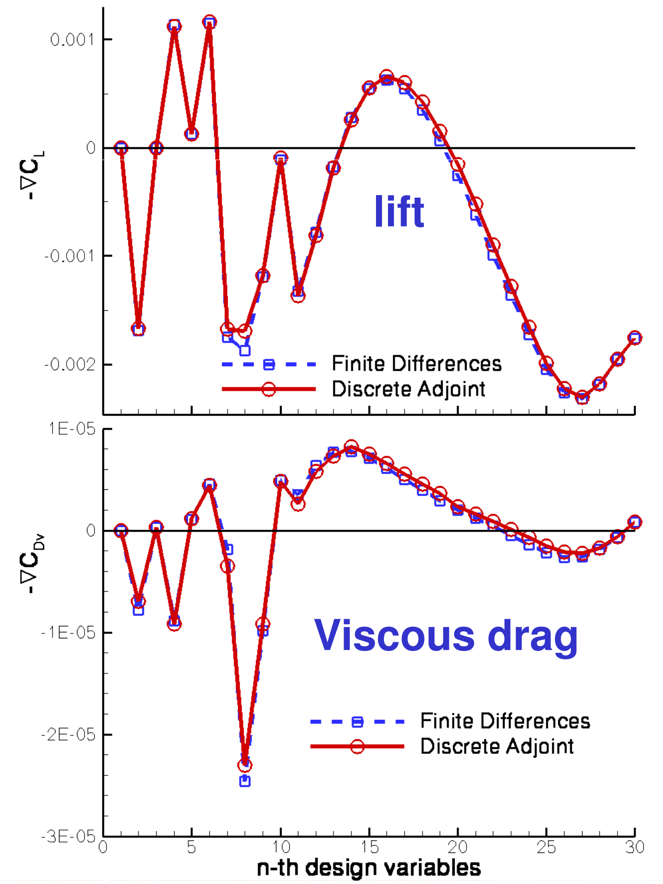
$$\frac{\partial I}{\partial D} \approx \frac{I(W, D+\Delta D) - I(W, D)}{\Delta D}$$

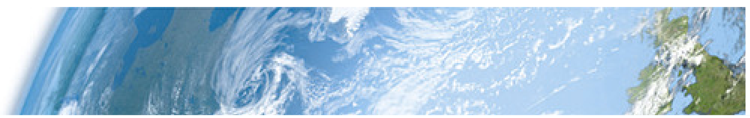
$$\frac{\partial R}{\partial D} \approx \frac{R(W, D+\Delta D) - R(W, D)}{\Delta D}$$

Need to interpolate the residual on the modified shape

Applications

- RAE 2822 airfoil
- Parameterisation with 30 design variables (10 for the thickness and 20 for the camberline)
- M_∞=0.73, α = 2.0°, Re=6.5x10^6
- 2D viscous calculation with SAE model
- Discrete flow adjoint and finite differences for the metric terms





Markus Widhalm

Computation of the metric terms

$$\frac{dI}{dD} = \frac{\partial I}{\partial X}\frac{\partial X}{\partial D} + \Lambda^T \frac{\partial R}{\partial X}\frac{\partial X}{\partial D}$$

Strategy 2: the metric adjoint

By introducing the metric adjoint equation

$$\frac{\partial I}{\partial X} + \Lambda^T \frac{\partial R}{\partial X} + \Phi^T \frac{\partial M}{\partial X} = 0$$

the derivatives of I with respect to D is simply

$$\frac{dI}{dD} = \Phi^{\mathrm{T}} \frac{\partial X_{surf}}{\partial D}$$

Consequence: if the design vector D represents the mesh points at the surface, the gradient of the cost function is equal to the metric adjoint vector

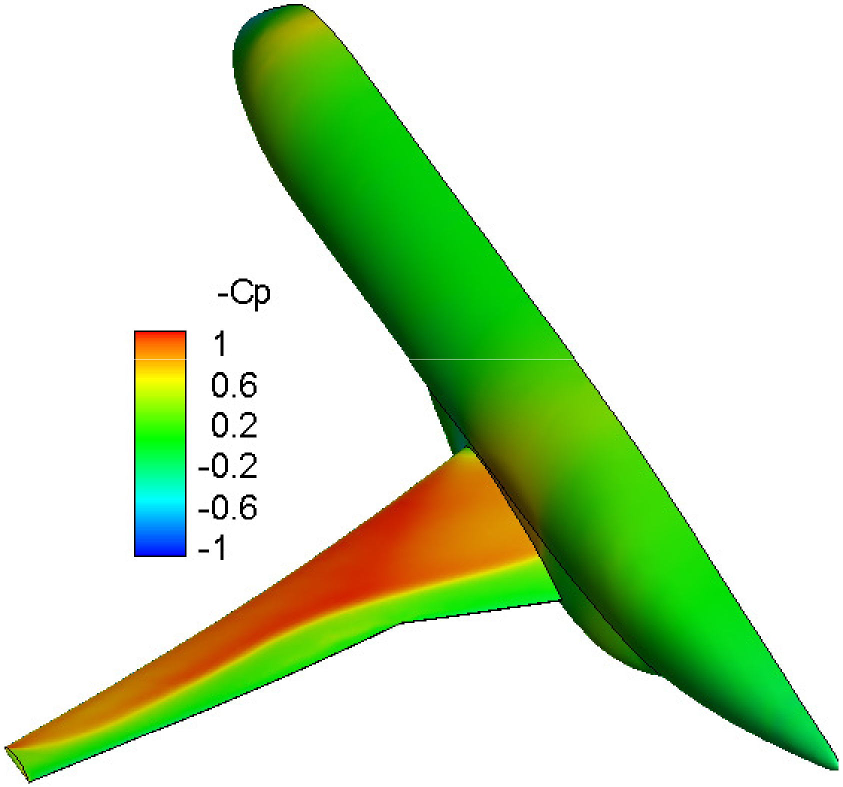
$$\frac{dI}{dD} = \Phi^{\mathrm{T}}$$

$\boldsymbol{I}$	the function of interest
$\boldsymbol{D}$	the design vector
$\boldsymbol{W}$	the flow variables
$\boldsymbol{R}$	the RANS residual
$\boldsymbol{X}$	the mesh
$\boldsymbol{\Lambda}$	the flow adjoint vector
$\boldsymbol{M}$	the mesh deformation
$\boldsymbol{\Phi}$	the metric adjoint vec.

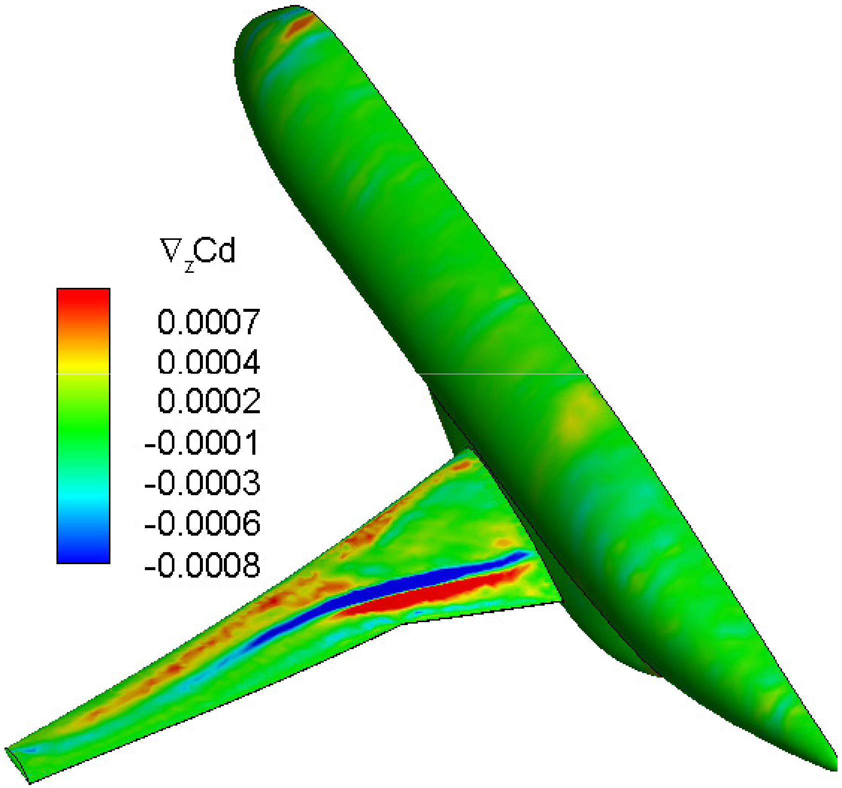
Metric adjoint: demonstration on 3D viscous case

Wing Body configuration – RANS computation (SA model)

Mach=0.82, Alpha=1.8°, Re=21x10^6

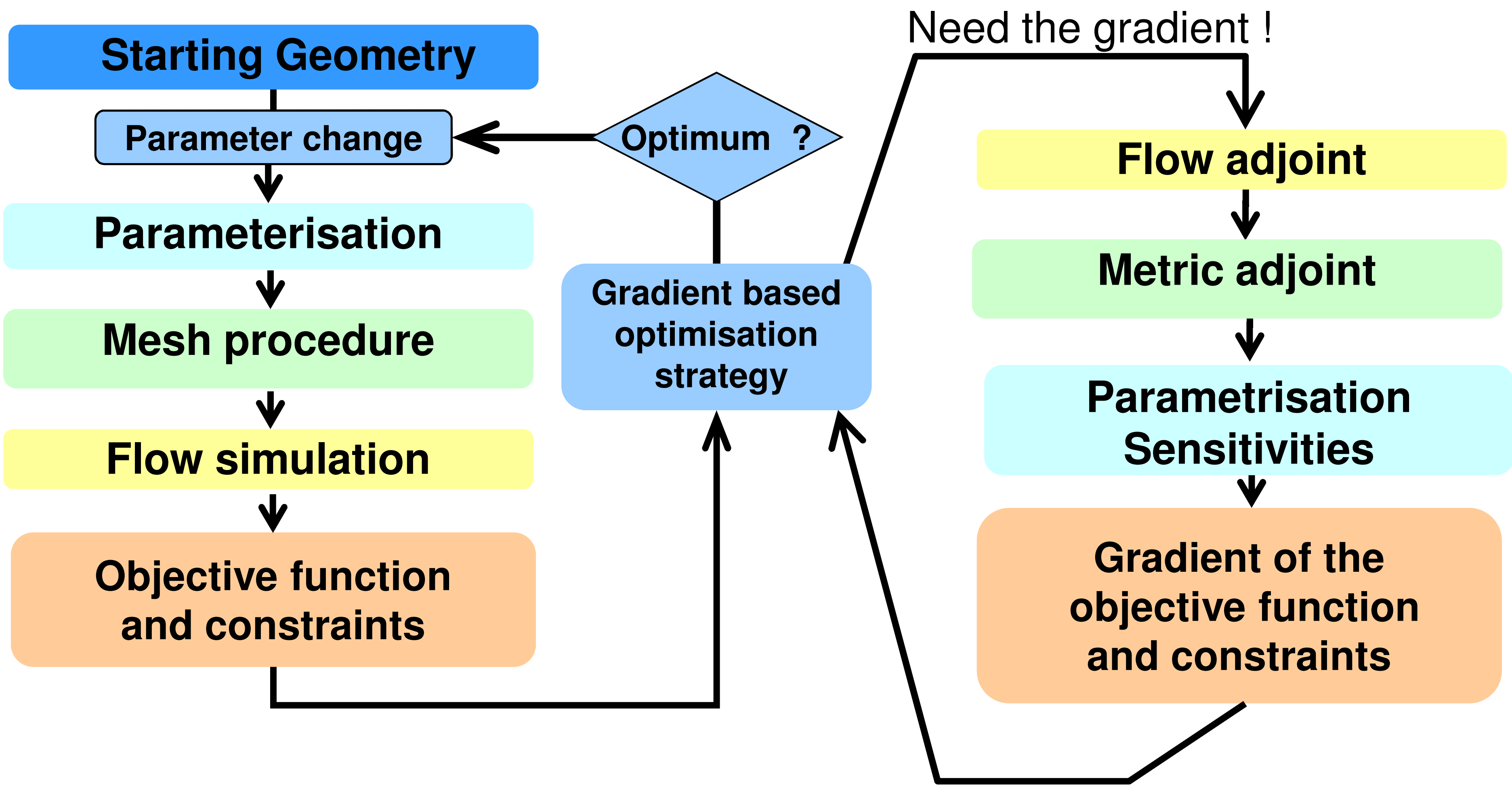


Cp distribution on the surface

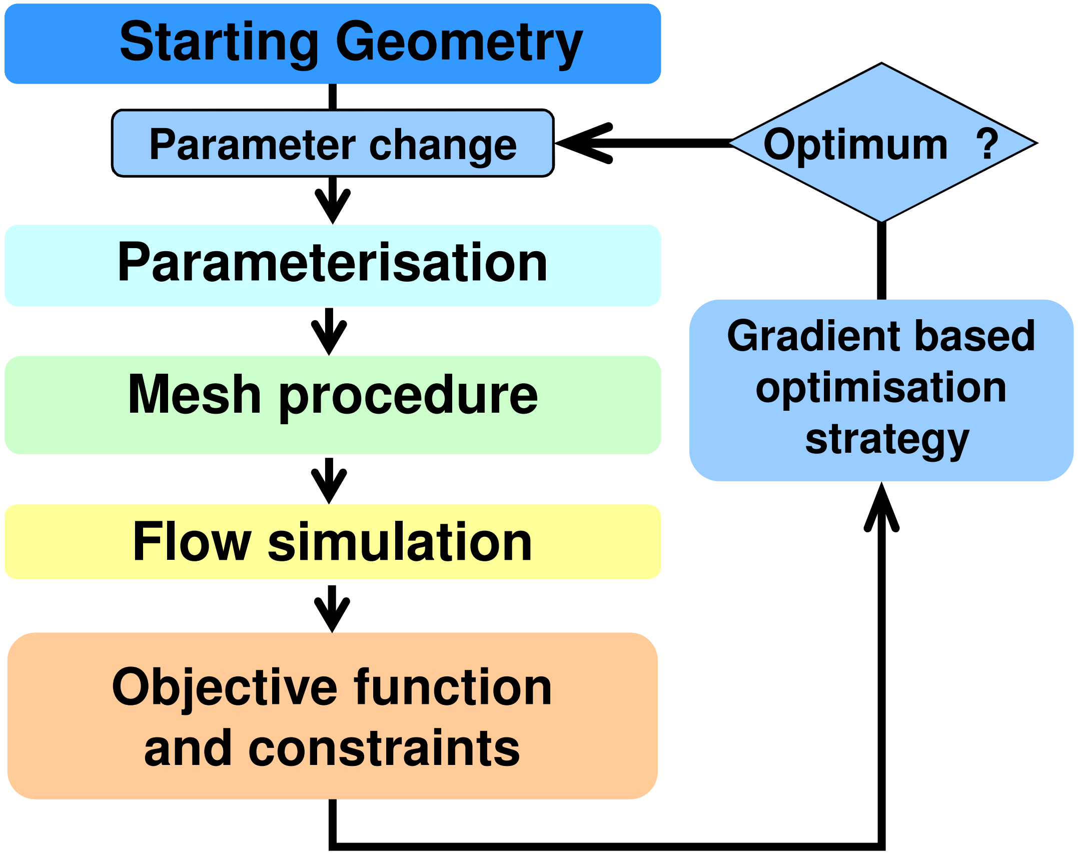


Drag Sensitivity on the surface

Introduction to the adjoint approach in the process chain



Introduction to the adjoint approach



Gradient based optimiser:

- Requires the objective function and the constraints
- Requires the <u>gradients</u> !

How to compute the gradient:

- with finite differences
- with adjoint approach
  - add process chain
  - need converged solution
  - not all function available
  - accurate gradient
  - independent of n

2D airfoil shape optimisation

Single Point Optimisation

Optimisation problem

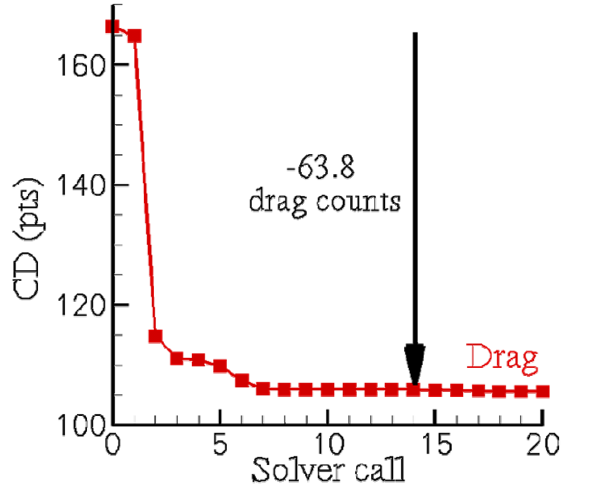
- RAE 2822 airfoil
- Objective: drag reduction at constant lift
- Maximal thickness is kept constant
- Design condition : M_{∞}=0.73, CL= 0.8055

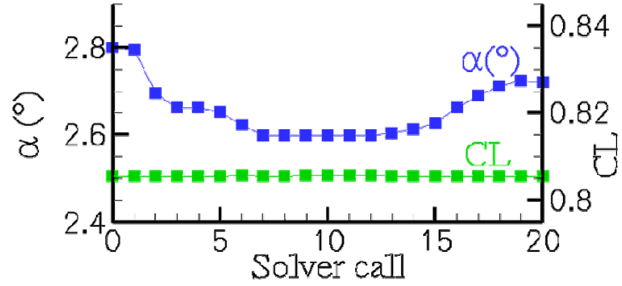
Strategy

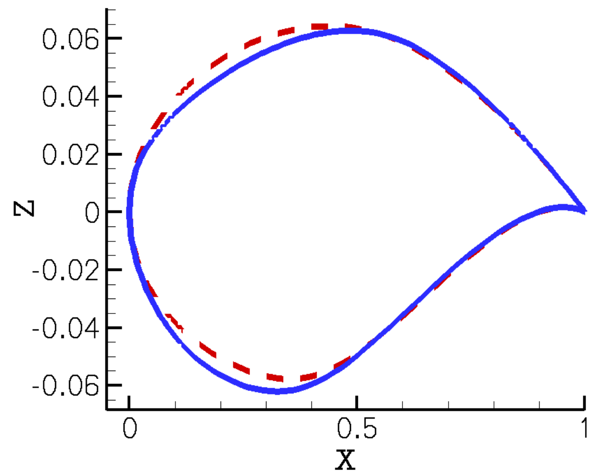
- Parameterisation with 20 design variables changing the camberline
- Mesh deformation
- 2D Tau calculation on unstructured mesh
- Resolution of adjoint solutions

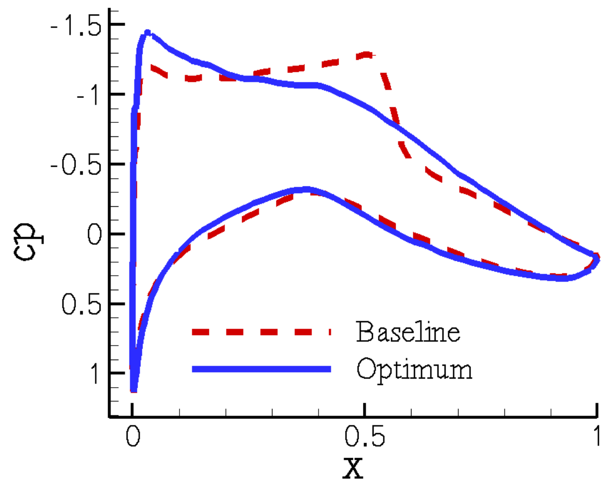
Results

- No lift change
- 21 states and 21x2 gradients evaluations
- Shock free airfoil









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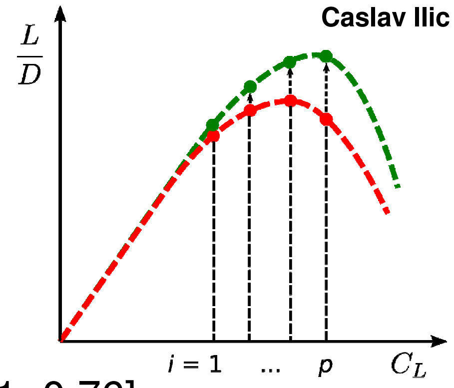
Multi-Point optimisation



Objective

- Maximize the weighted average of L/D at p points
- Equidistant points, equally-weighted
- p=1 CL=0.76; p = 4 points in CL=[0.46, 0.76]; p = 8 points in CL=[0.41, 0.76]

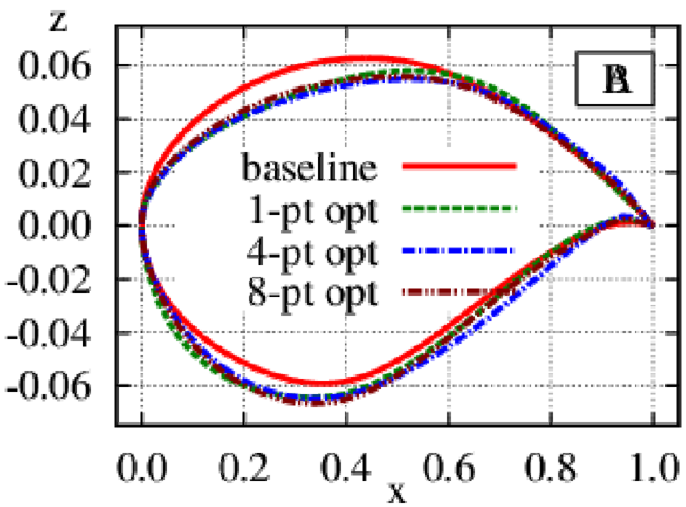
Constraints

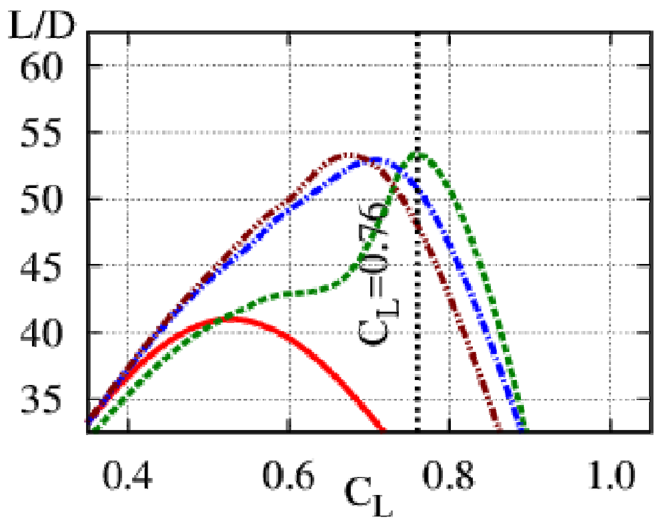
- Lift (to determine the polar points) → implicitly (TAU target lift)
- Pitching moment (at each polar point) → explicitly handled (SQP)
- Enclosed volume constant → explicitly handled (SQP)

Parametrisation

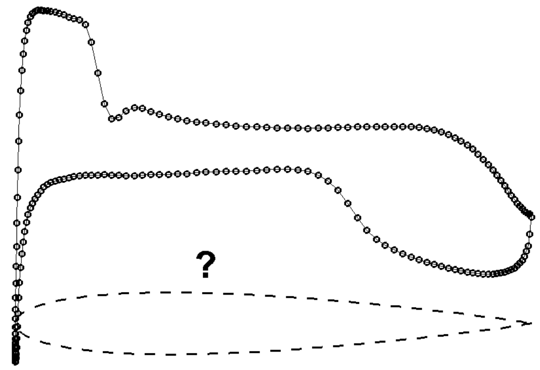
- In total 30 design parameters controlling the pressure and suction sides

Results





Optimisation approach for solving inverse design problem



Principle

- Find the geometry that fit a given pressure distribution

Strategy

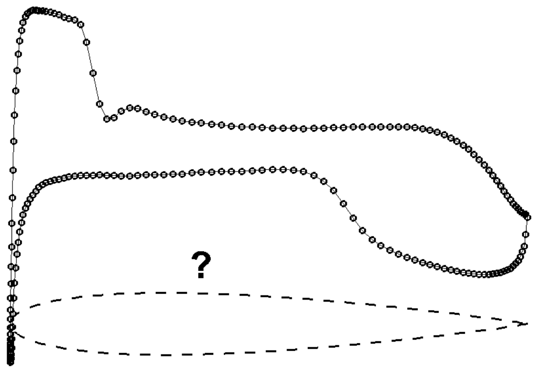
- Treat the problem as an optimisation problem with the following goal function to minimise:

$$Goal = \int_{Body} \left(Cp - Cp_{\text{target}}\right)^2 dS$$

- Parametrisation: angle of attack + each surface mesh point
- Sobolev smoother to ensure smooth shape during the design
- Mesh deformation
- Use of TAU-restart for fast CFD evaluation
- TAU-Adjoint for efficient computation of the gradients
- Gradient based approach as optimisation algorithm

Test Case: Transonic Condition

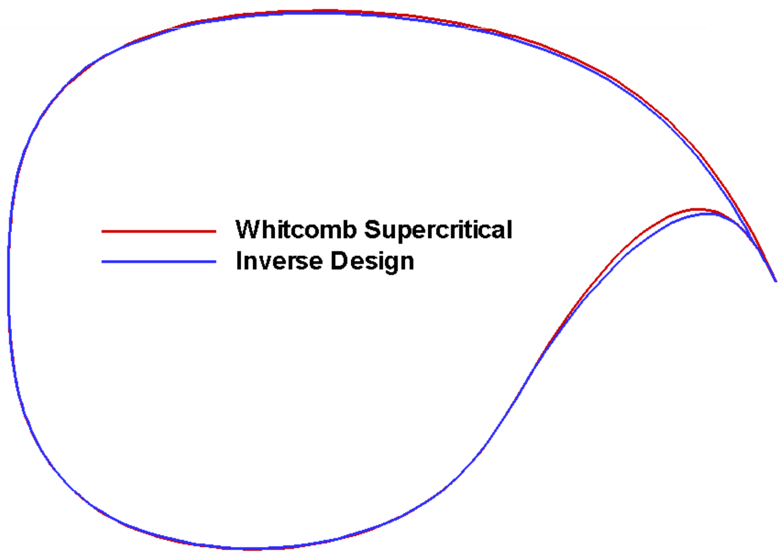
M_∞=0.7; Re= 15x10^6

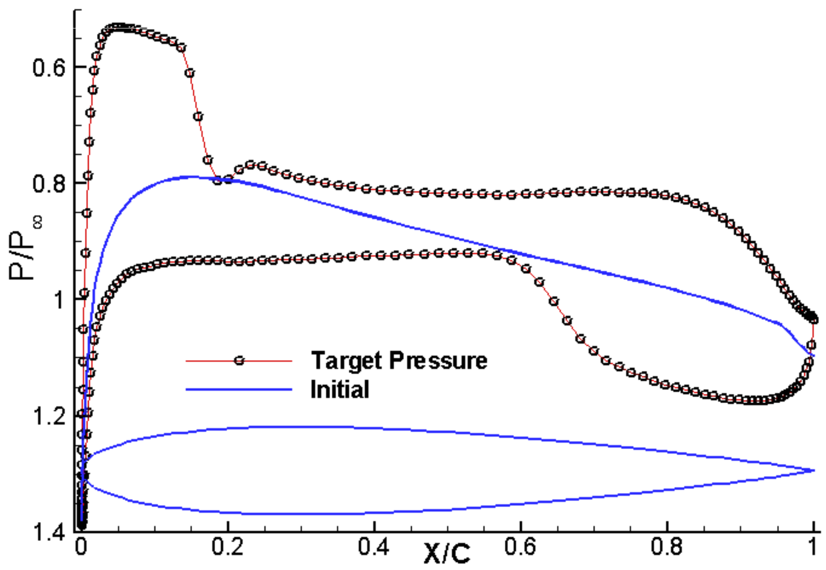


Result

- 400 design cycle to match the target pressure
- Final geometry with blunt nose, very sharp trailing edge, flow condition close to separation near upper trailing edge

Verification: pressure distribution computed on the Whitcomd supercritical profile at AoA=0.6





Next steps

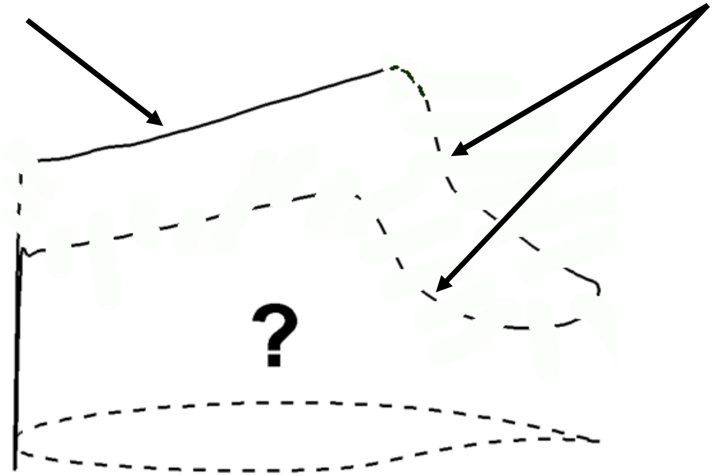
Problems

- All components for efficient optimizations are integrated but still requires more time than the conventional Takanashi approach
- Need to define the full pressure distribution (upper and lower side): lengthy iterations to define a feasible target pressure that ensure minimum drag, a given lift and pitching moment coefficients

Solution

- Combine target pressure at specific area (like the upper part) and “close” the optimisation problem with aerodynamic coefficients

$$Goal = \int_{Part\ Body} \left(Cp - Cp_{\text{target}}\right)^2 dS + Cd + a(Cl - Cl_{\text{target}}) + b(Cm - Cm_{\text{target}})$$

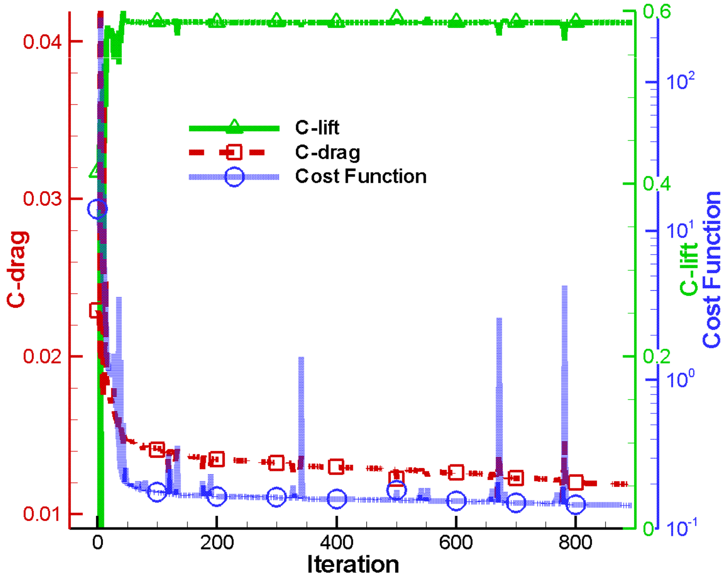


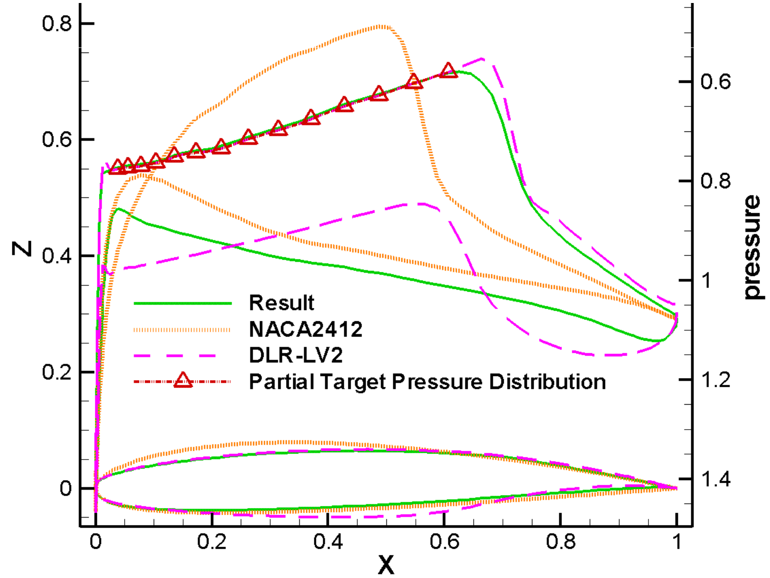
Fei Ma

Next steps

Preliminary Result

- Pressure distribution at the upper part of the LV2 airfoil
- Drag minimisation at target lift
- Starting geometry is the NACA2412 at M=0.76 ; Re=15’000’000
- Optimized geometry match the target pressure and the required lift, with 17.4% less drag than the LV2 profile





Promising approach for laminar design based on adjoint approach without the need of the derivation of the transition criteria

2D High-Lift problem

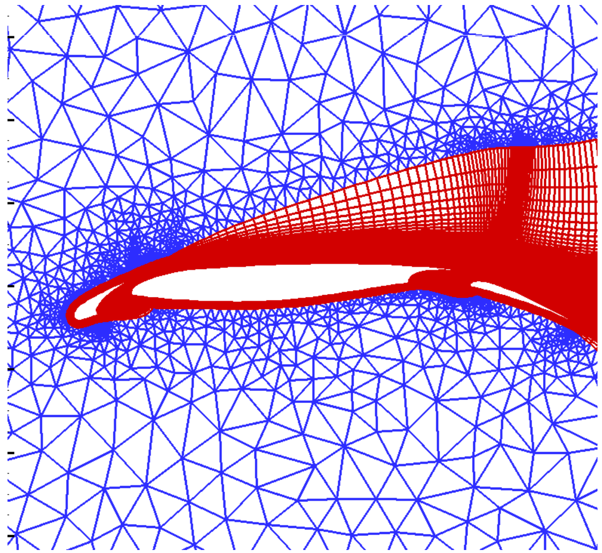
Test case specification (derived from Eurolift II project)

Configuration

- Section of the DLR-F11 at M_∞=0.2 ; Re=20x10^6 ; α=8 º

Objective and constraints

- Maximization of $OBJ = \left(\frac{CL_{3D}^3}{CD_{3D}^2} \right)$
- $CL > CL_{initial}$
- $Cm > Cm_{initial}$, with Cm the pitching nose up moment
- Penalty to limit the deployment of the flap and slat (constraints from the kinematics of the high-lift system)

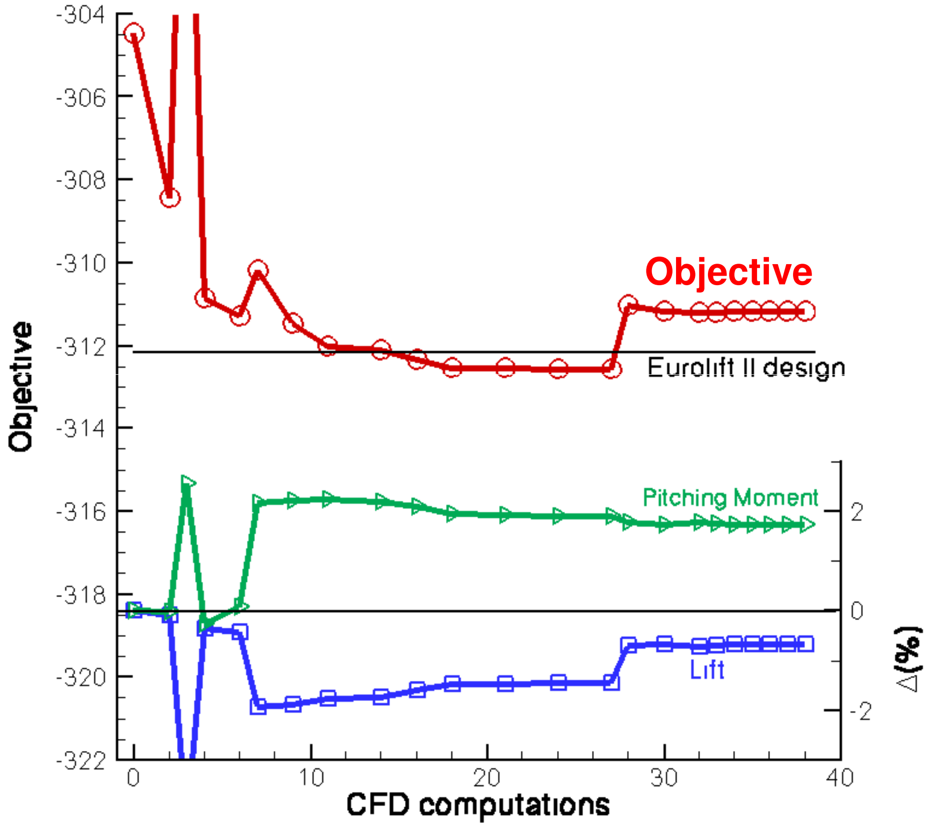


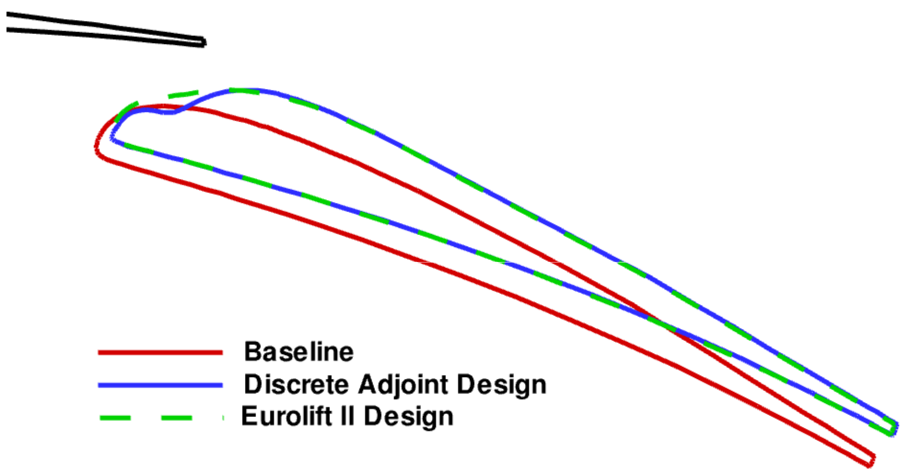
Strategy

- Flap shape and position (10 design variables)
- TAU-code in viscous mode with SAE model
- All TAU discretisations have been differentiated
- Krylov-based solver to get the adjoint field

Flap design with NLPQL and adjoint approach

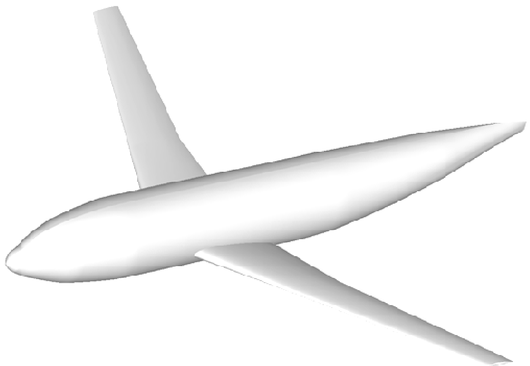
Results





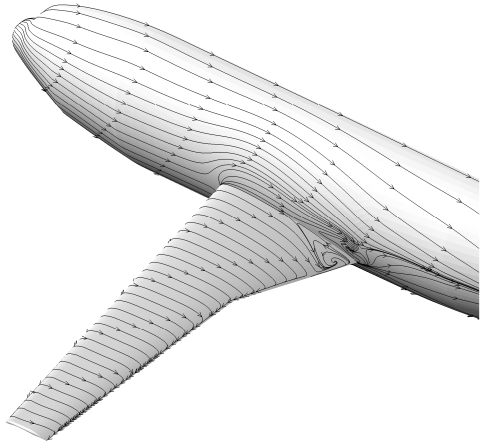
Eurolift II design: optimisation with genetic algorithm + constraints on CLmax

Cruise Configuration DLR F6 wing-body configuration



DLR

Wing optimization of the DLR-F6

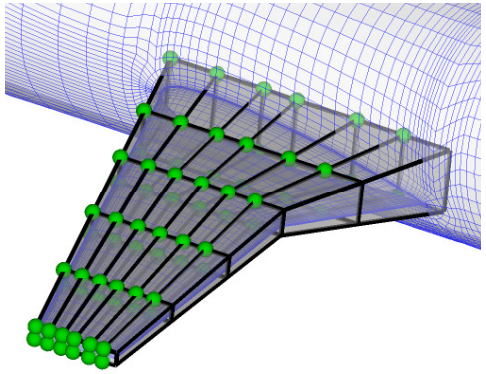


Configuration

- DLR-F6 wing-body configuration

Objective and constraints

- Minimisation of the drag
- Lift maintained constant
- Maximum thickness constant

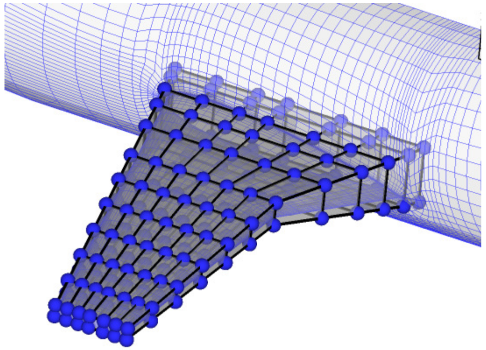


Flow condition

- M_∞=0.75 ; Re=3x10^6 ; CL=0.5

Approach used

- Free-Form Deformation to change the camberline and the twist distribution – thickness is frozen
- Parametrisation with 42 or 96 variables
- Update of the wing-fuselage junction
- Discrete adjoint approach for gradients evaluation
- Lift maintained constant by automatically adjusting the angle of incidence during the flow computation

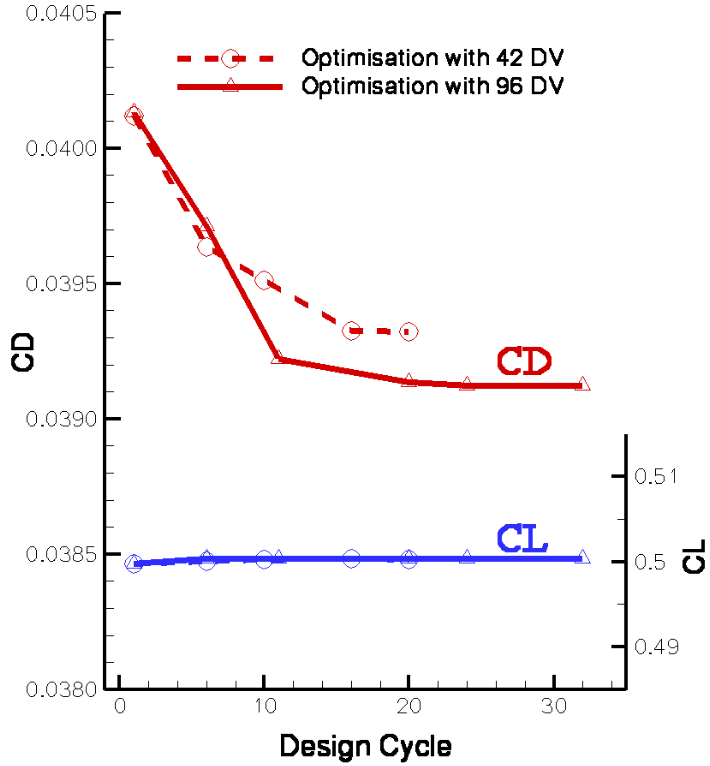


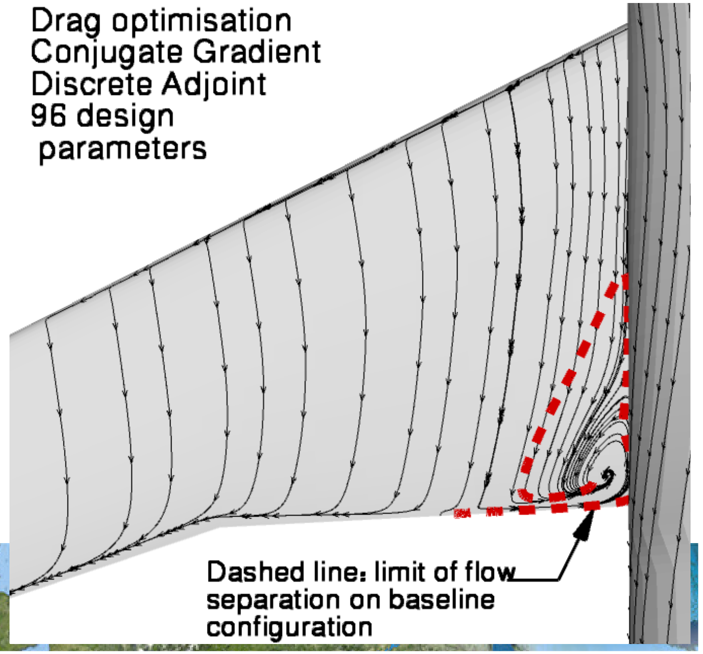
Wing optimization of the DLR-F6

Results

- Optimisation with 42 design variables
  - 20 design cycles
  - 4 gradients comp. with adjoint
  - 8 drag counts reduction

- Optimisation with 96 design variables
  - 32 design cycles
  - 5 gradients comp. with adjoint
  - 10 drag counts reduction

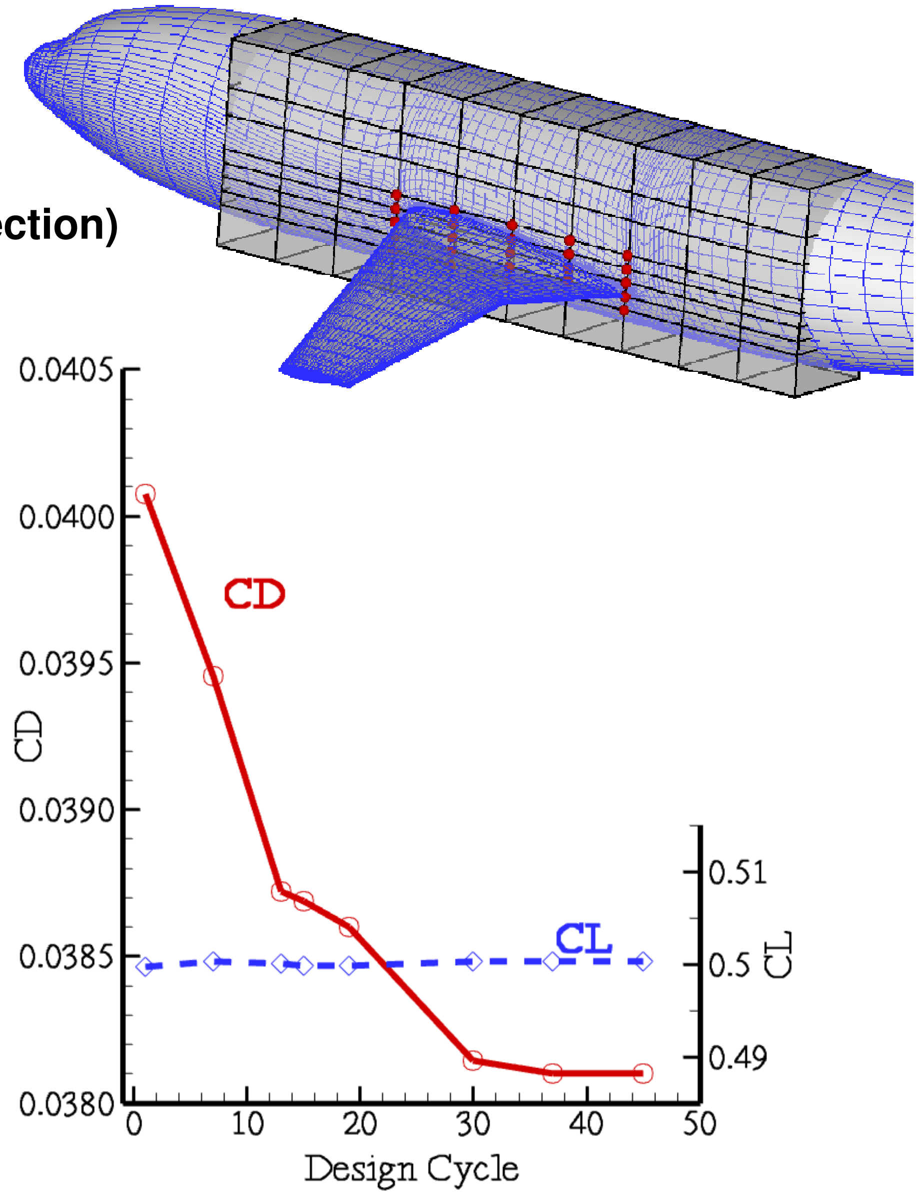




Fuselage optimization of the DLR-F6

Strategy

- Definition of the Free-Form box around the body only
- 25 nodes are free to move (in spanwise direction)
- Update of the wing-fuselage junction
- Gradient based optimizer
- Discrete adjoint approach for gradients evaluation
- Lift maintained constant by automatically adjusting the angle of incidence during the flow computation

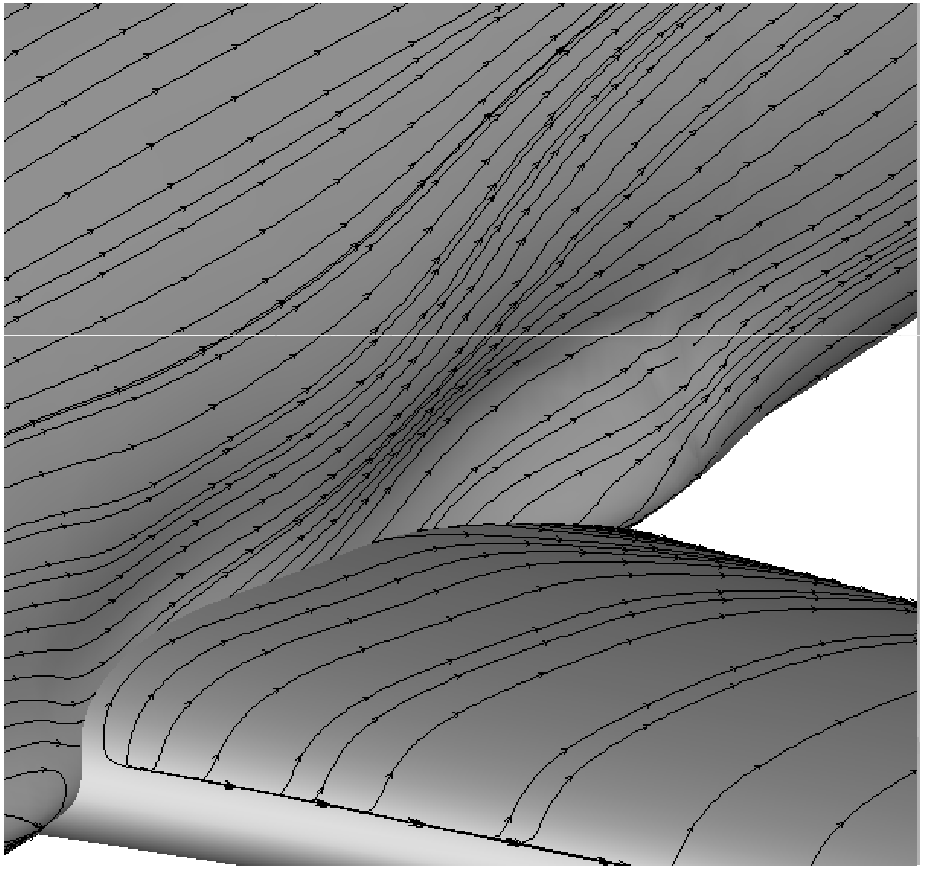


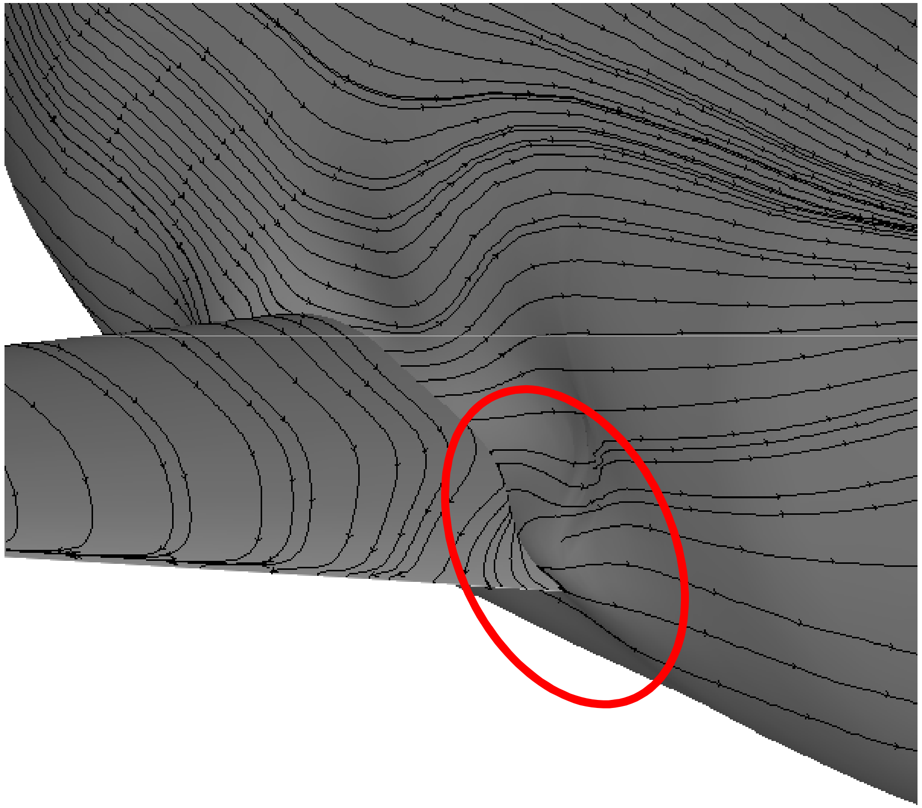
Results

- 30 design cycles
- 5 gradients comp. with adjoint
- 20 drag counts reduction !!!
- Lift maintained constant

Fuselage optimization of the DLR-F6

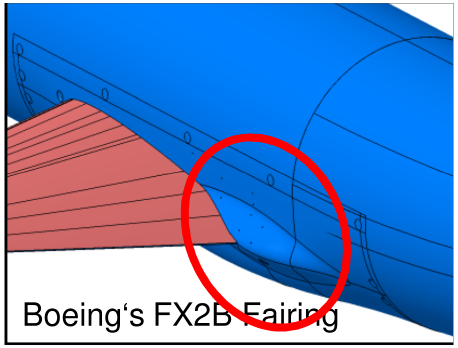
Streamtraces on the body wing

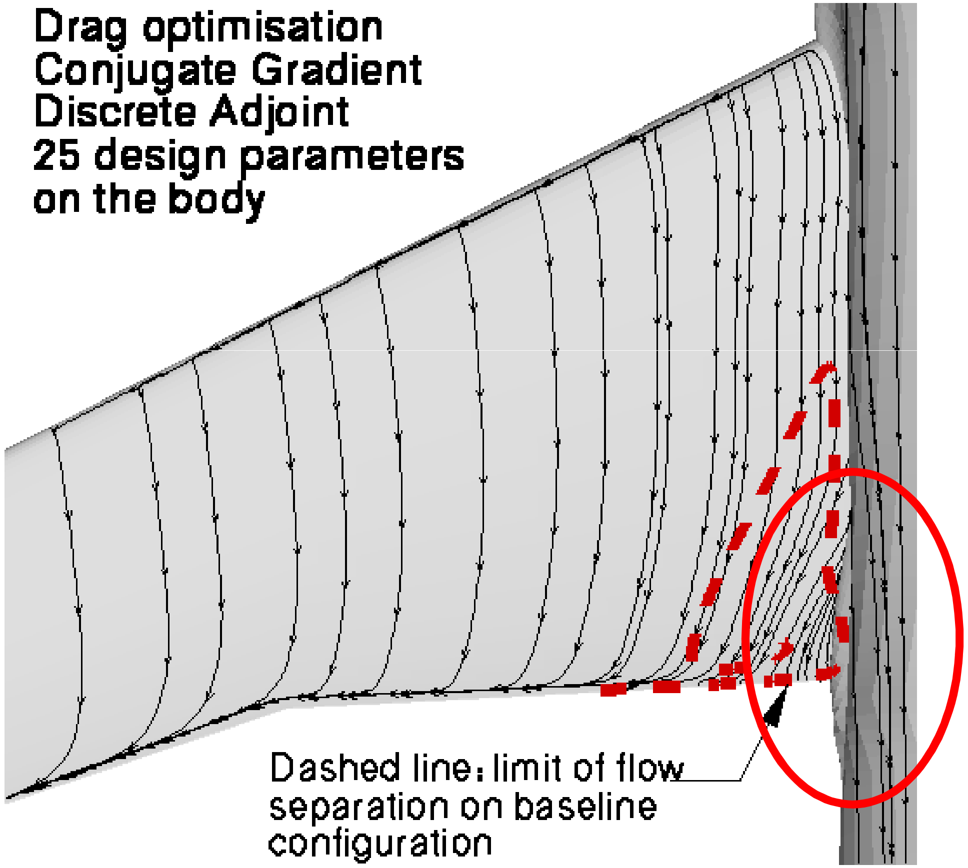




Fuselage optimization of the DLR-F6

Streamtraces on the body wing

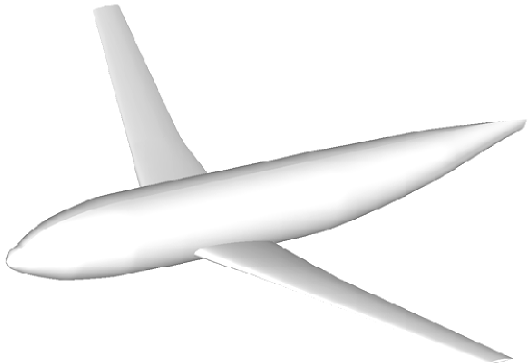




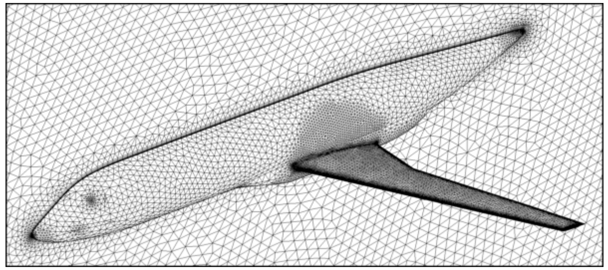
Tests of WB Configuration in the Onera S2 Facility (2008)

Moh’d Abu-Zurayk,
Caslav Ilic

Multi-point wing-body optimisation

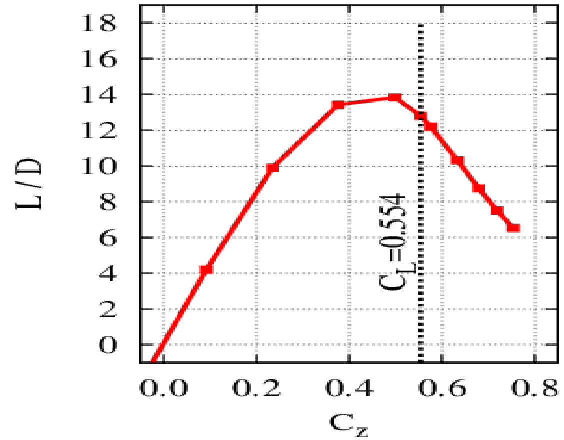


Single-Point L/D in 3D: Problem Setup



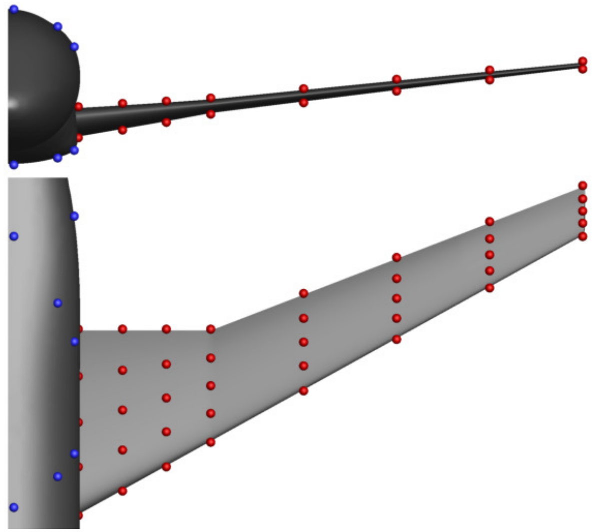
Objective:
- ➢ maximize the lift to drag ratio

Main design point:
- M = 0.72, Re = $21 \cdot 10^6$, CL = 0.554.

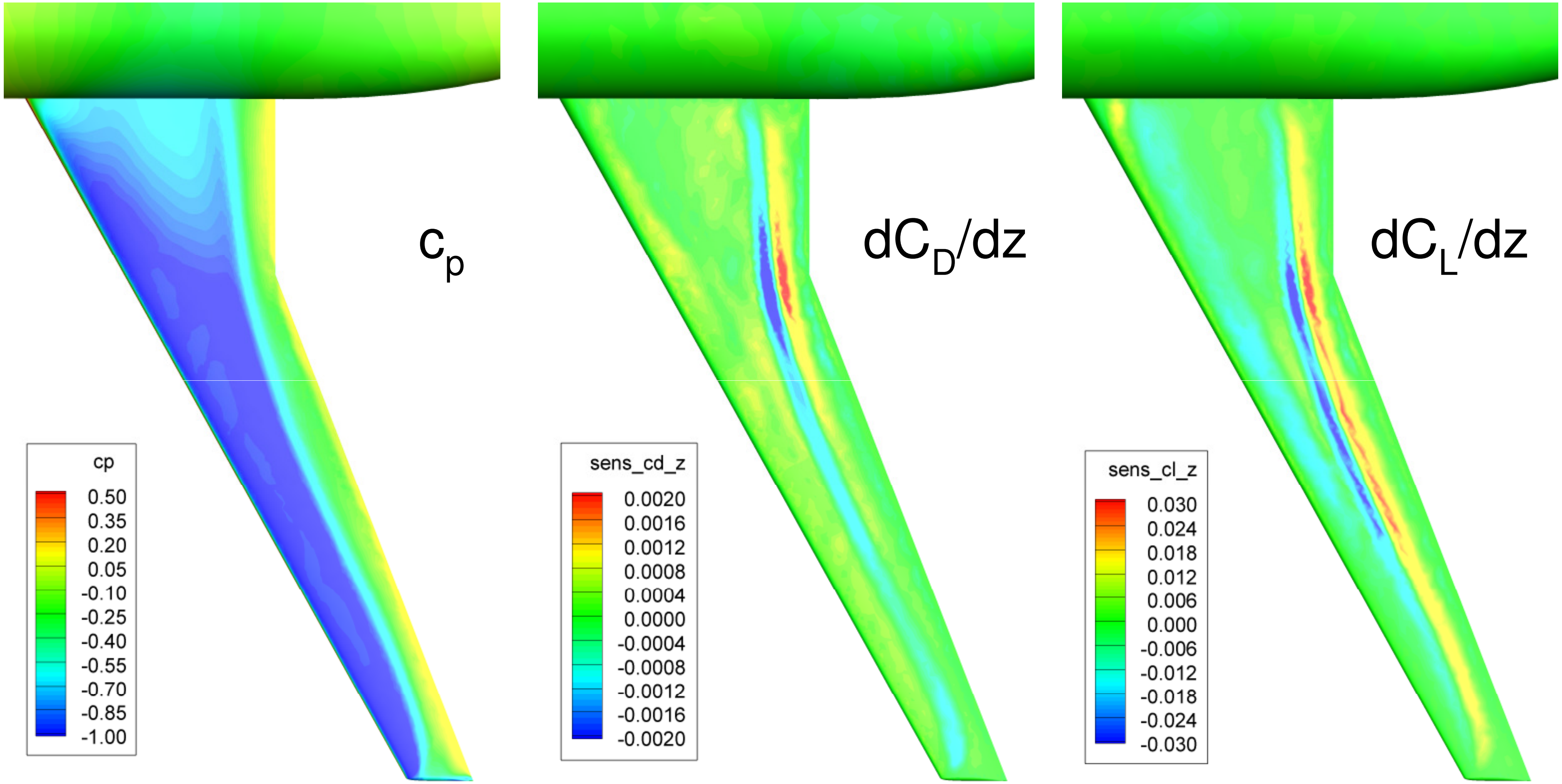


Constraints:
- ➢ lift → implicitly handled (TAU target lift)
- ➢ wing thickness → implicitly handled (parametrization)

Parametrization:
- ➢ 80 free-form deformation control points on the wing.
- ➢ z-displacement, upper/lower points linked
  → 40 design parameters.

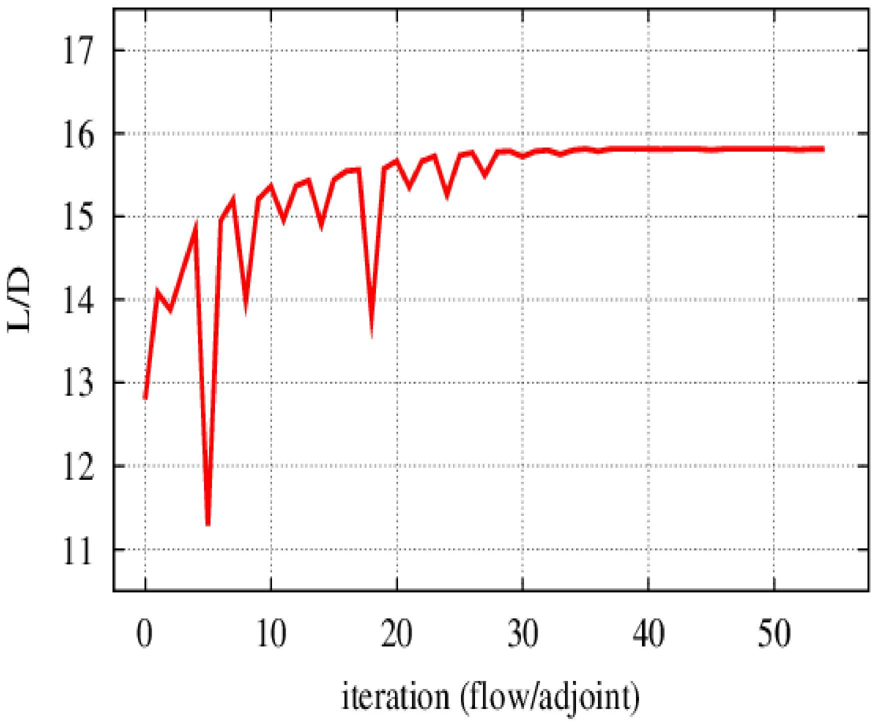


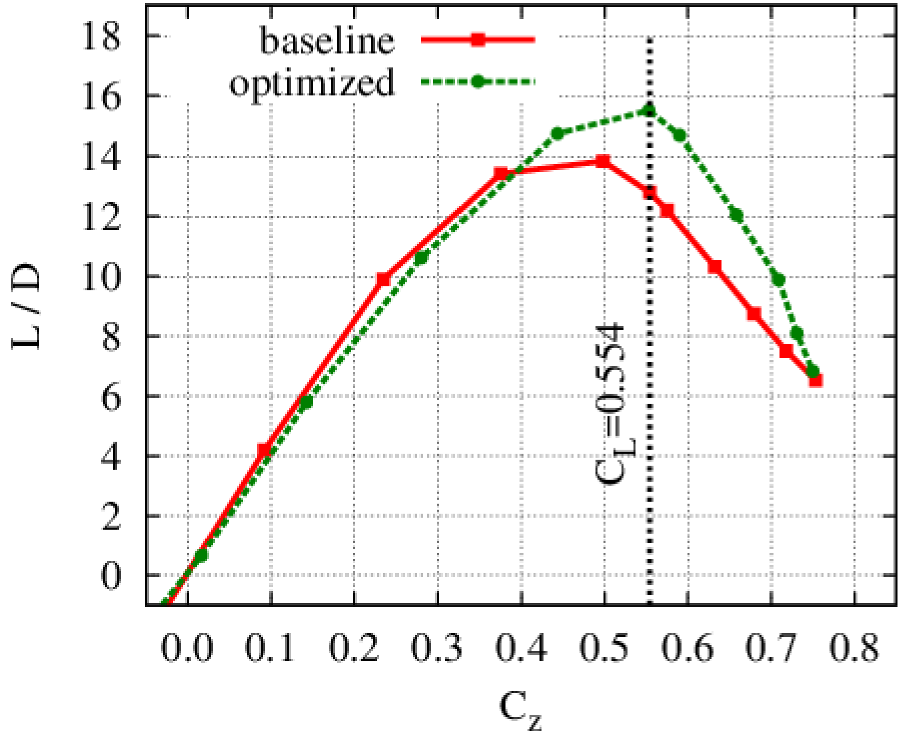
Single-Point L/D in 3D:
Flow Solution and Sensitivities with adjoint approach



Single-Point L/D in 3D: results

- L/D increased from 12.8 to 15.6 (21% up) at design point.

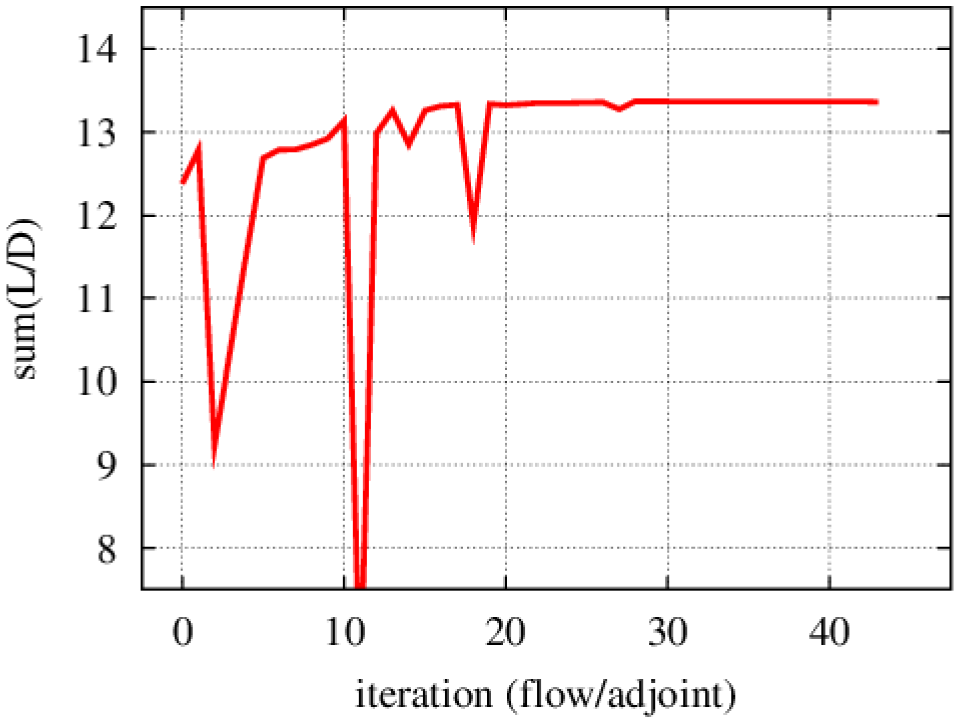


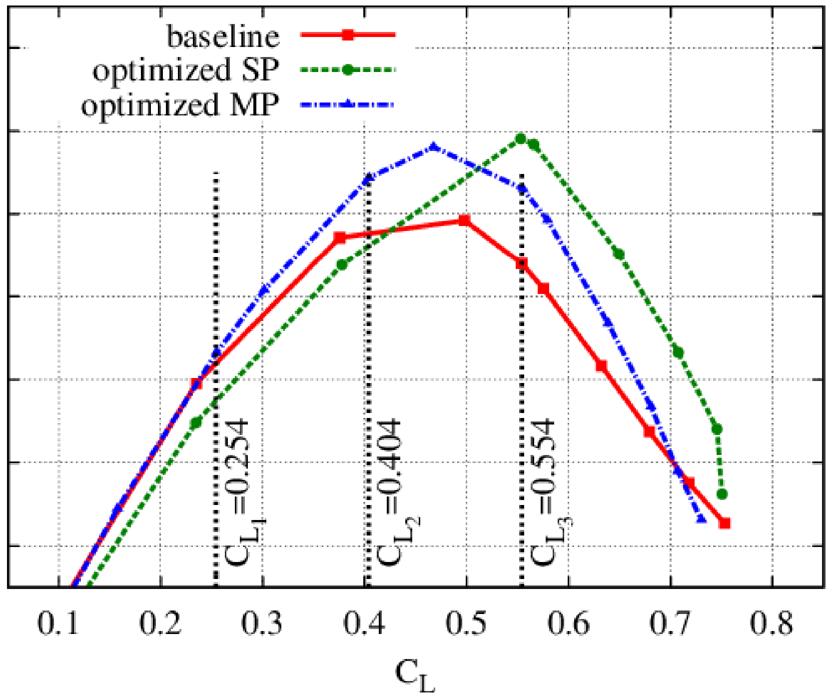


- Wall clock time: 43 hr on 4×8-core Intel Xeon E5540 nodes.

Multi-Point L/D in 3D: results

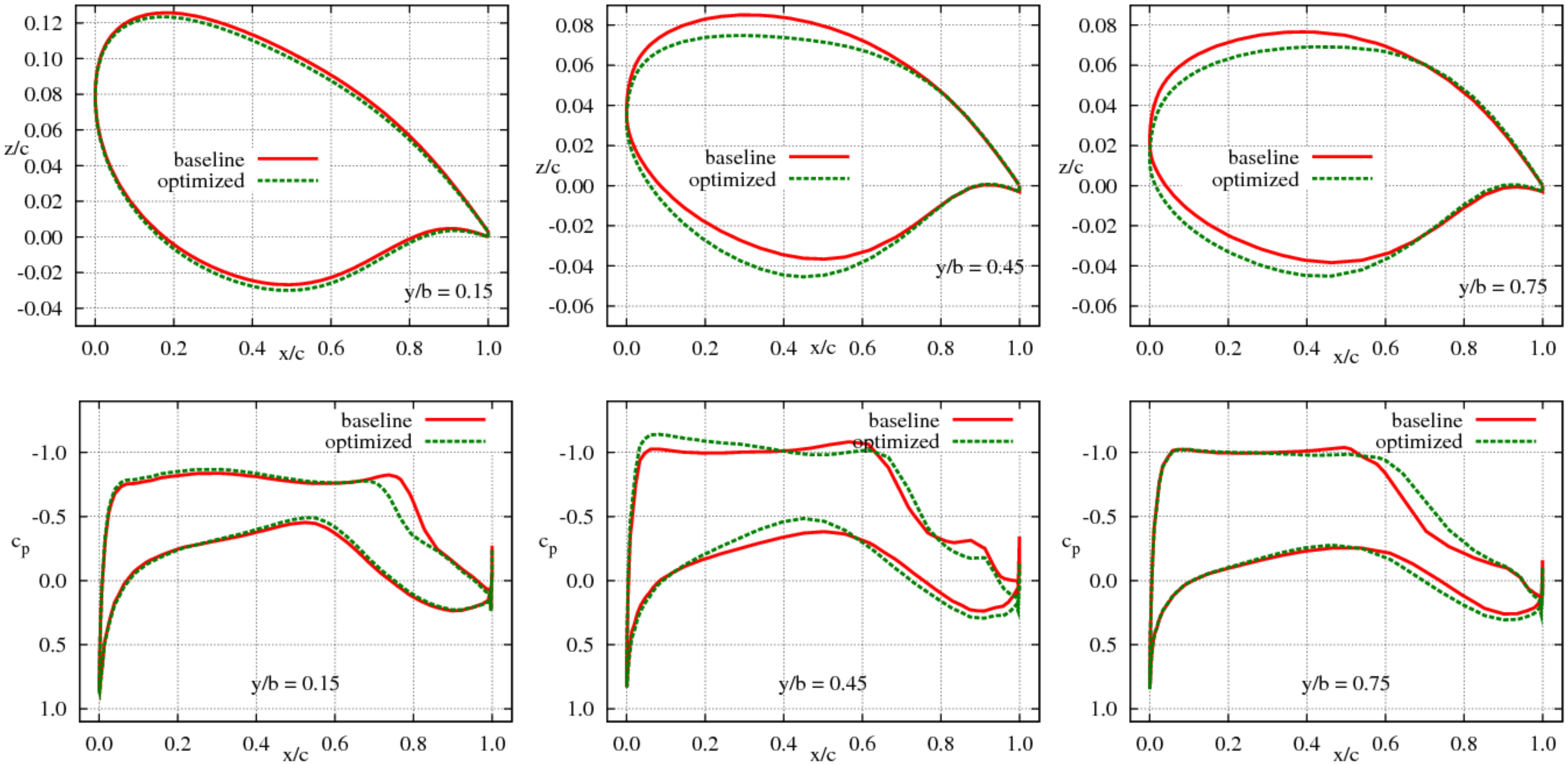
- Main Design point: M = 0.82, Re = $19.5 \cdot 10^6$, CL = 0.554
- Polar points: CL1 = 0.254, CL2 = 0.404, CL3 = 0.554





- Wall clock time: 87 hr on 4×8-core Intel Xeon E5540 nodes.

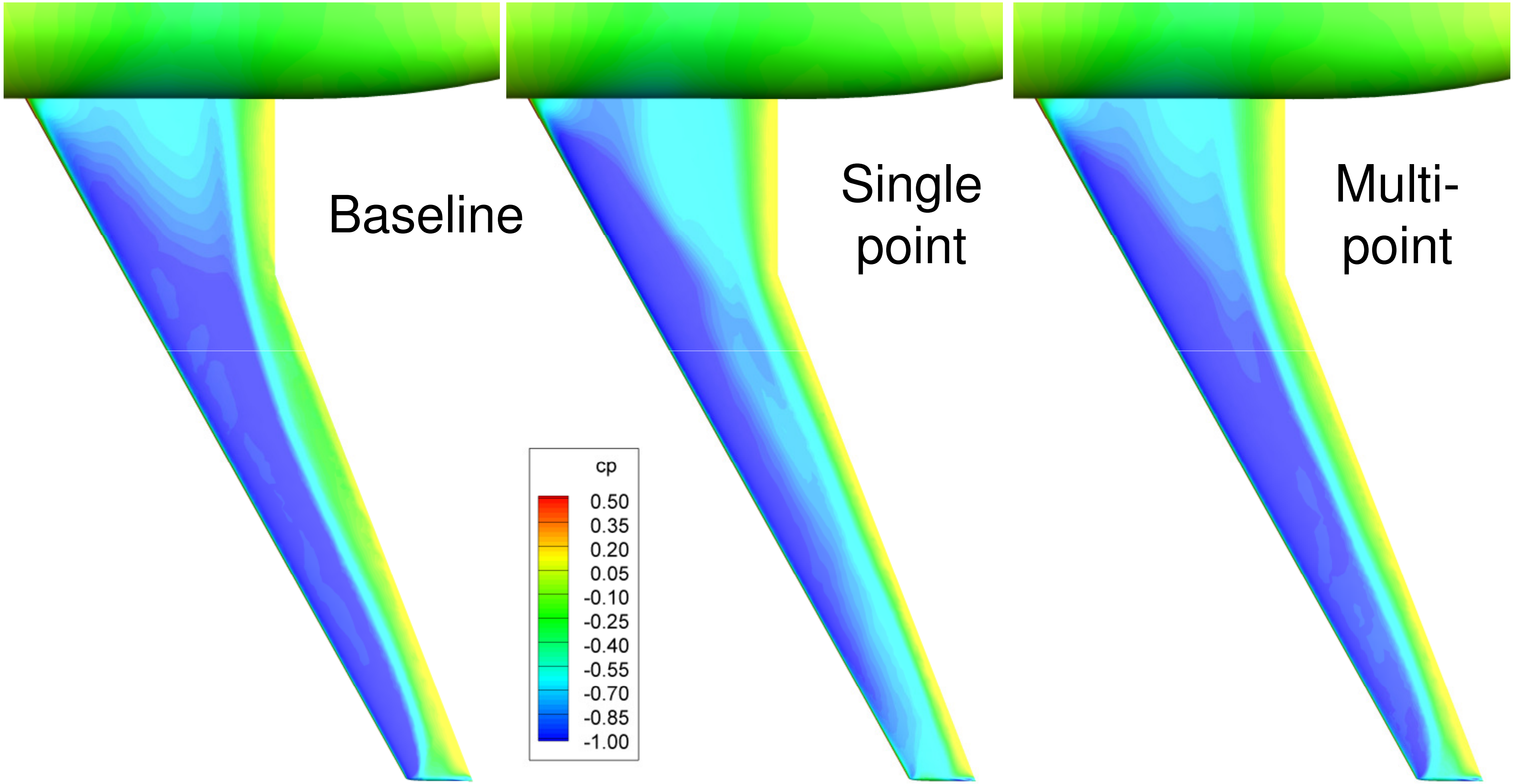
Multi-Point L/D in 3D: results



- At SP design point (C_{L3} = 0.554).

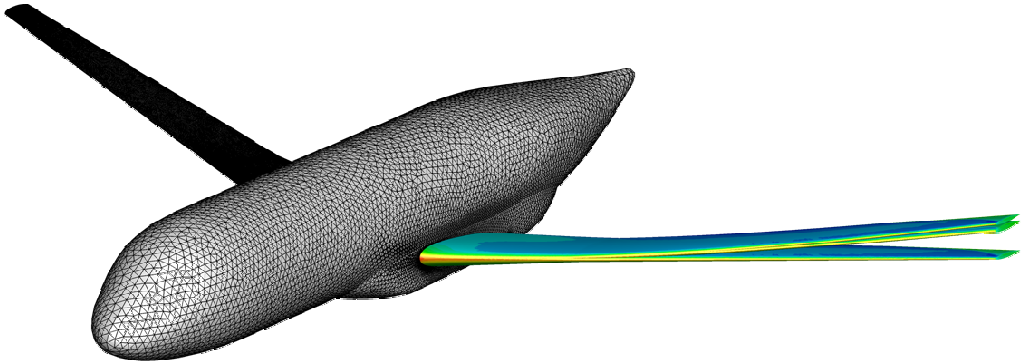
DLR

Single / Multi-Point L/D in 3D



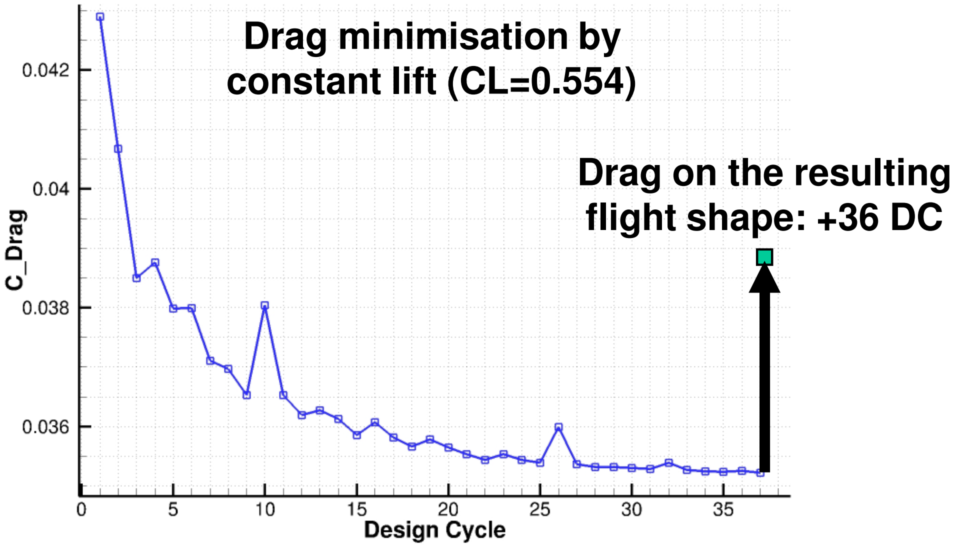
Moh'd Abu-Zurayk

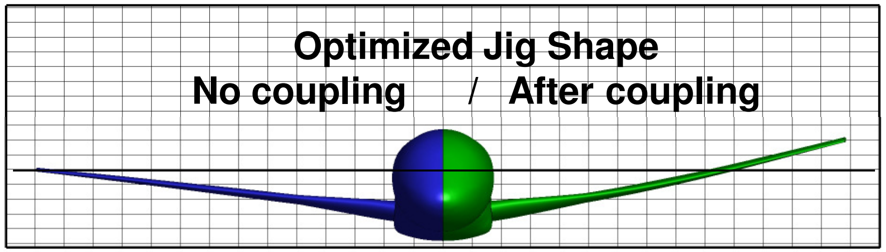
Wing flight shape optimisation

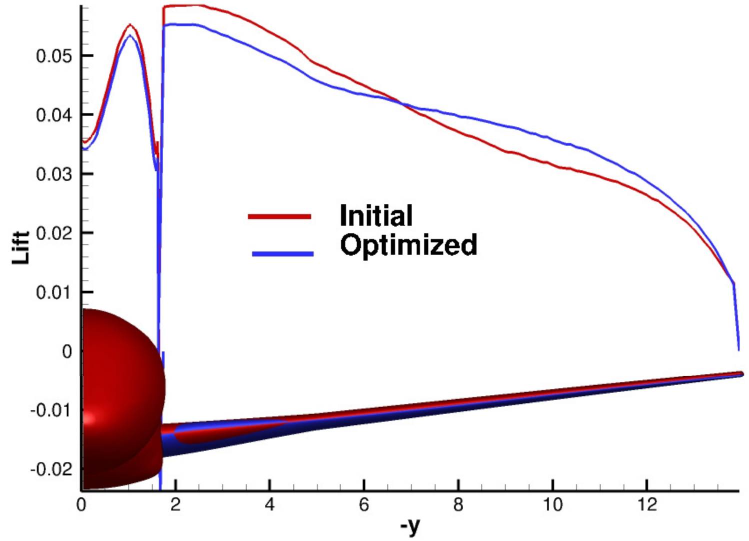


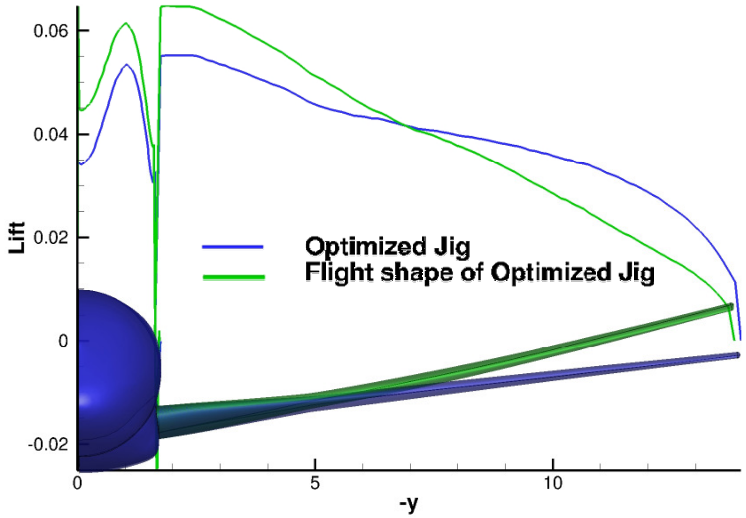
DLR

Introduction: limitation with classical optimisation (w/o considering structure deformation during the process)



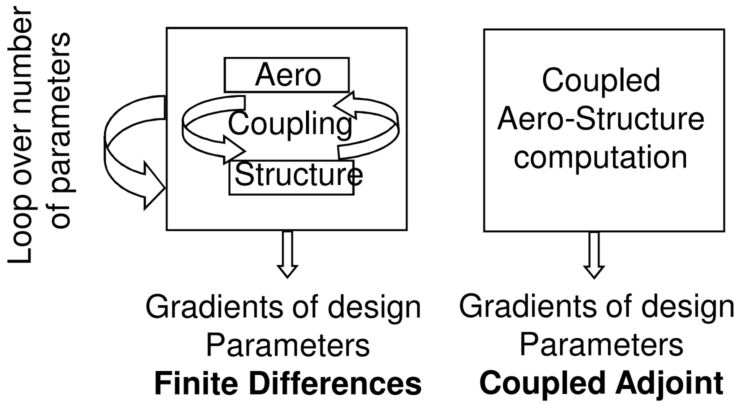


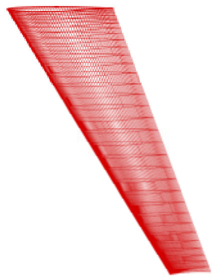


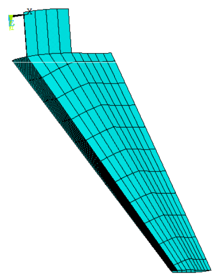


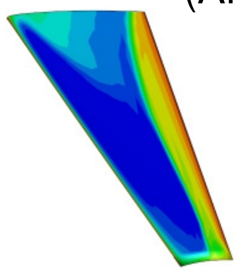
The coupled aero-structure adjoint
Motivation and formulation

- Aero-structure deformation has to be considered during the optimisation
- Need efficient strategy for fast optimisation
  - ⇒ Gradient approaches are preferred
- There is a need for an efficient approach to compute the gradients
  - ⇒ The coupled aero-structure adjoint permits efficient gradient computation
- The coupled adjoint formulation was derived and implemented in TAU and Ansys
- Advantages: huge time reduction and affordability of global sensitivity



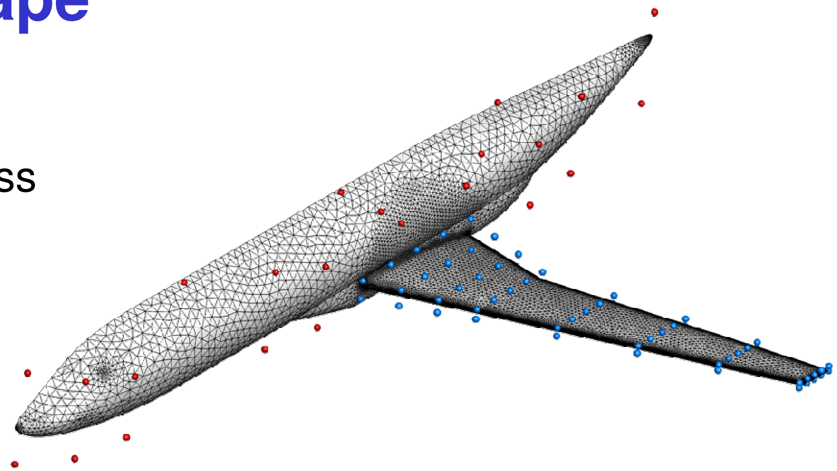

CFD model (TAU)


CSM model (ANSYS)


Global Sensitivity of Drag

DLR

Optimization of the wing flight shape



Objective and constraints

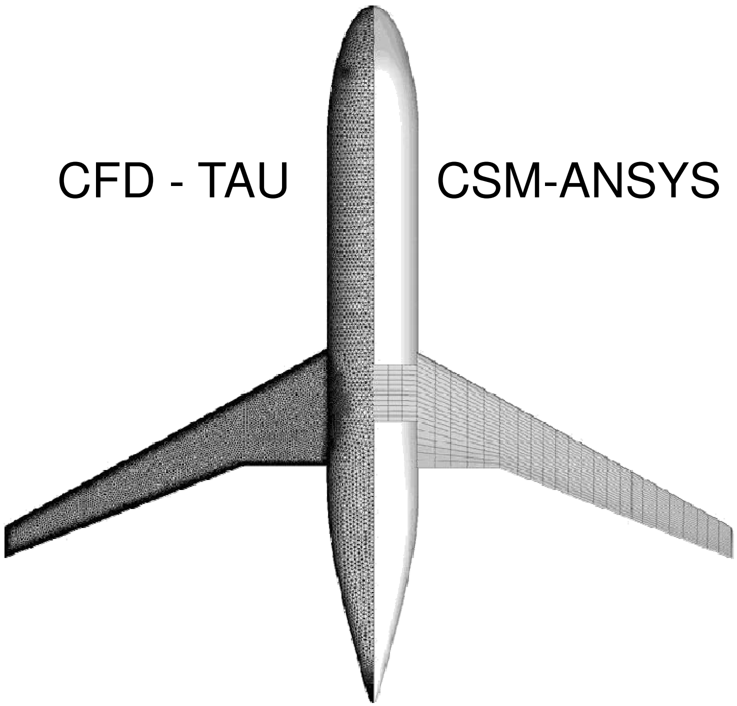
- Drag minimisation by constant lift and thickness
- Fluid/Structure coupled computations

Flow condition

- M_∞=0.82 ; Re=21x10^6 ; CL=0.554

Shape parametrisation

- 110 FFD design parameters
- Body shape kept constant
- Wing thickness law kept constant
- Wing shape parametrisation with 40 variables



CFD Mesh

- Centaur hybrid mesh
- 1.7 Million nodes
- Mesh deformation using RBF

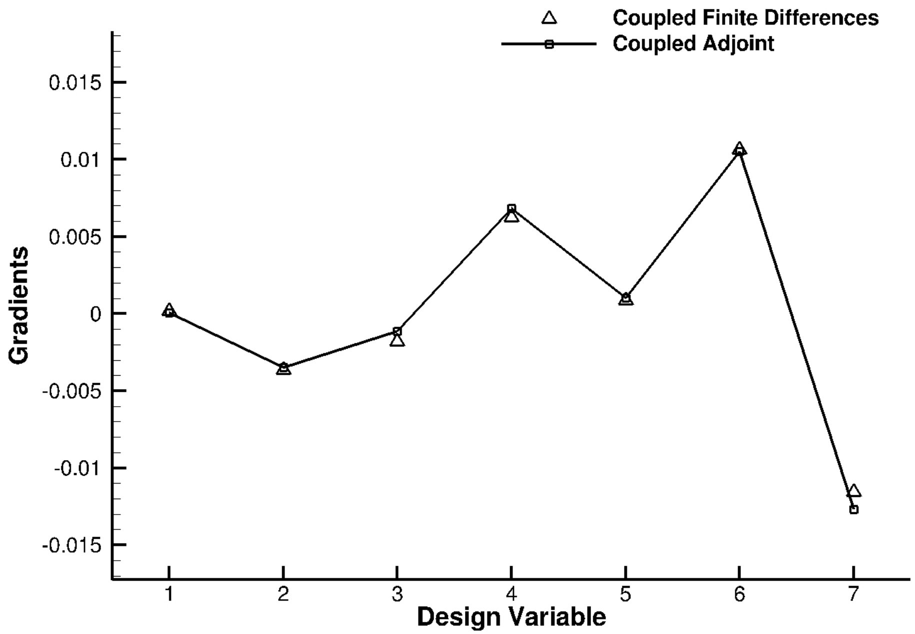
CSM Mesh

- 27 Ribs, 2 Spars, Lower & Upper Shell
- 4000 nodes

Optimization of the wing flight shape

- The coupled adjoint gradients were verified through comparison with gradients obtained by finite differences for Lift and Drag
- The structure is “frozen” (i.e. the structure elements are not changed) but the aero-elastic deformation is considered (flight shape)

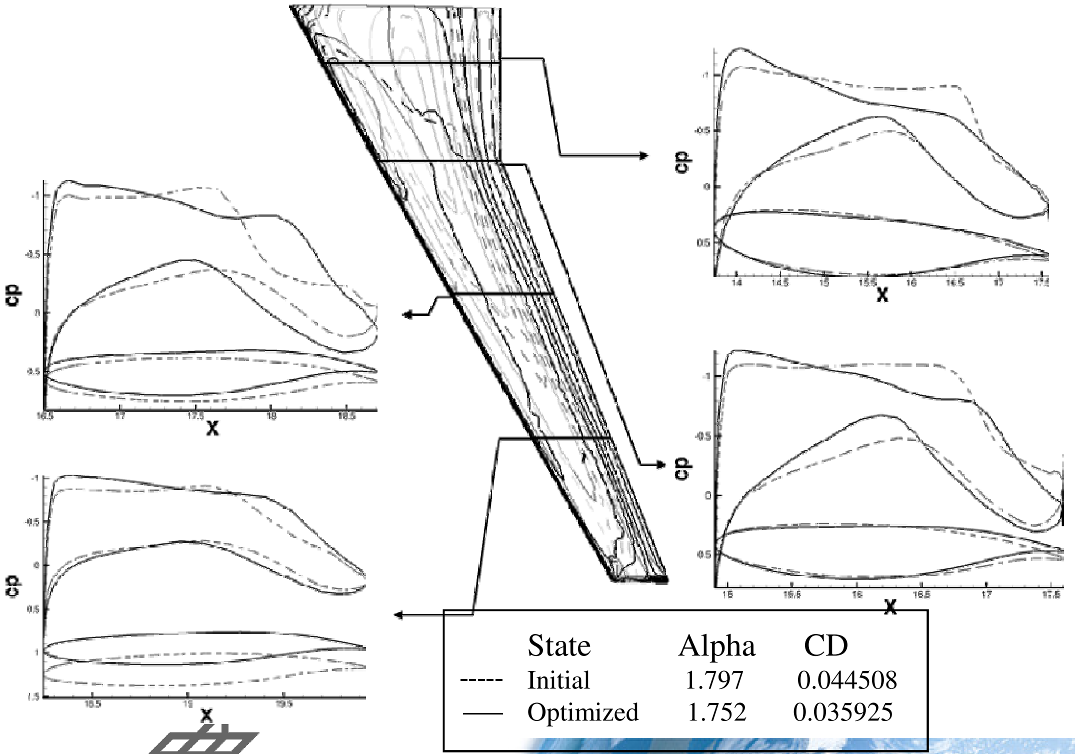
$$\frac{d(C_D)\,@\,\text{constant Lift}}{dD} = \frac{dC_D}{dD} - \left(\frac{dC_D}{d\alpha} / \frac{dC_L}{d\alpha}\right)\frac{dC_L}{dD}$$

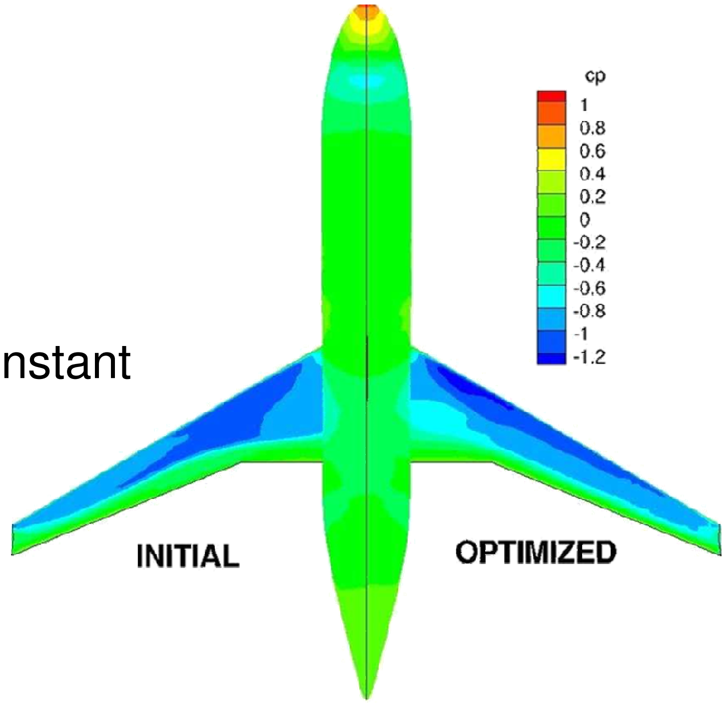


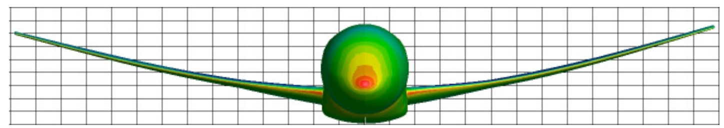
Optimization of the wing flight shape

Results

- Optimization converged after 35 aero-structural couplings and 11 coupled adjoint computations
- The optimization reduced the drag by 85 drag counts while keeping the lift and the thickness constant







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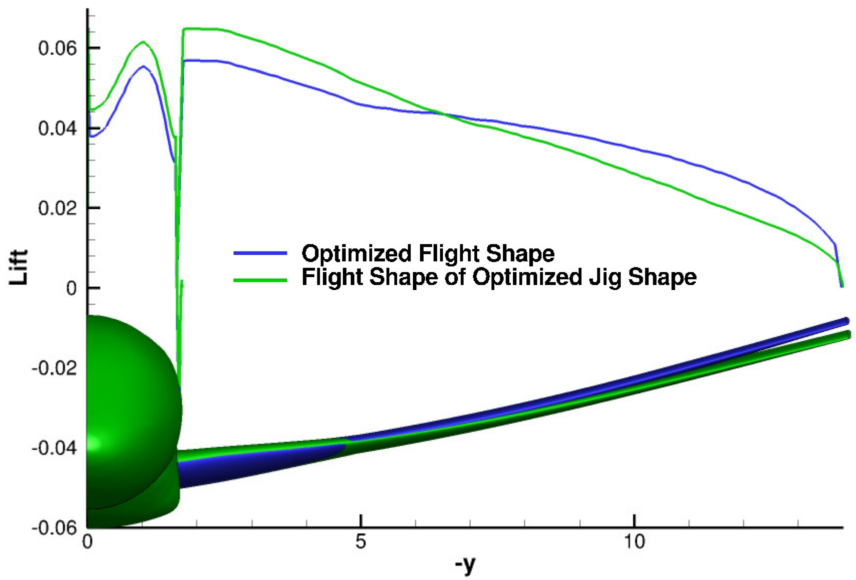
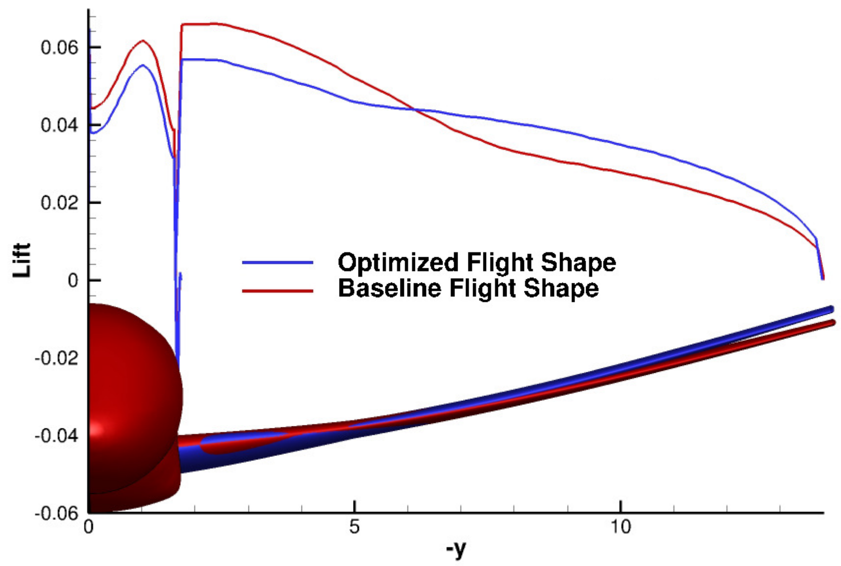
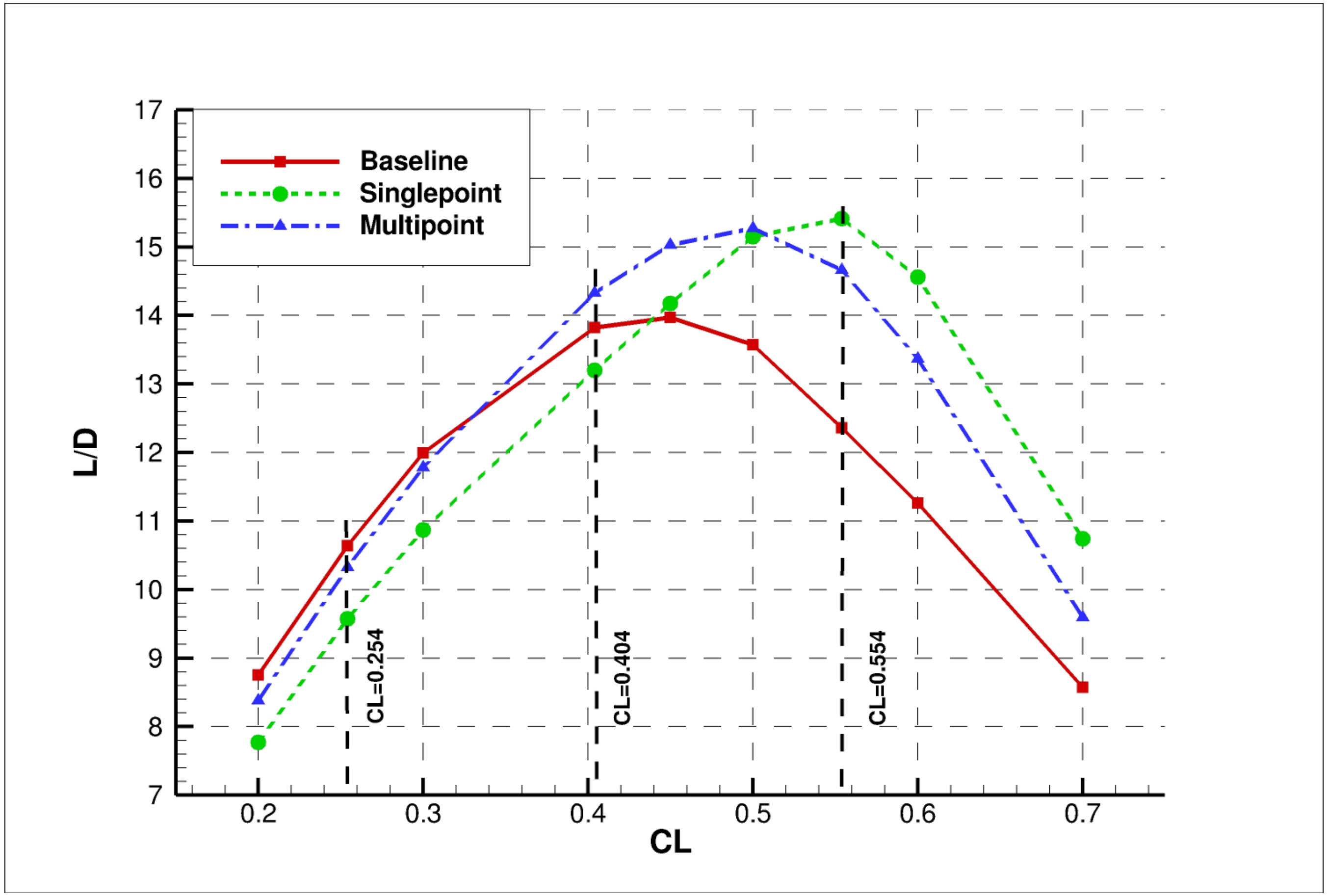




Multipoint flight shape optimization, early results

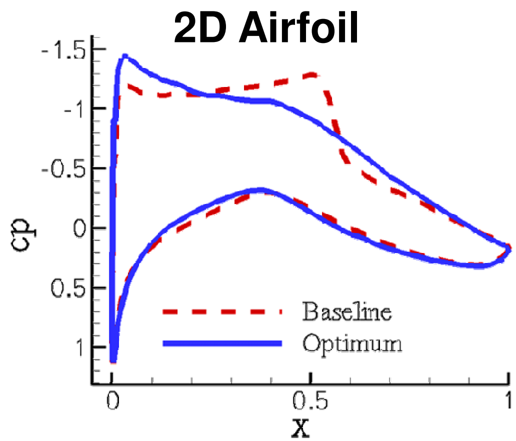


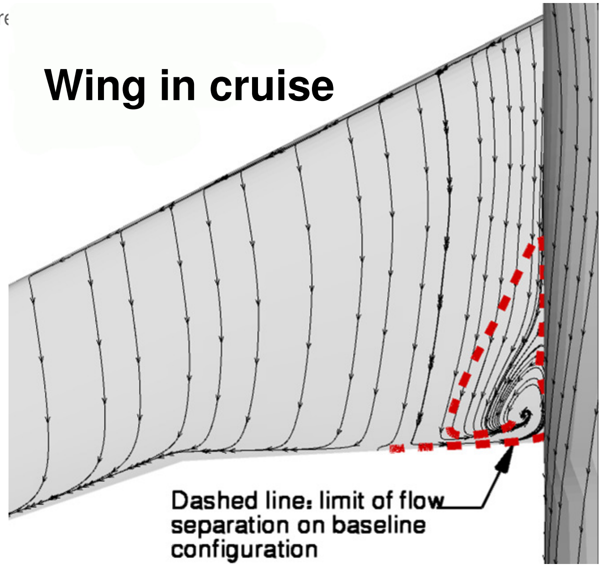
Conclusion / Outlook

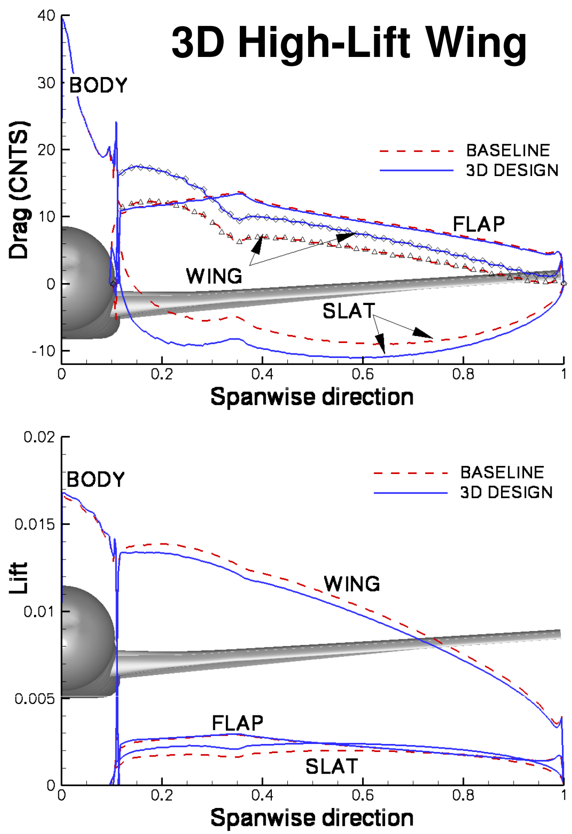
- Optimisation based on adjoint approach successfully demonstrated
  - on 2D and 3D cases on hybrid grids
  - from Euler to Navier-Stokes (with turbulent model) flows
  - for inverse design and problems based on aero. coefficients
- Efficient approach to handle detailed aerodynamic shape optimisation problems involving large number of design parameters
- The coupled aero-structure adjoint is the first step for MDO

- Next steps toward design capability of a future aviation:
  - More efficiency in solving 3D viscous adjoint flow with turbulence models
  - Efficient computation of the metric terms up to the CAD system
  - Specific cost functions needed by the designer (inverse design on specific area, loads distribution…)

> FlowHead Confere







Questions ?