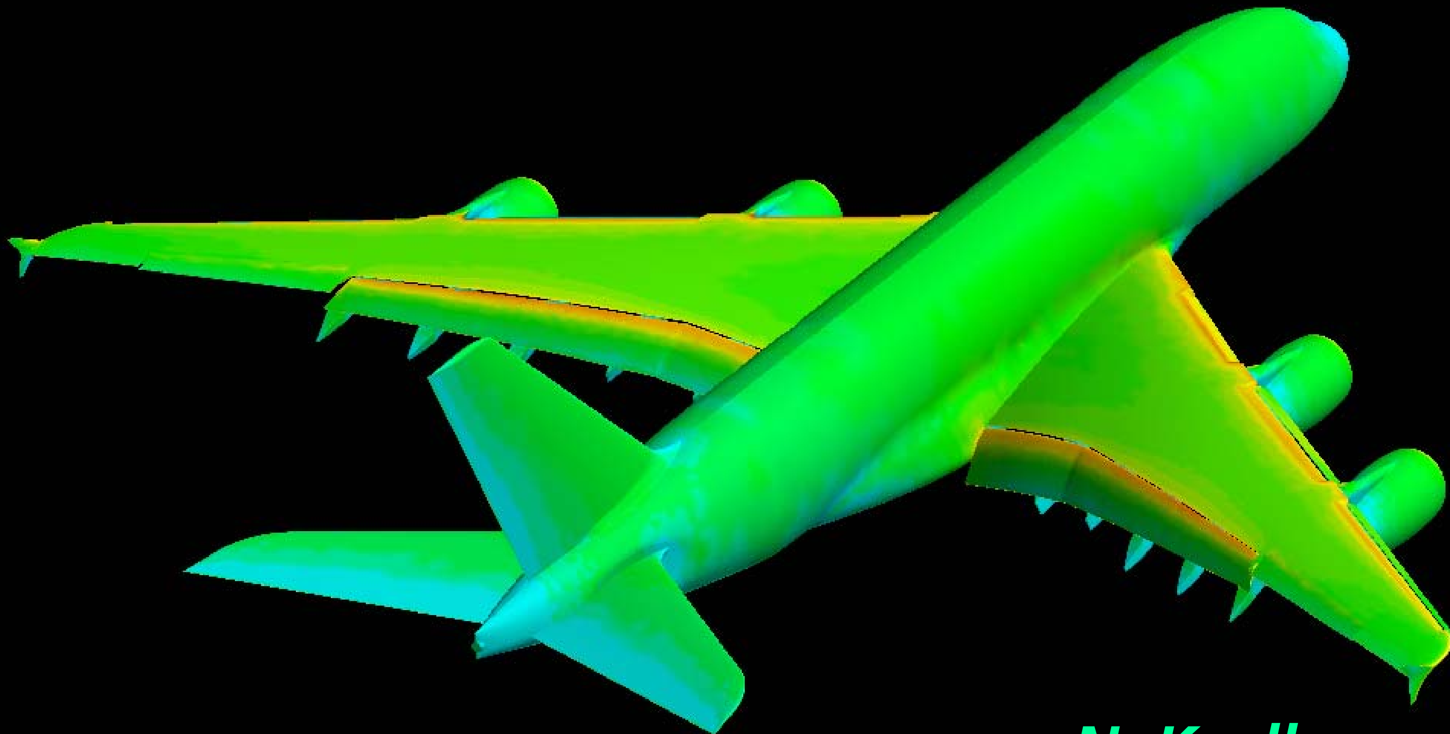
# Flow Simulation and Shape Optimization for Aircraft Design



*N. Kroll*

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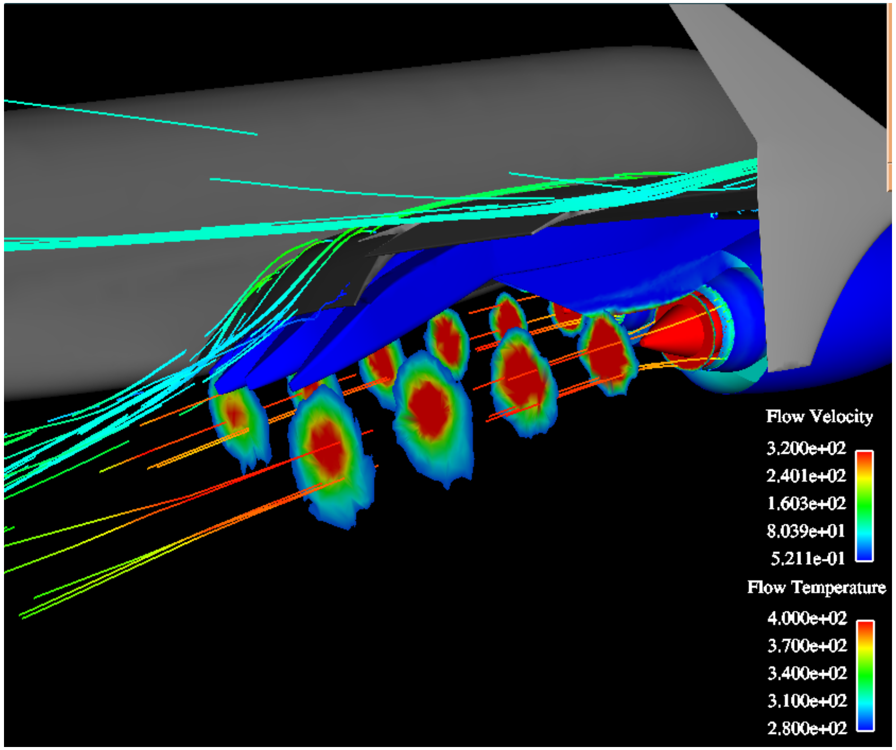
Braunschweig

Workshop Optimization in Aerodynamics
9th May 2005, HU Berlin

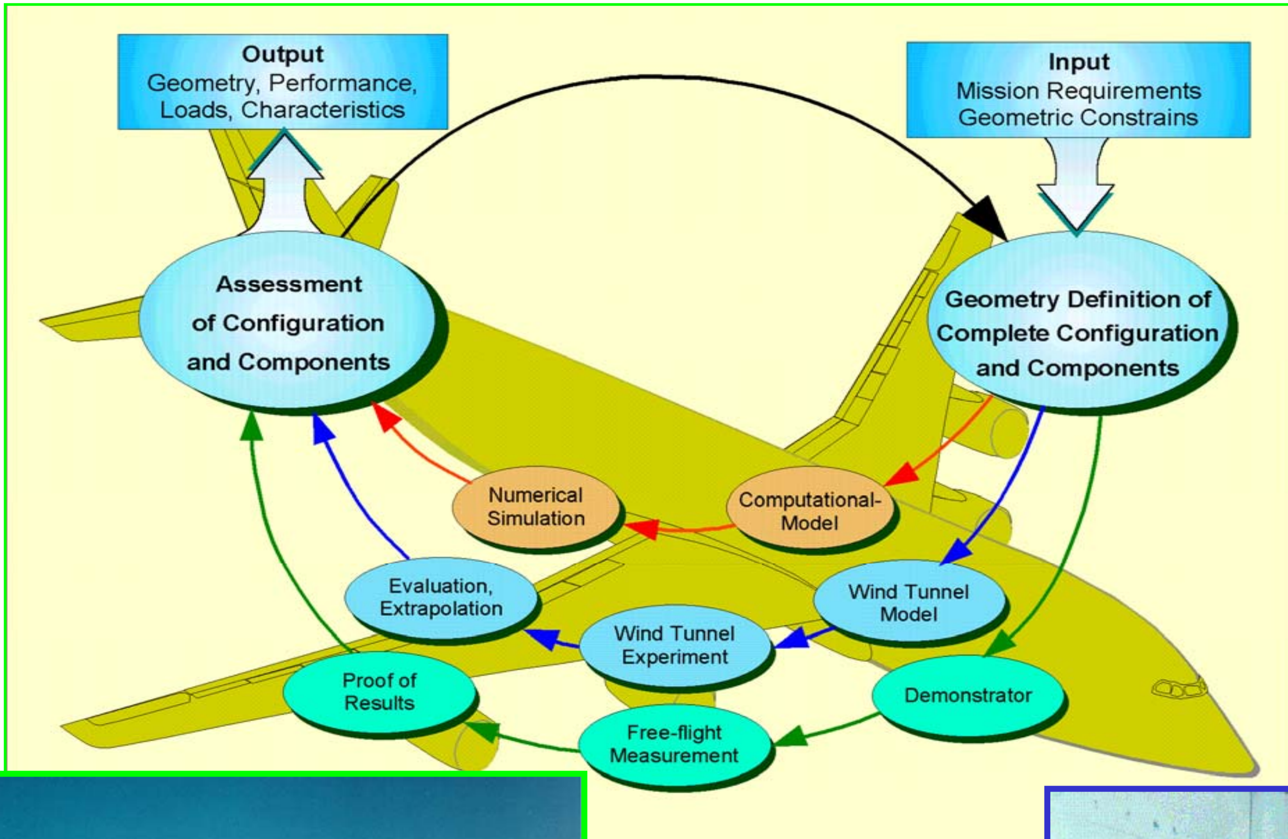
# Flow Simulation and Shape Optimization for Aircraft Design

## Outline

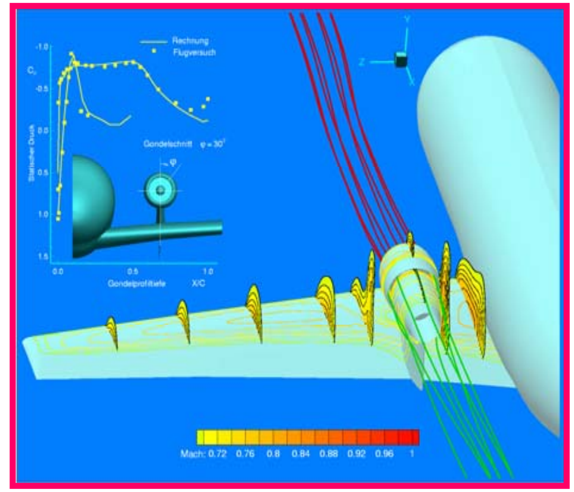
- Introduction
- Flow Solvers
- Validation & Applications
- Shape Design and Optimization
- Perspectives



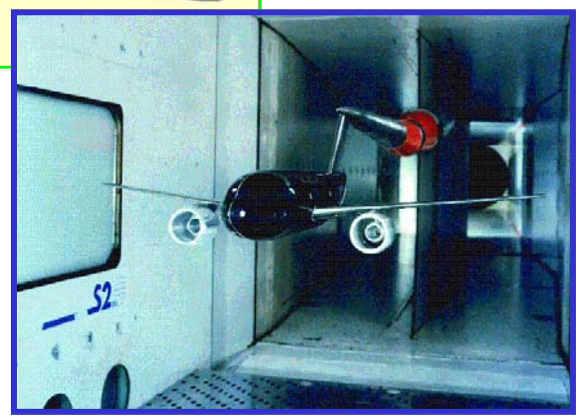
# Aerodynamic Design Cycle




**Computational Fluid Dynamics (CFD)**



**flight test**

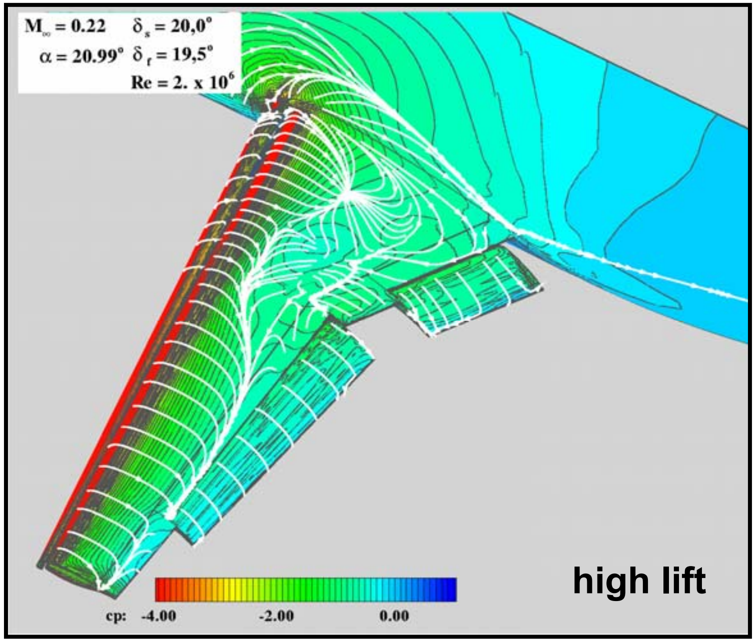



**wind tunnel experiment**

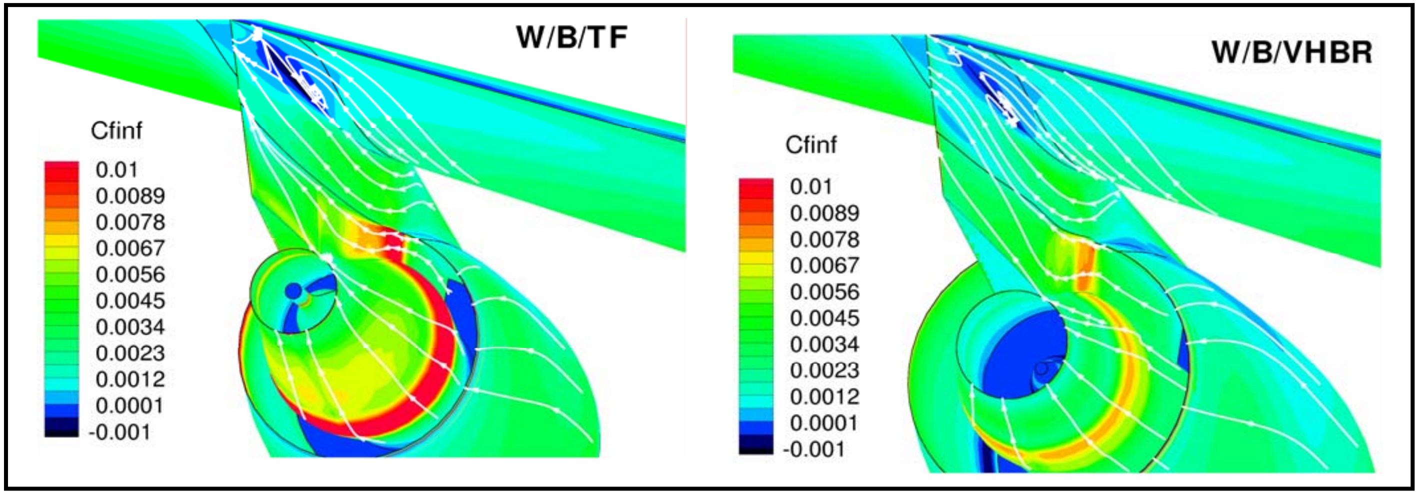
# Use of CFD in Aerodynamic Aircraft Design

## Objectives of CFD

- detailed analysis of complex flow fields
- cost efficient configuration studies
- extrapolation of wind tunnel results to free flight conditions
- shape optimization

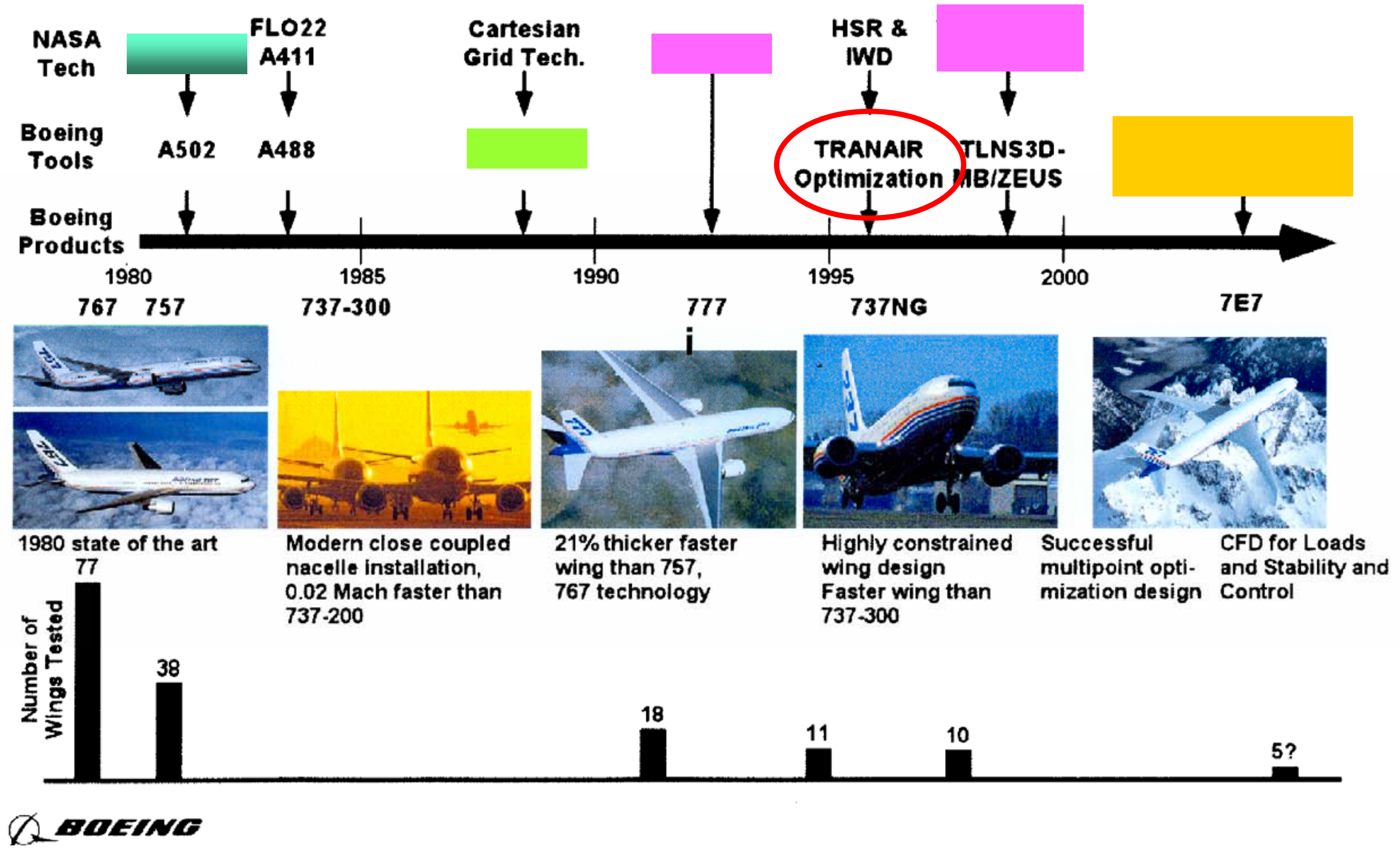



high lift




engine integration

# Impact of CFD on Wind Tunnel Testing



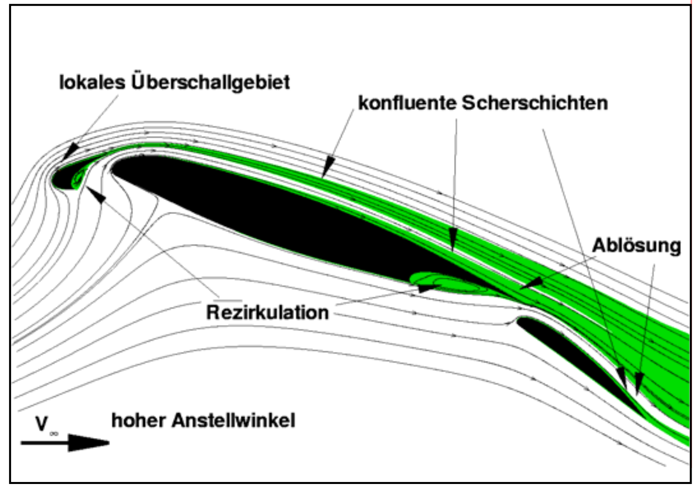

Effect of CFD on Configuration Lines Wind Tunnel Development Testing

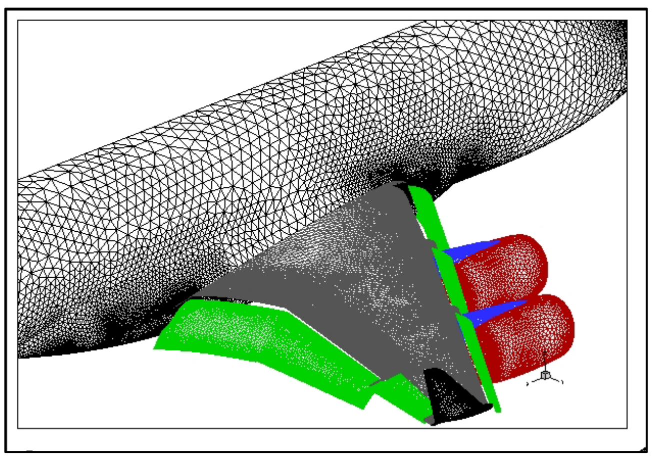
Source: Boeing (Rubberts, 1994; Johnson et al., 2003, Ball)

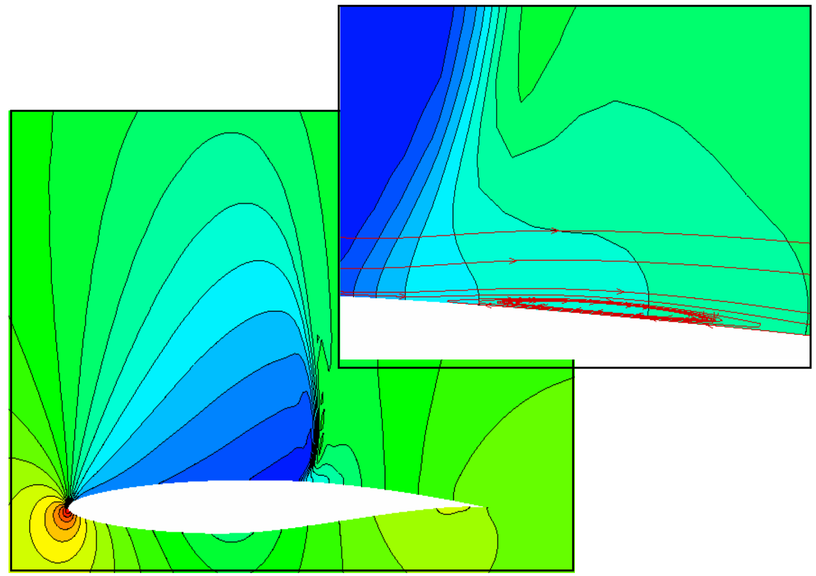
# Use of CFD in Aerodynamic Aircraft Design

## Requirements on CFD

- high level of physical modeling
  - compressible flow
  - transonic flow
  - laminar - turbulent flow
  - high Reynolds numbers (60 million)
  - large flow regions with flow separation
  - steady / unsteady flows
- complex geometries
- short turn around time





# Use of CFD in Aerodynamic Aircraft Design

## Consequences

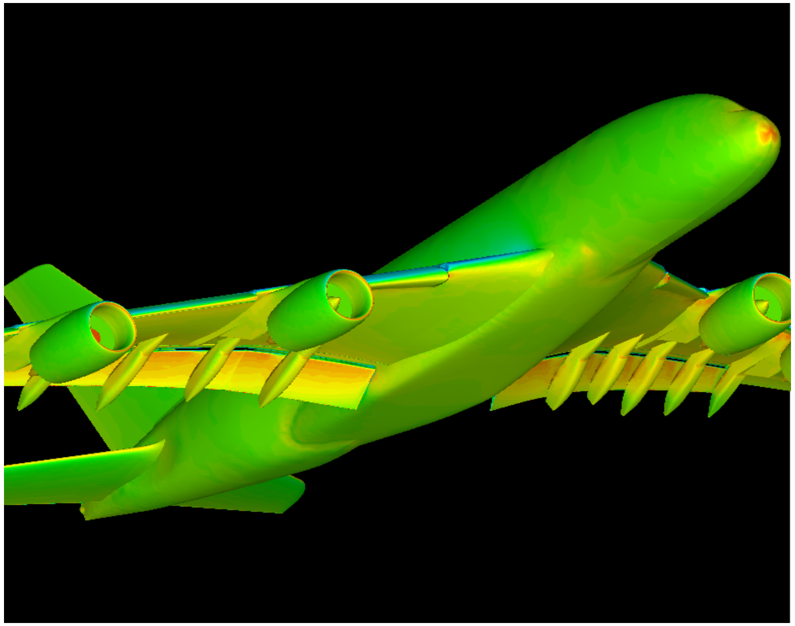
- solution of 3D compressible Reynolds averaged Navier-Stokes equations
- turbulence models based on transport equations (2 – 6 eqn)
- models for predicting laminar-turbulent transition
- flexible grid generation techniques with high level of automation (block structured grids, overset grids, unstructured/hybrid grids)
- link to CAD-systems
- efficient algorithms (multigrid, grid adaptation, parallel algorithms...)
- large scale computations ( ~ 10 - 25 million grid points)

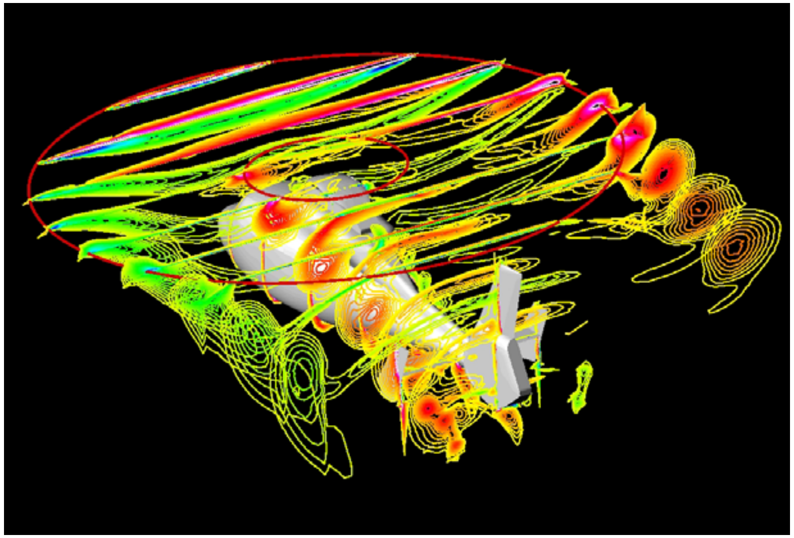
# National CFD Sotwrae MEGAFLOW

## Main Goal

**Development/validation of a national CFD software for complete aircraft applications which**

- **allows Navier-Stokes computations for 3D complex configurations at cruise and high-lift conditions**
- **establishes numerical flow simulation as a routinely used tool at DLR and in German aircraft industry**
- **CFD kernel for multidisciplinary simulation and optimization**
- **serves as a development platform for universities**

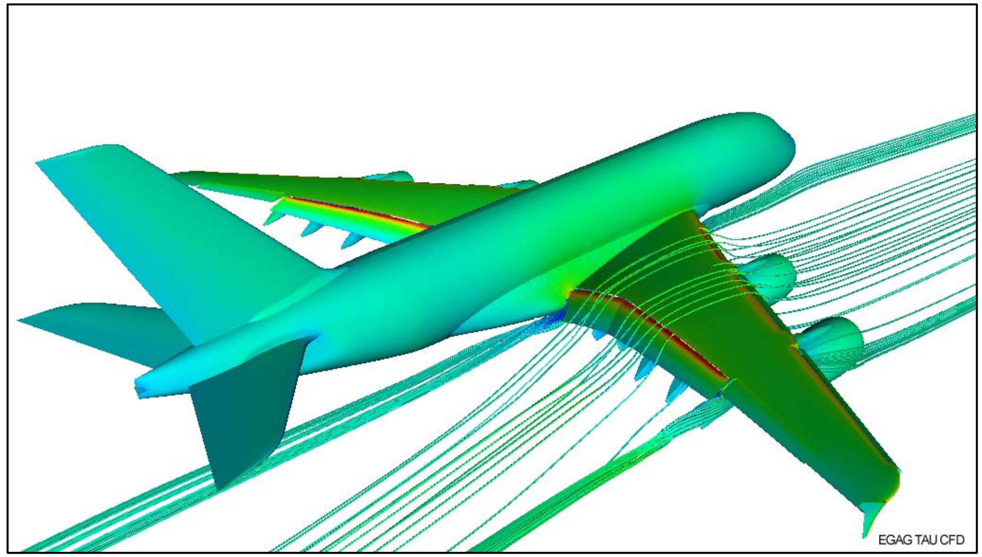


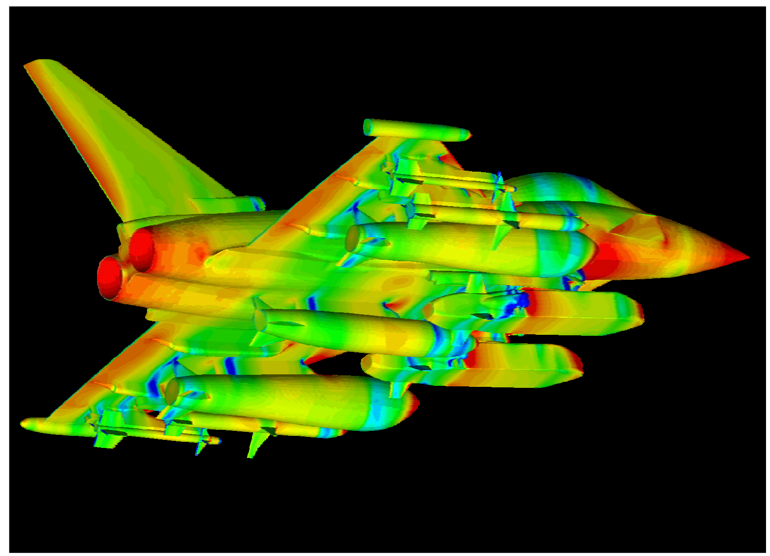


# National CFD Software MEGAFLOW

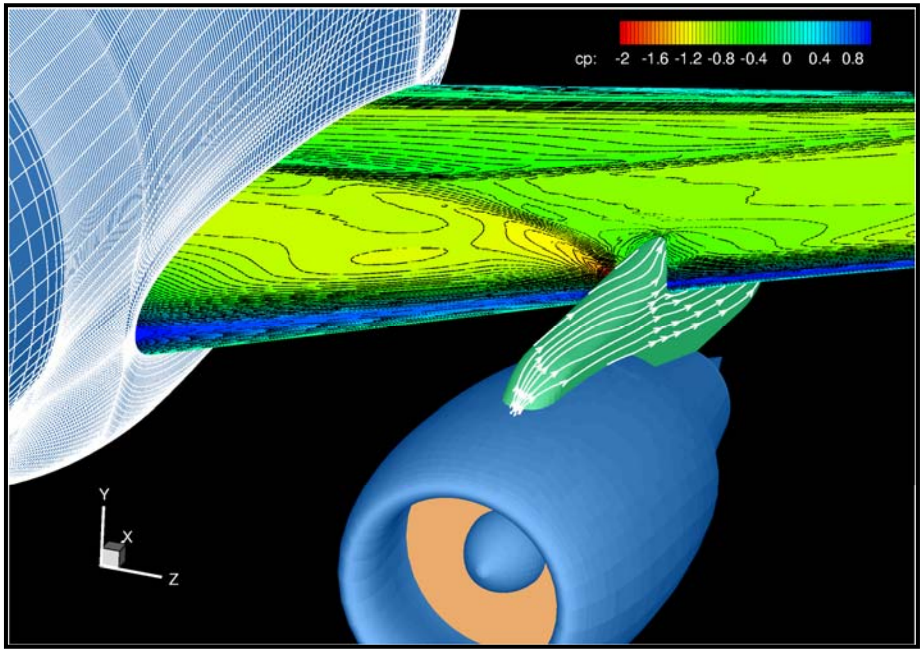
## Approach

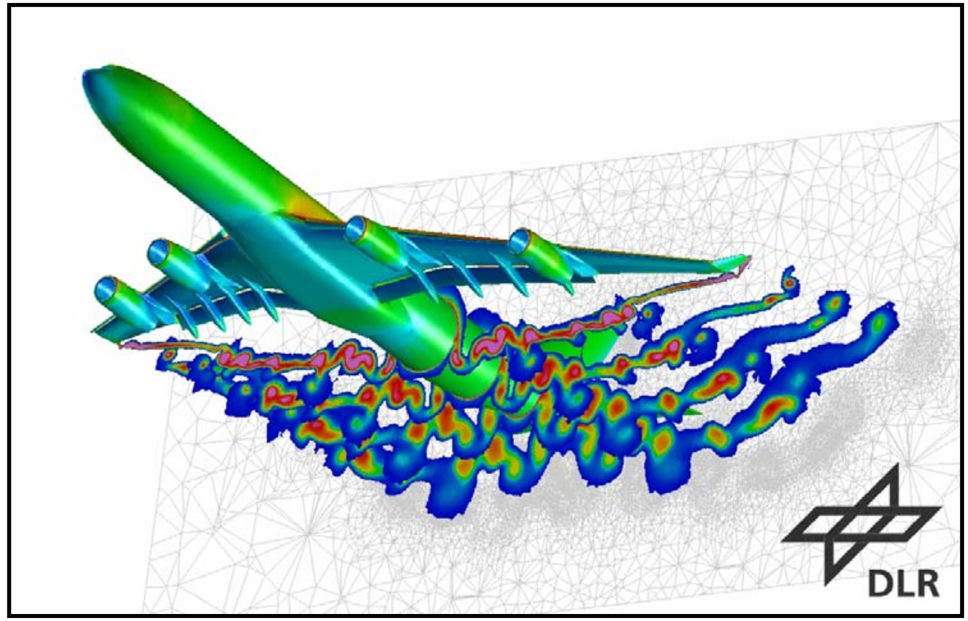
- common effort of aircraft industry, DLR, several universities
- development activities driven by industrial requirements
- single software platform for research and industrial application
- early implementation of software components in industry
- validation based on industrial relevant applications
- links to other disciplines for multidisciplinary simulations
- quality assurance of software system
- open source policy
- coordination and software support by DLR



# MEGAFLOW Software



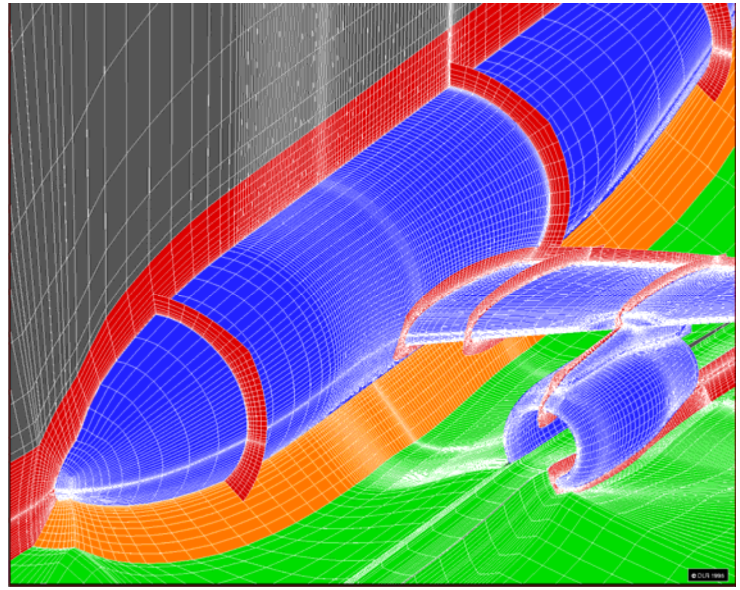

**Structured RANS solver FLOWer**
- block-structured grids
- moderate complex configurations
- fast algorithms (unsteady flows)
- design option

**Unstructured RANS solver TAU**
- hybrid grids
- very complex configurations
- grid adaptation
- fully parallel software

# Reynolds-Averaged Navier-Stokes Solver FLOWer

## Physical model

- → 3D compressible Navier-Stokes equations
- → arbitrarily moving bodies
- → steady and time accurate flows
- → state-of-the-art turbulence models (RSM)

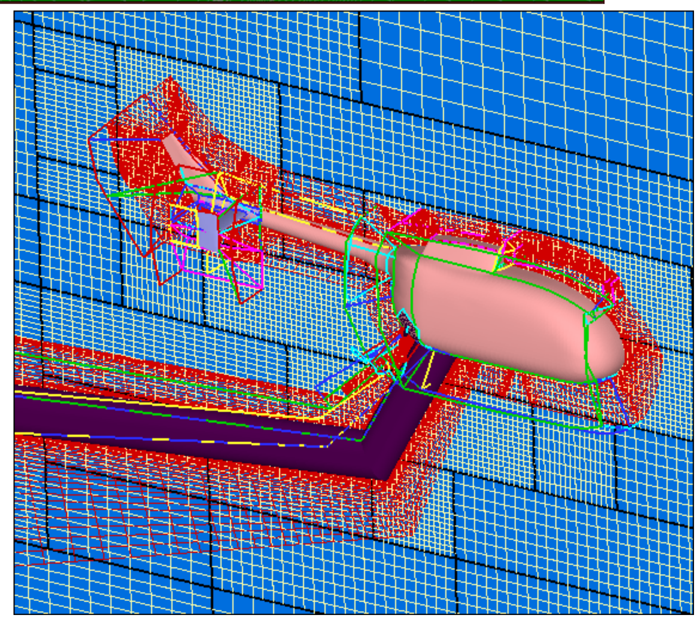


## Grid strategy

- → block-structured grids
- → discontinuous block boundaries
- → overset grids (Chimera)
- → deforming grids

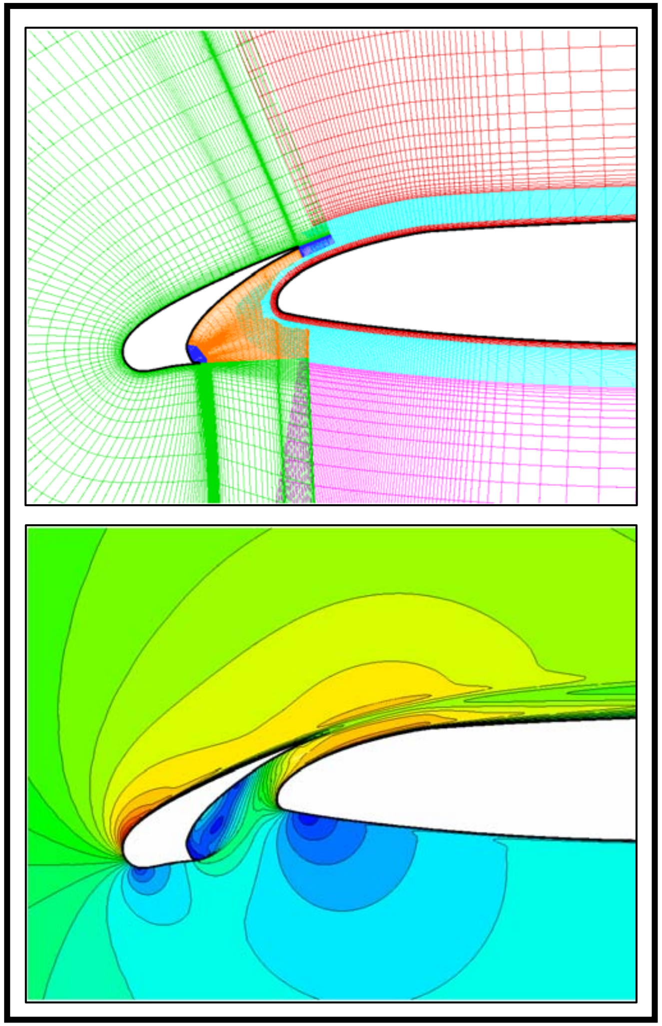
## Numerical algorithms

- → 2nd order finite volume discretization
(cell centered & cell vertex option)
- → central and upwind schemes
- → multigrid
- → implicit treatment of turbulence equations
- → implicit schemes for time accurate flows
- → preconditioning for low speed flow
- → vectorization & parallelization
- → adjoint solver

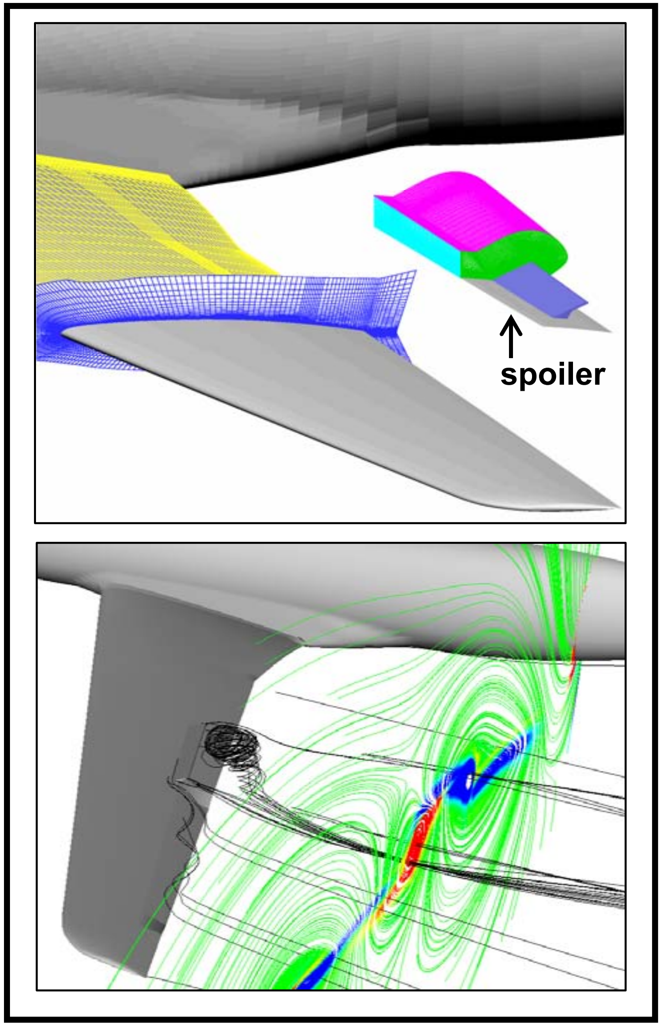


# FLOWer - Overset Grids (Chimera)

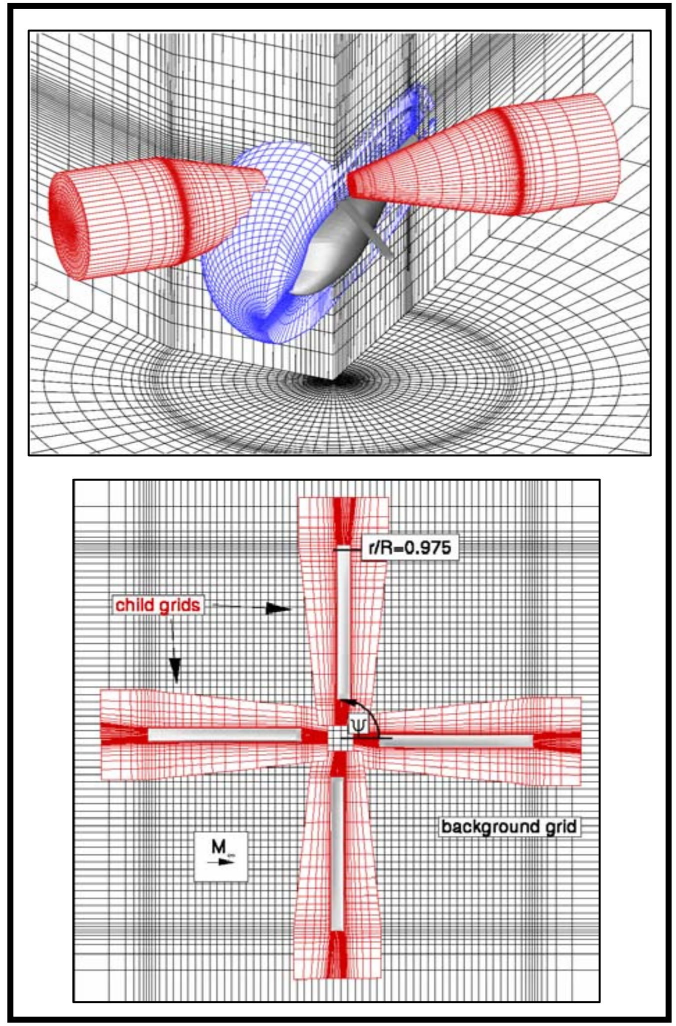
***simplification of grid generation***



***increased flexibility in application***



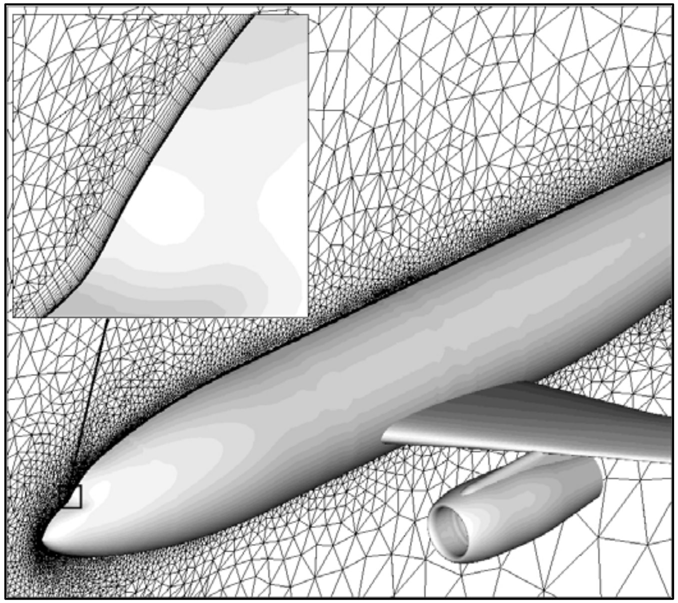

***efficient treatment of bodies in relative motion***



# Reynolds-Averaged Navier-Stokes Solver TAU

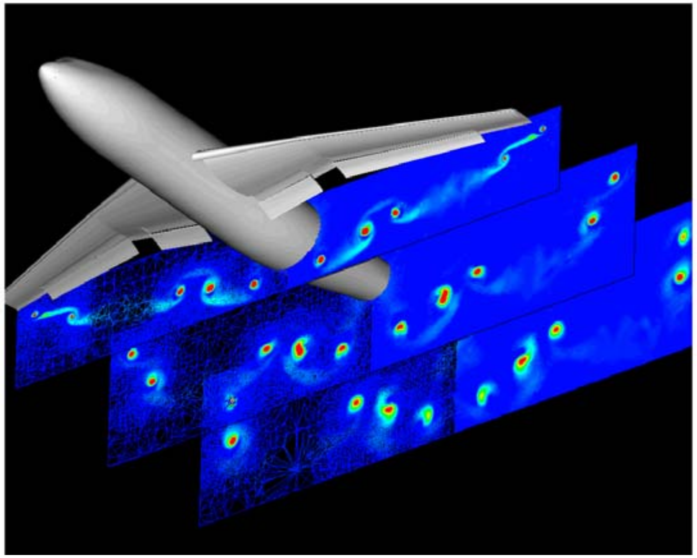
## Physical model

→ 3D compressible Navier-Stokes equations
→ arbitrarily moving bodies
→ steady and time accurate flows
→ state-of-the-art turbulence models



## Grid strategy

→ unstructured/hybrid grids
→ semi-structured sublayers
→ overset grids (Chimera)
→ deforming grids
→ grid adaptation (refinement, de-refinement)



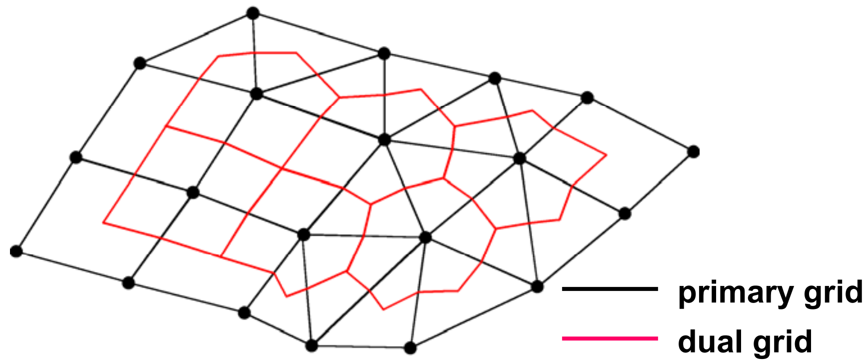
## Numerical algorithms

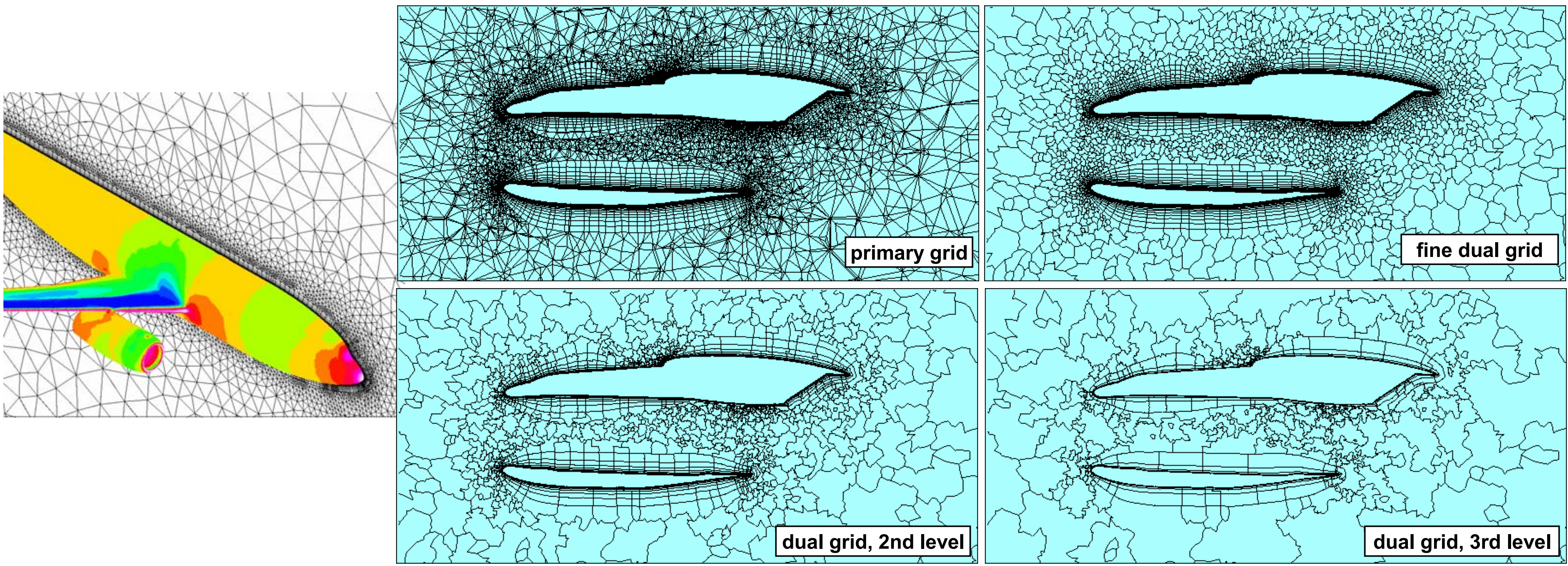
→ 2nd order finite volume discretization based on dual grid approach
→ central and upwind schemes
→ multigrid based on agglomeration
→ implicit schemes for time accurate flows
→ preconditioning for low speed flow
→ optimized for cash and vector processors
→ MPI parallelization

# Hybrid Navier-Stokes Solver TAU

## Dual grid approach

- solver independent of
  cell types of primary grid
- efficient edge-based data structure
- agglomeration of dual cells
  for coarser meshes (multigrid)

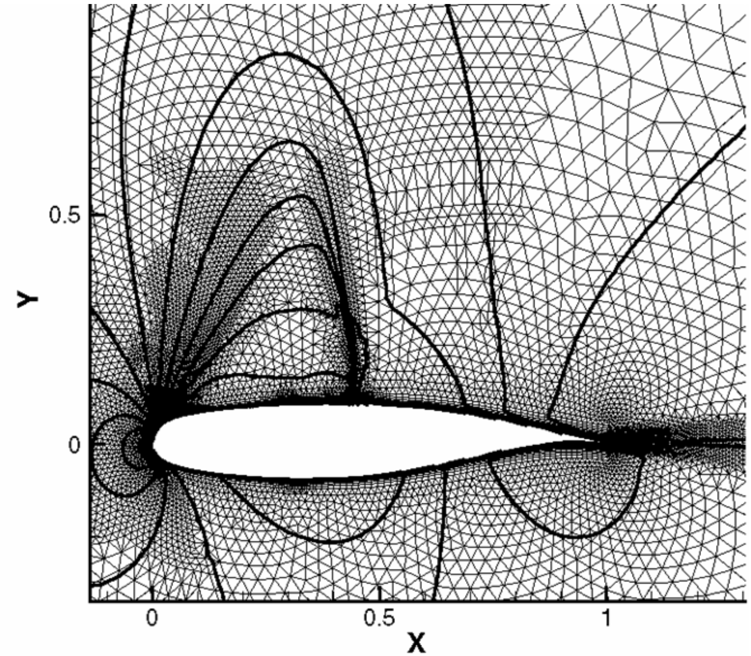


# Hybrid Navier-Stokes Solver TAU

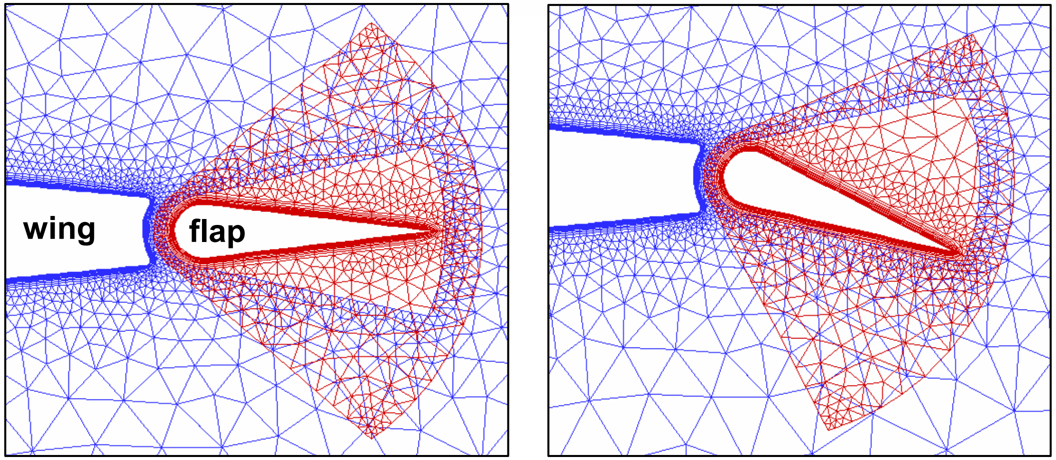
## Local Mesh Adaptation

- **local grid refinement and de-refinement depending flow solution**
- **reduction of total number of grid points**
- **efficient simulation of complex flow phenomena**

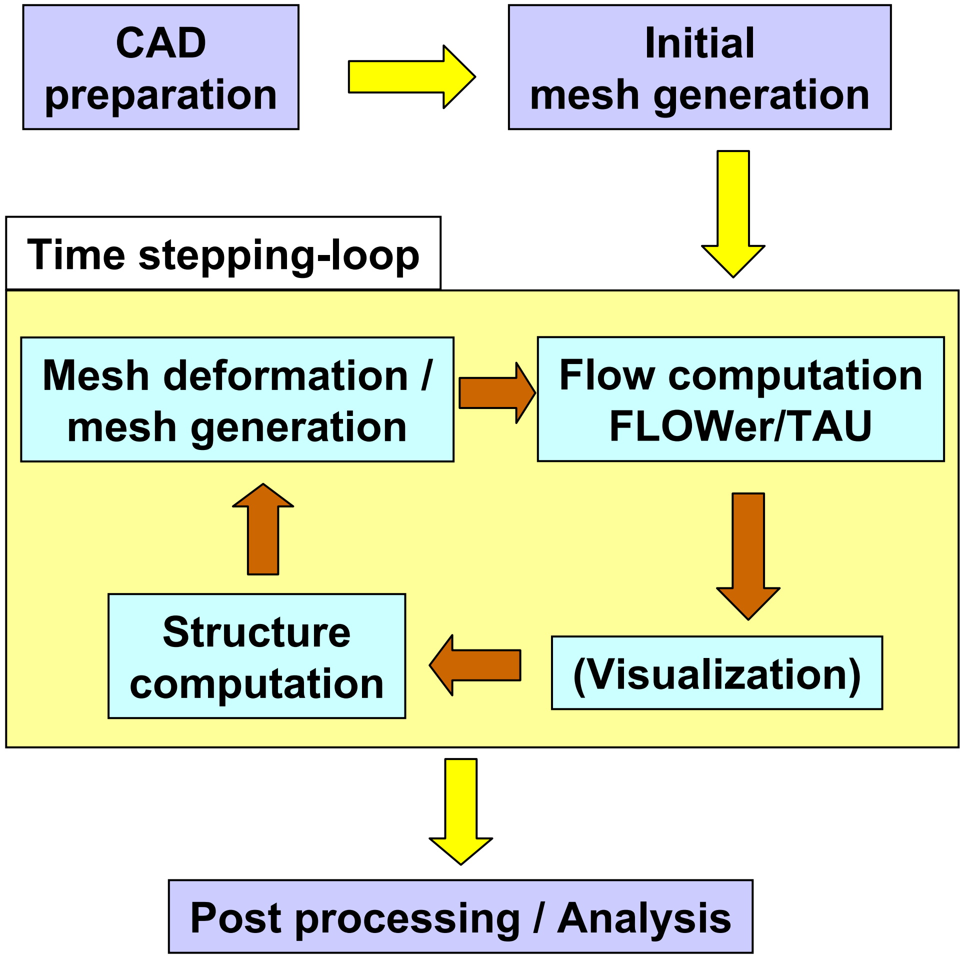


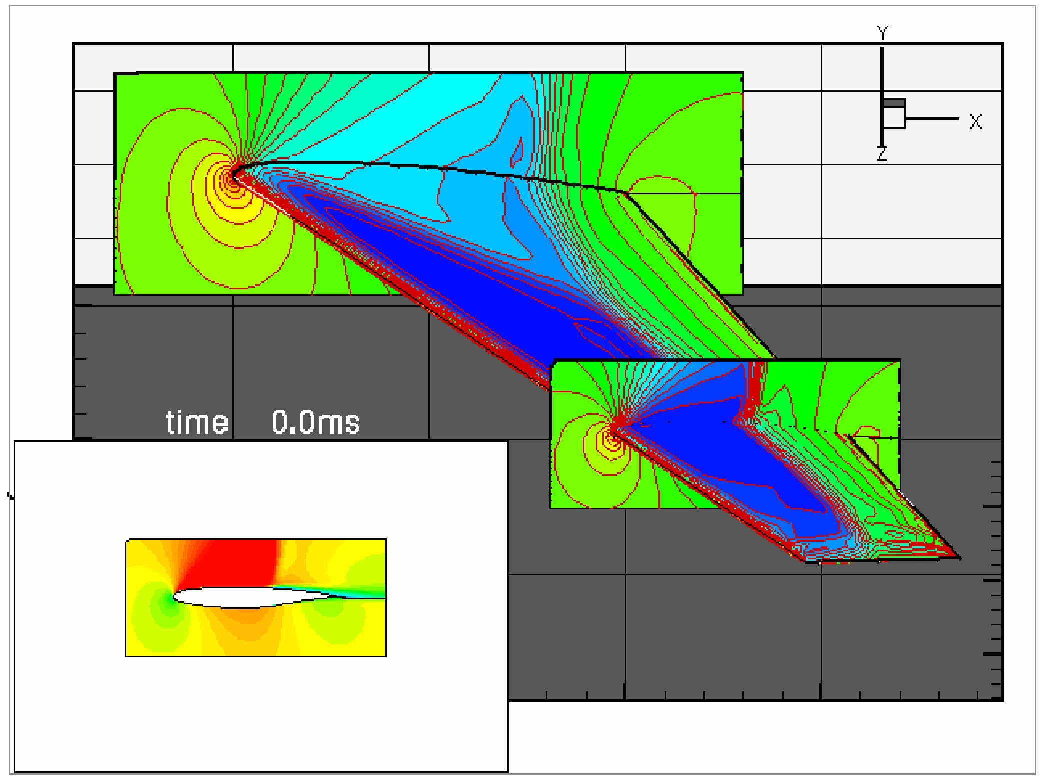

## Overlapping grid technique

- **efficient approach for simulation of complex configurations with movable control surfaces *(maneuvering aircraft)***
- **separate grids for movable surfaces**
- **parallel implementation**



# Fluid / Structure Coupling



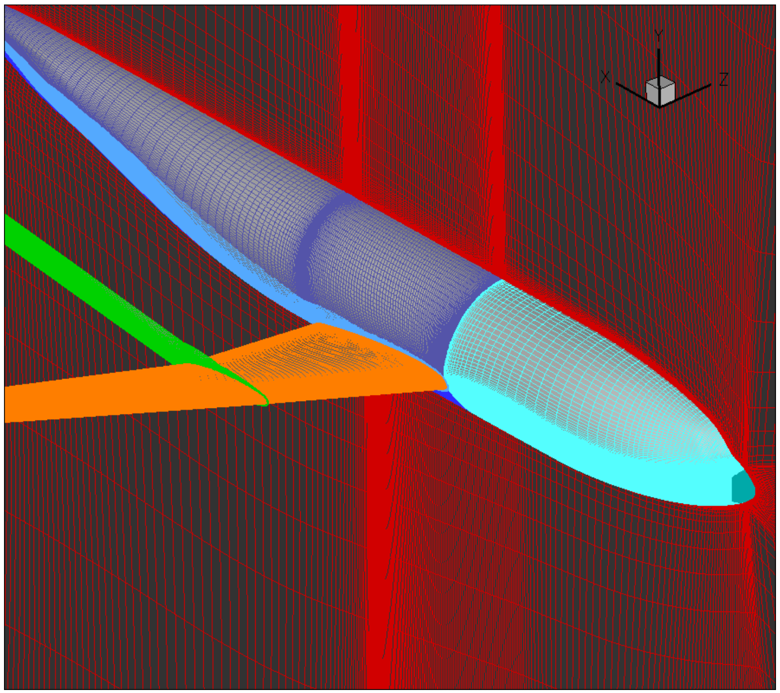



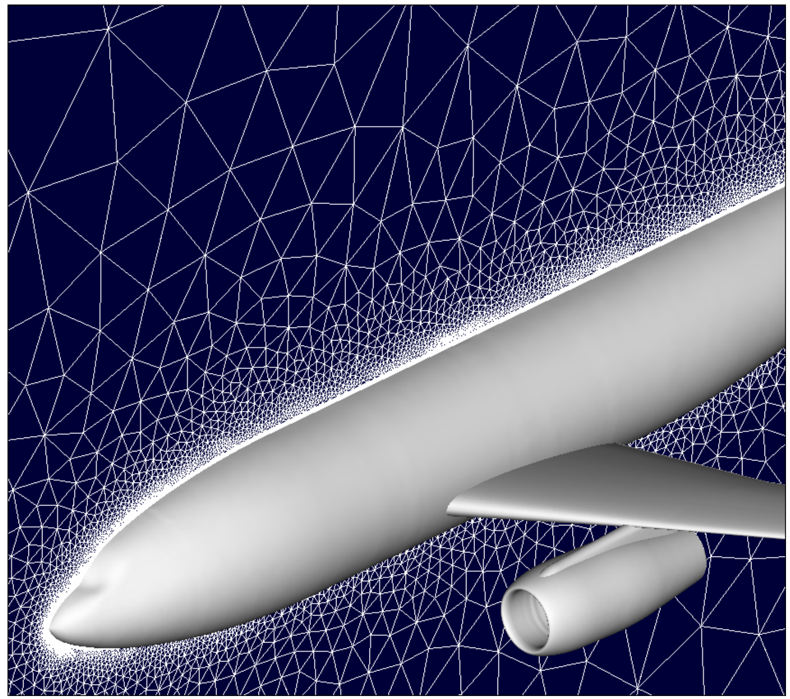

FLOWer

RWTH Aachen

# Validation

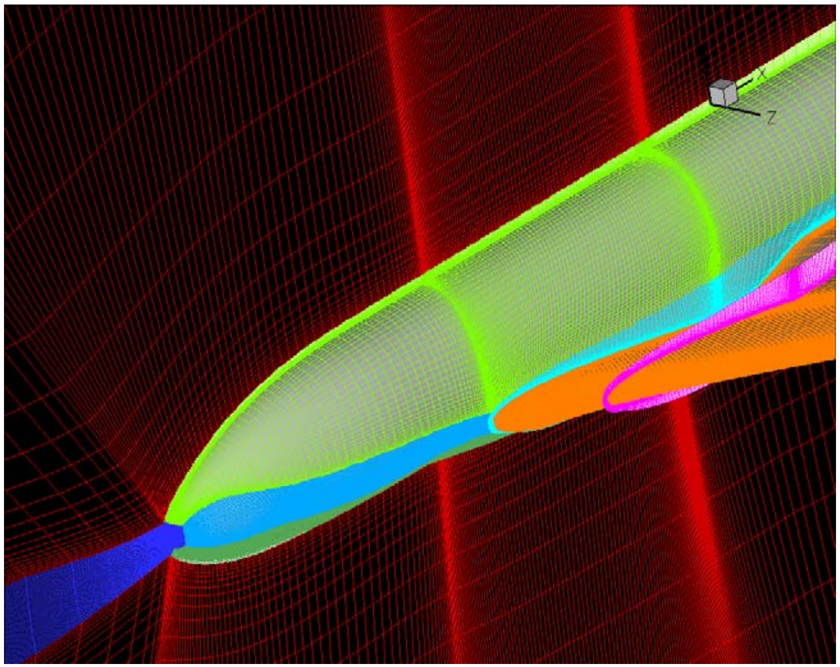
- **Aerodynamic performance of wing/body configuration in cruise condition**
- **Engine/airframe integration – installation drag**



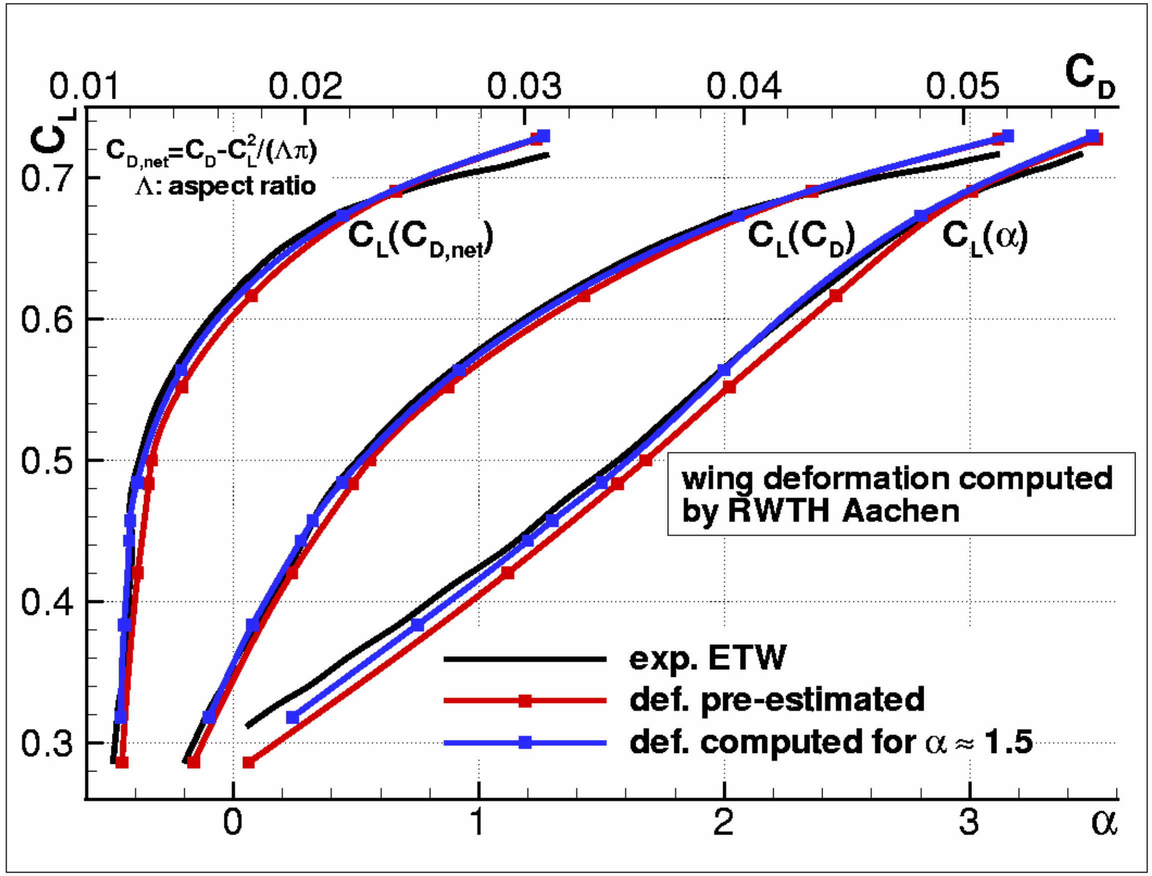



# HiReTT Wing/Body Configuration

- $M_\infty$=0.85, Re=32.5x$10^6$
- coupled CFD/structural analysis for wing deformation at $\alpha \approx 1.5°$
- FLOWer, k$\omega$ turbulence model, fully turbulent



3.5 million grid points

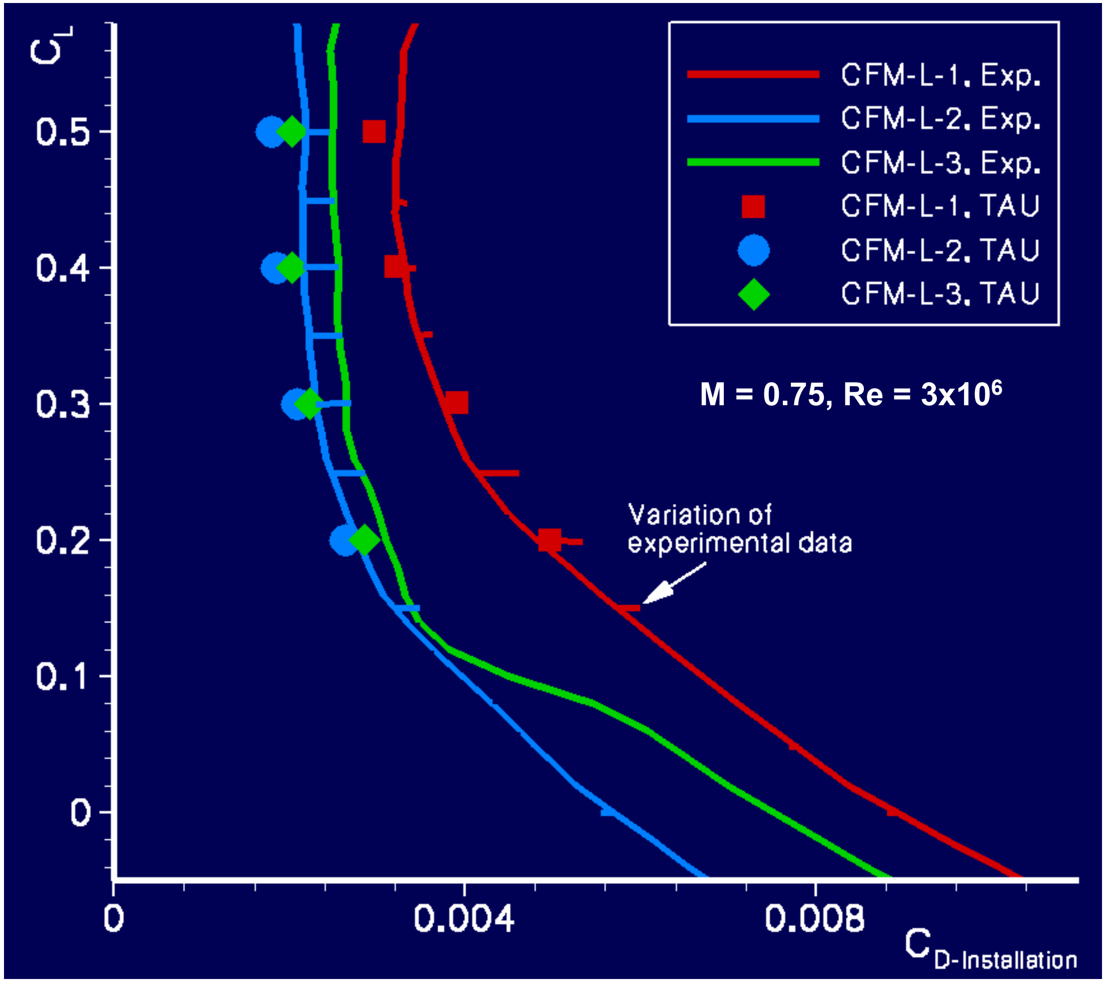


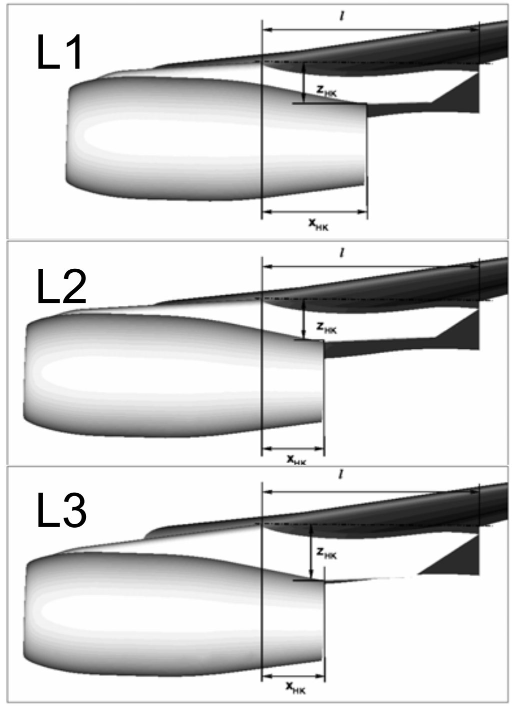

Krumbein, Rakowitz

# Engine-Airframe Installation Drag – TAU-Code

*Objective:* Drag prediction for different nacelle positions & shapes

*Configuration:* DLR F6 wing/body/pylon/nacelle configuration




**CFM56**

(L1,L2,L3,S)

| $C_{D\text{-Installation}}$ | Exp. | CFD |
|---|---|---|
| L1 – L2 | 10.7 | 11.8 |
| L2 – L3 | 3.0 | 2.3 |

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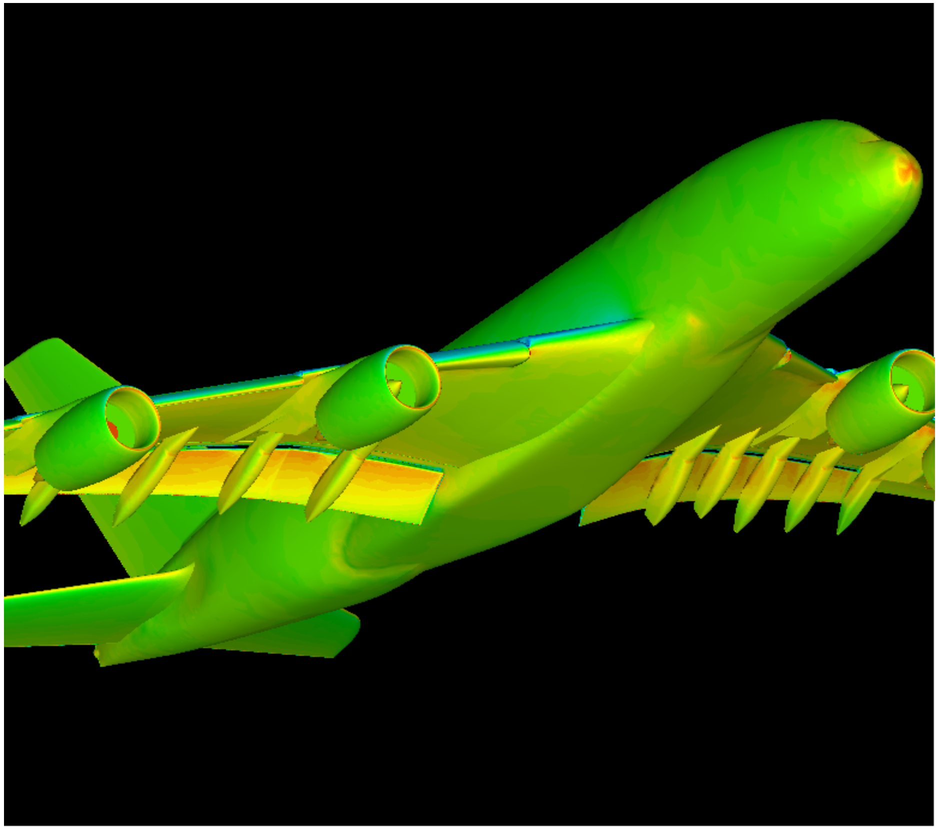
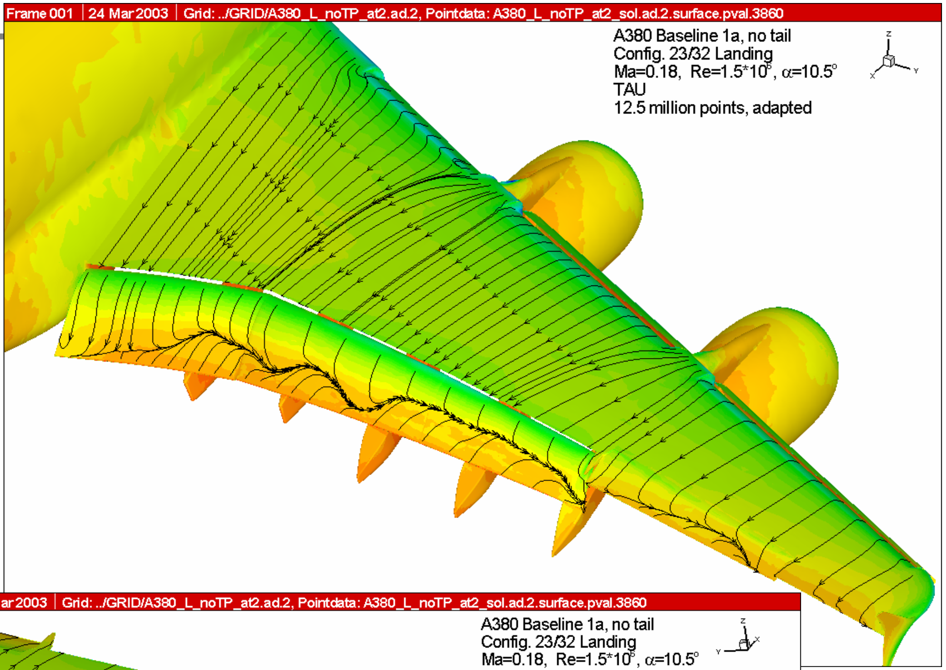
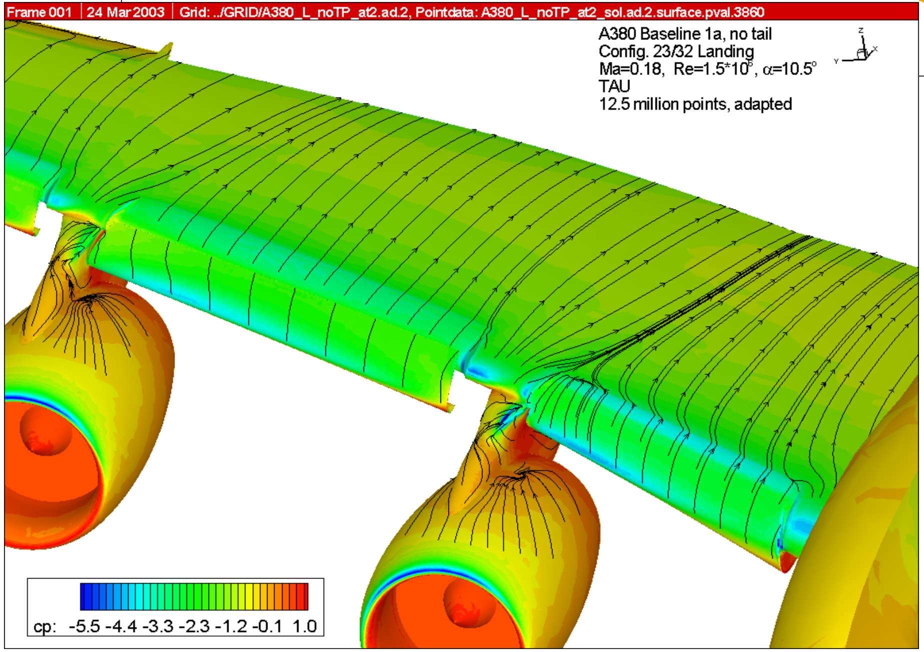
# Complex High- Lift Configurations

## Airbus A380/800 landing configuration






## TAU computations

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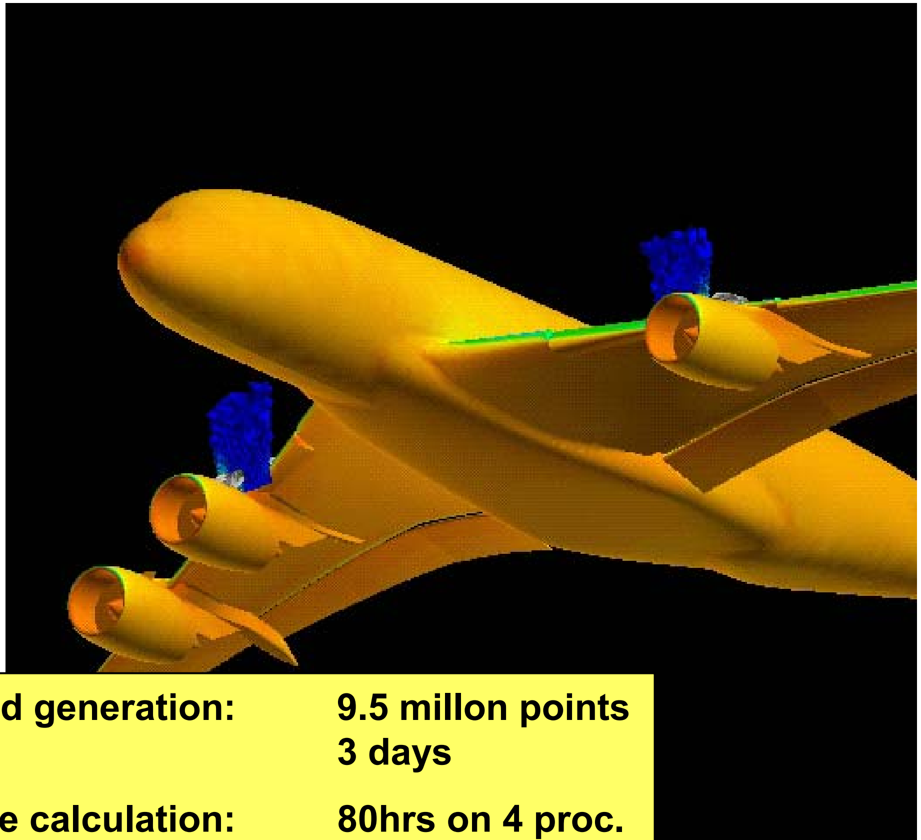
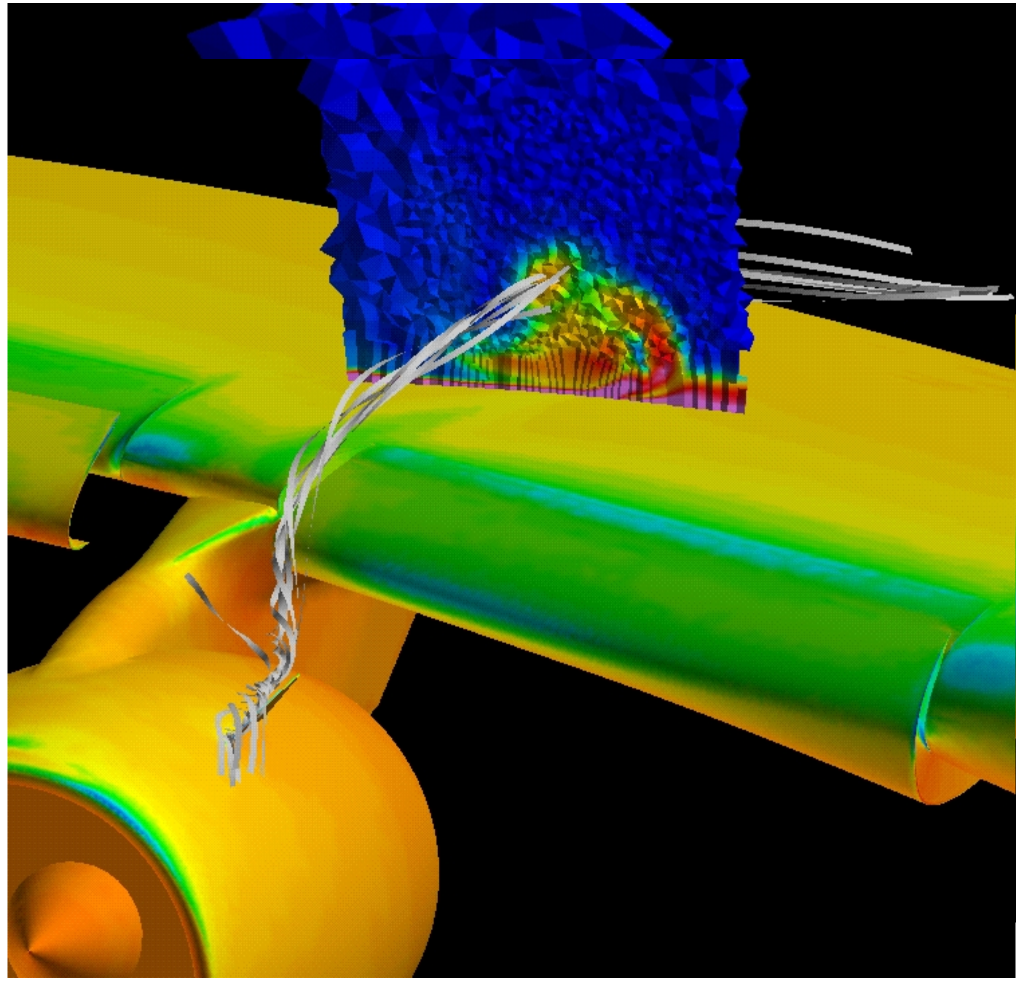
# Complex High- Lift Configurations

**Megaliner landing configuration**

**Influence of nacelle strakes**





| | |
|---|---|
| **grid generation:** | **9.5 millon points**<br>**3 days** |
| **one calculation:** | **80hrs on 4 proc.**<br>**NEC SX5** |

**TAU computations**

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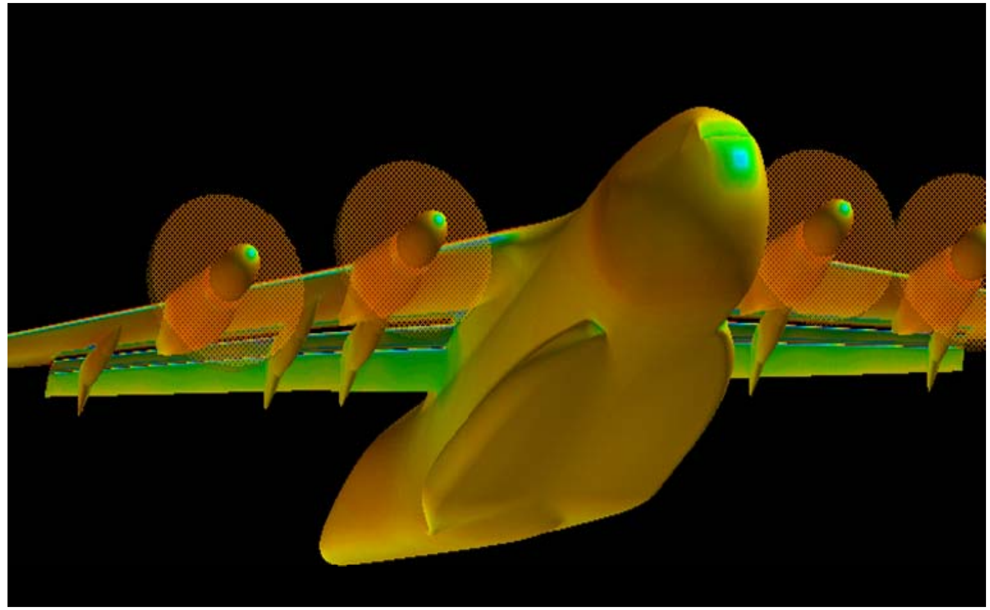
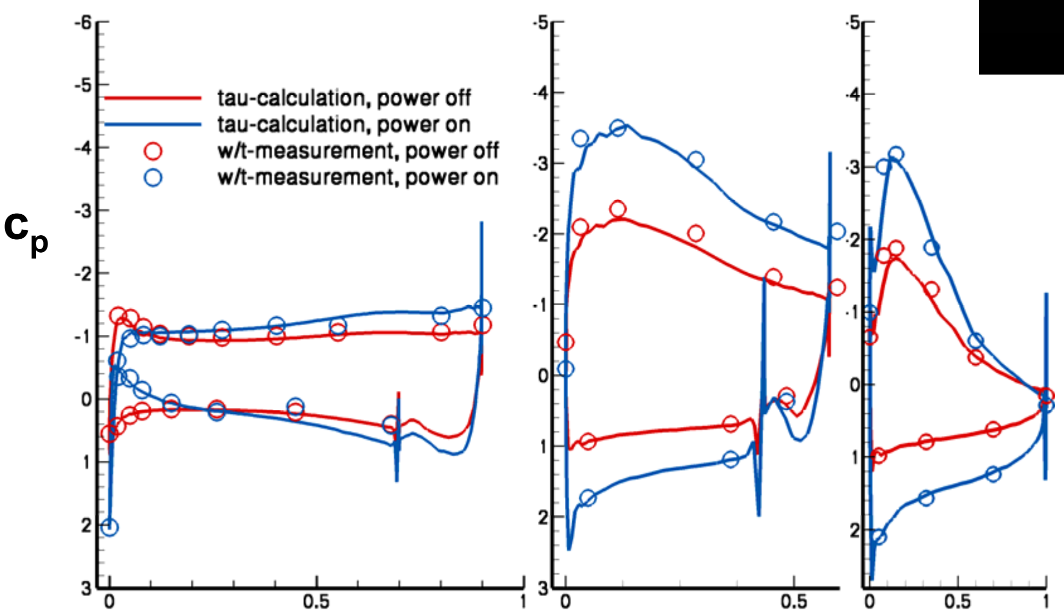
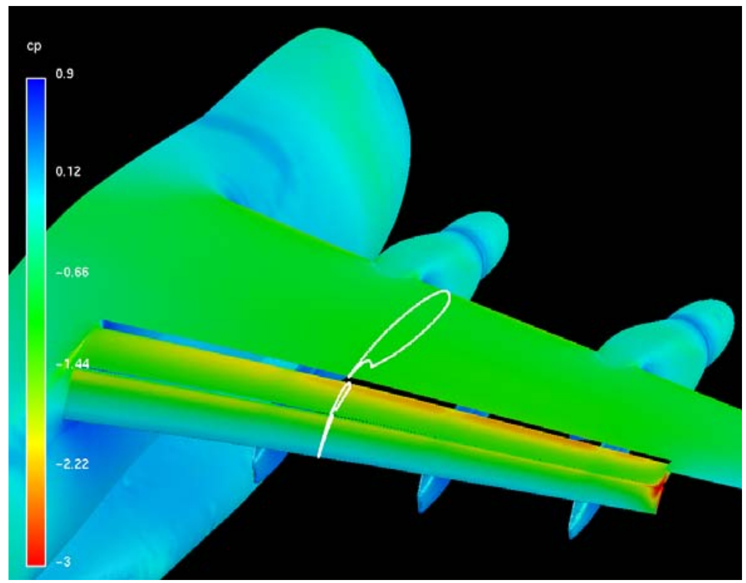
# Military Transport Aircraft

## TAU computation

- **hybrid mesh** (CENTAUR™)
- **30 prism layers**
- **440000 surface points**
- **Re = 1.3 x $10^6$**
- **12.9x$10^6$ field points**

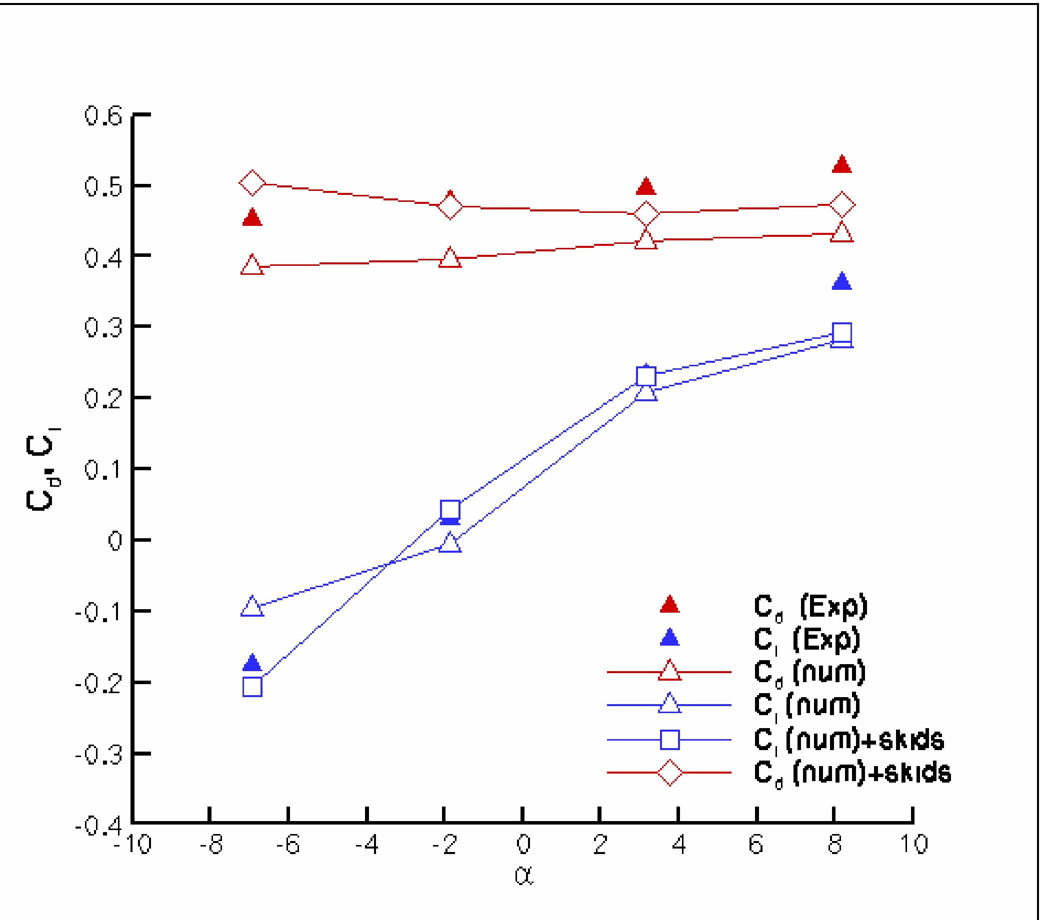




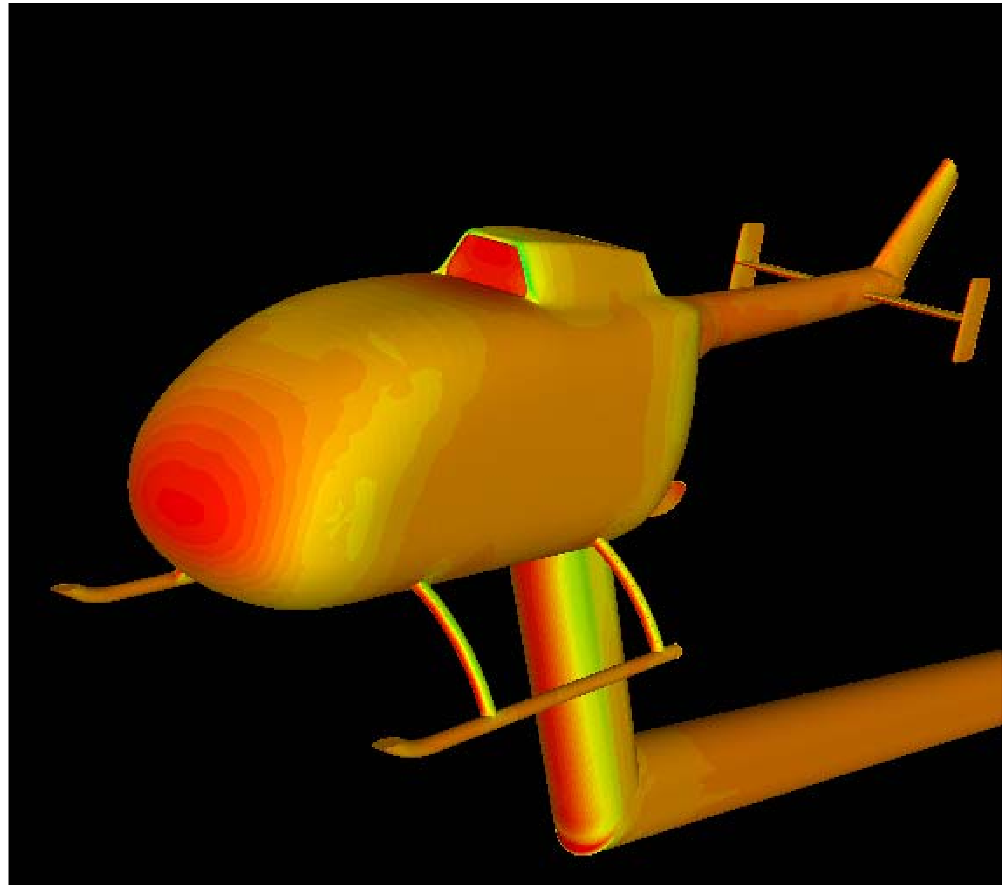



# Helicopter EC BO 105 – Influence of Skids

Chimera grid system
345 blocks, 5.8 mio. grid points




**FLOWer Chimera calculation**



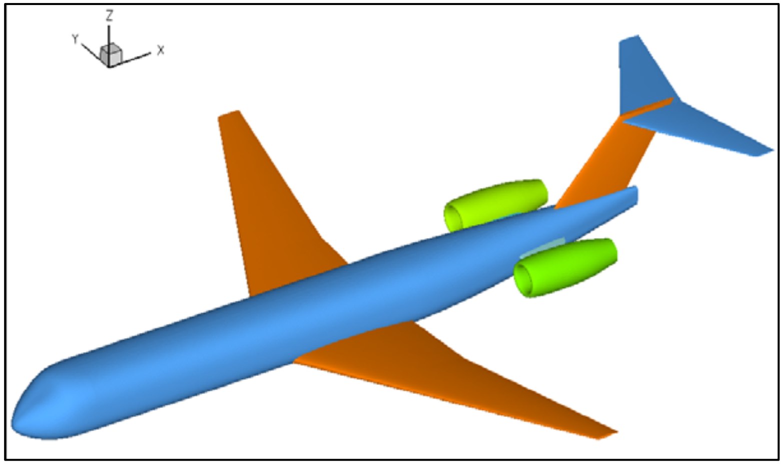
$c_p$- distribution

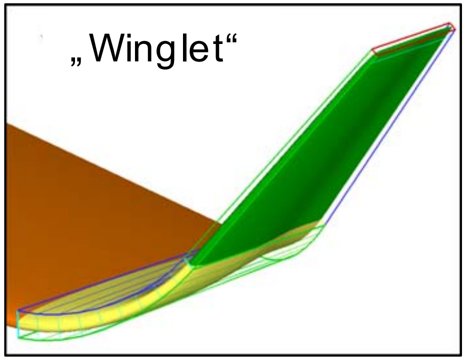
Khier

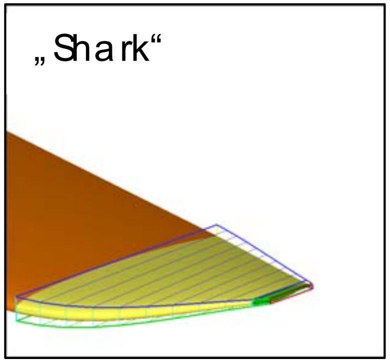
# Shape design and optimization

## Design studies by

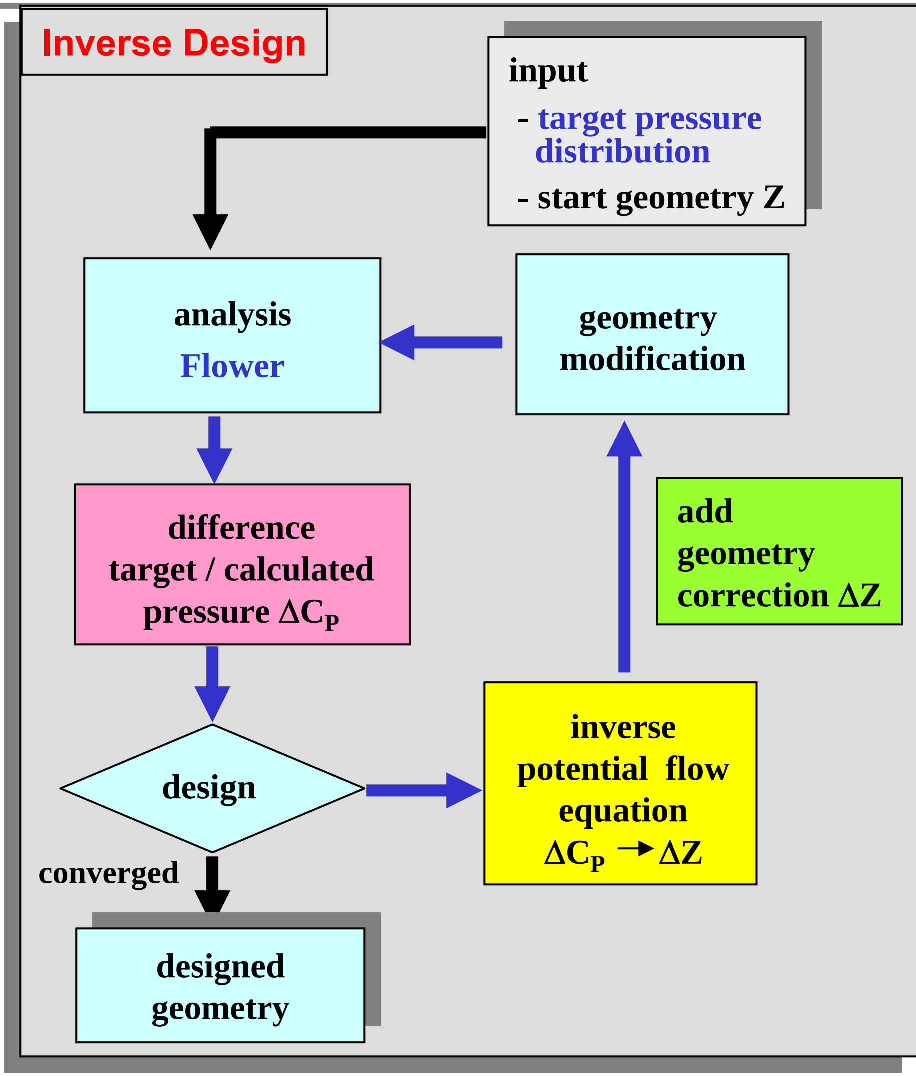
- analysis of different geometries
- inverse design
- numerical shape optimization



# Inverse Design (FLOWer option)



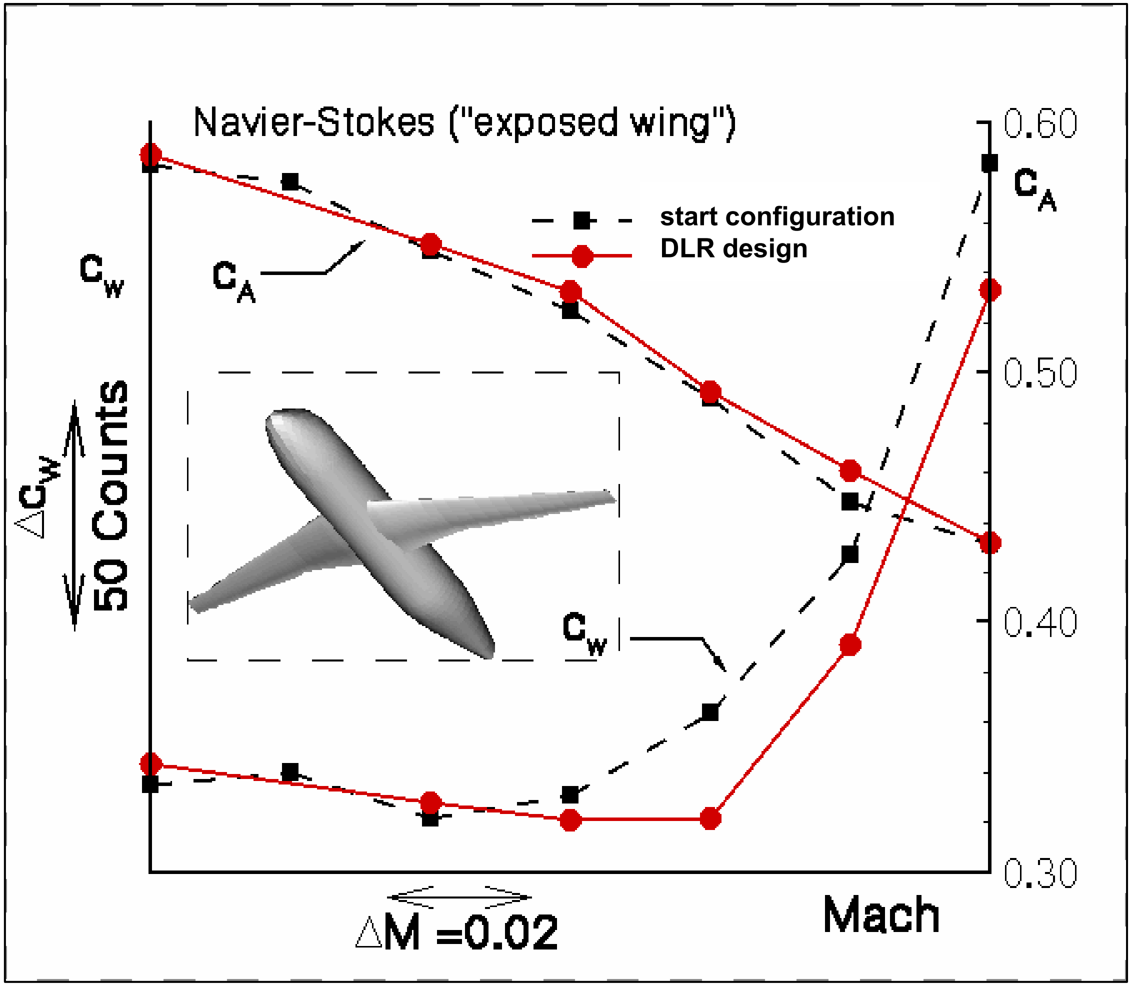

**<u>Inverse method</u>** ***(Bartelheimer/Takanashi)***

- **pressure difference $\Delta C_P$ converted to $\Delta Z$ by solving transonic small perturbation equation (TSP)**
- **robustness improvement for transonic flow by adding additional damping term**
- **smoothing of geometry differences $\Delta Z$ using Bézier curves**
- **specification of target pressure using GUI (TpEdit)**

## Applications

- **airfoil**
- **isolated wing**
- **isolated nacelle**
- **wing/body**

# Inverse Wing Design

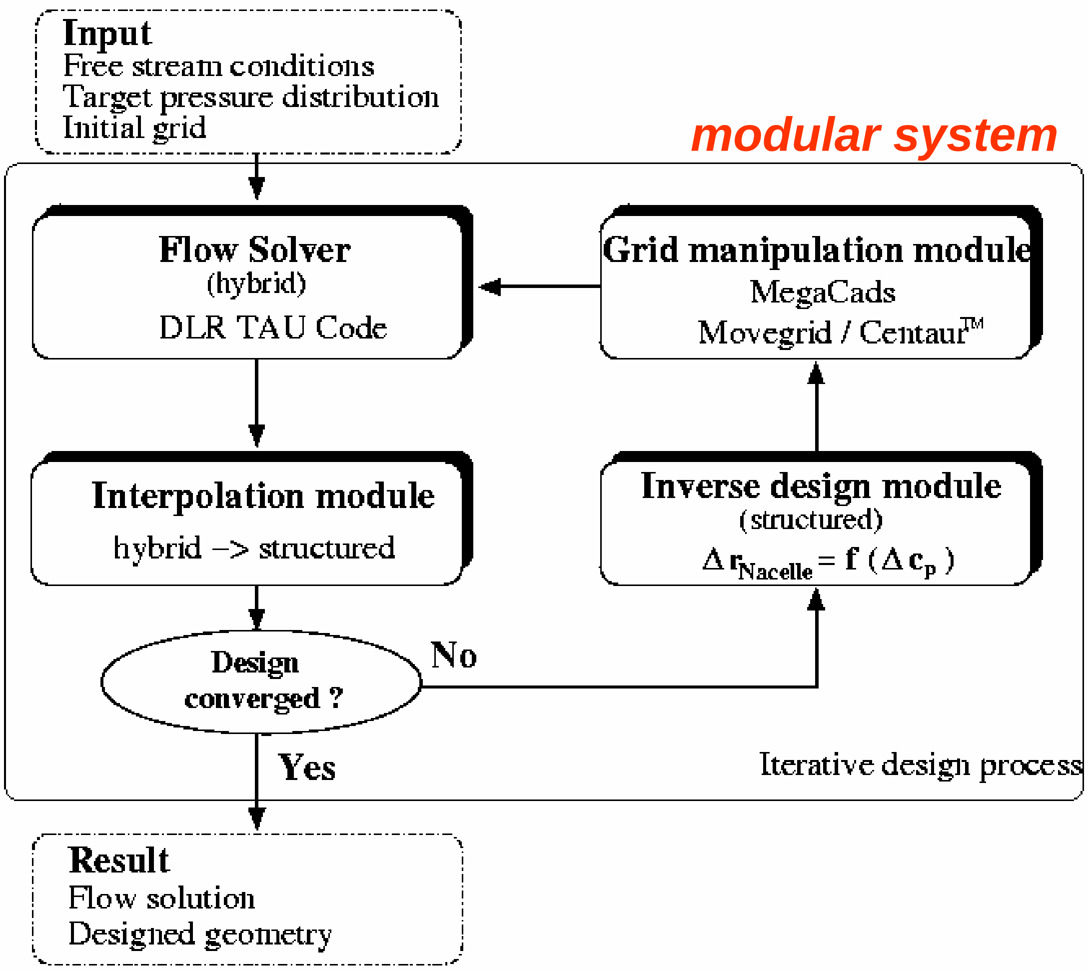



*Objective*
- drag rise improvement

*Configuration*
- F/D 728/928 (n=1.0g)

*Flow Solver*
- FLOWer, RANS

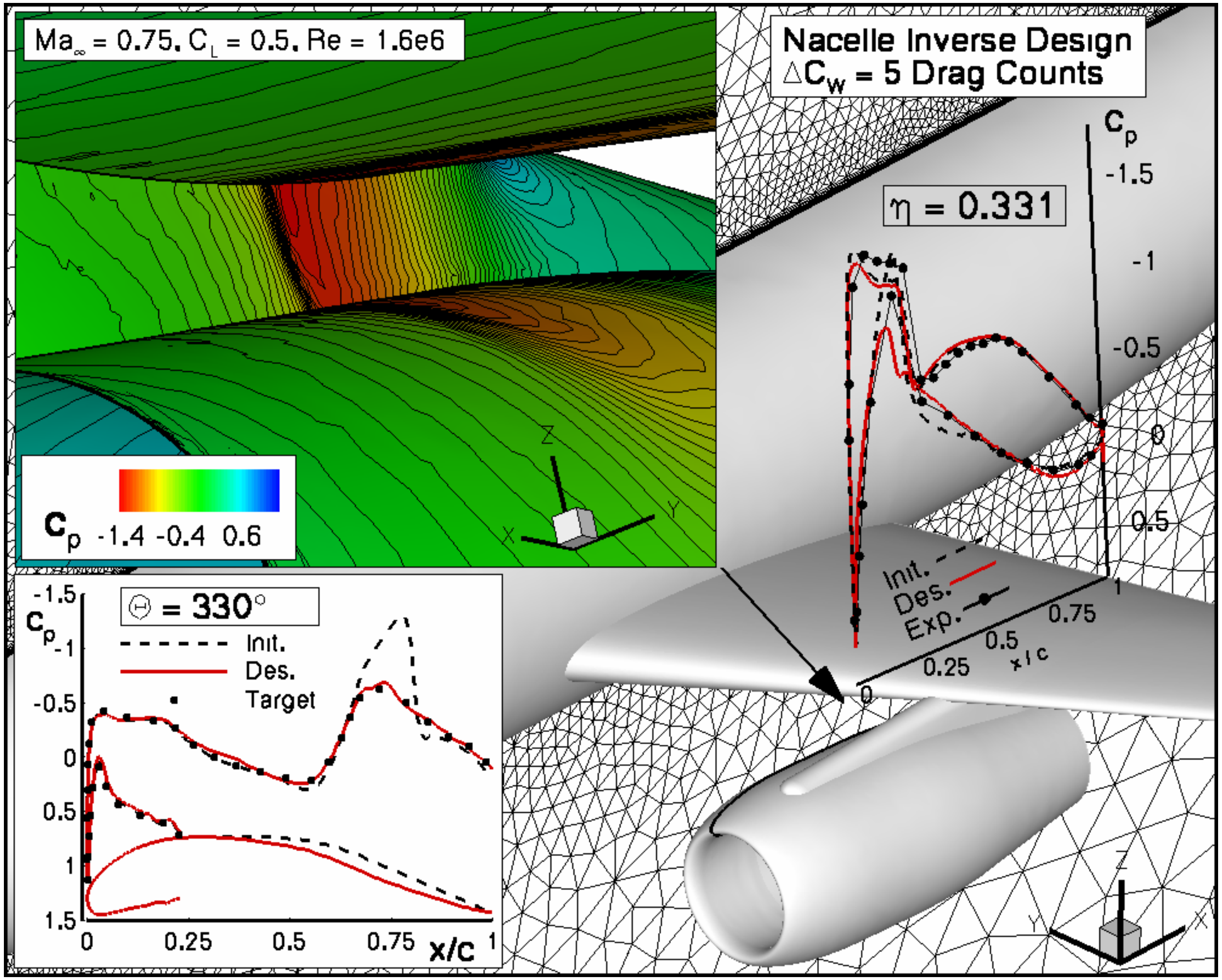
# Integrated Inverse Design System using Tau




## Applications

- isolated nacelle
- integrated nacelle
- integrated empennage design

# Integrated Inverse Nacelle Design




***Objective***

- **drag reduction through improved nacelle design**

***Configuration***

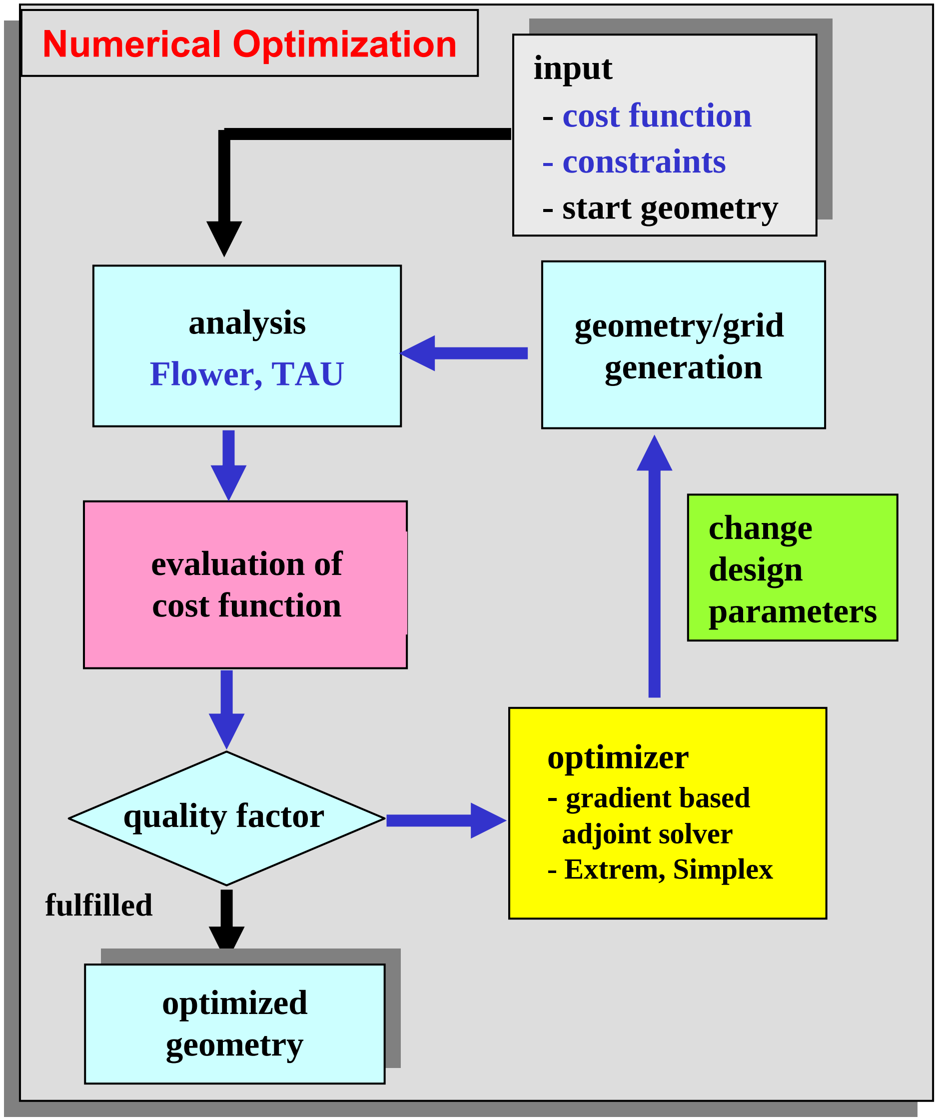
- **F6 wing/body/pylon/nacelle $M=0.75, C_L=0.5$, Re=3 Mil.**

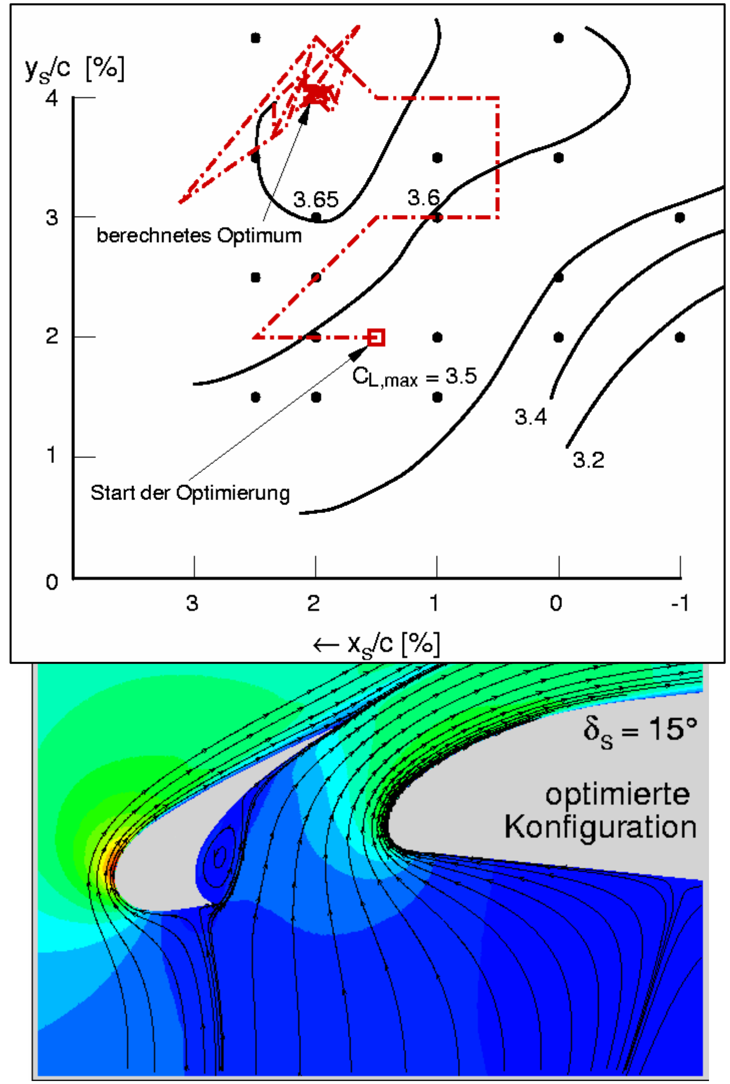
***Flow Solver***

- **TAU, inviscid**

DLR

# Aerodynamic Shape Optimization




**setting optimization, $C_{a_{max}}$**

**M=0.197, Re=3.52x10$^6$**

# Numerical Optimization of High-Lift 3-Element Airfoil

## single point, single discipline, single objective

## Application

- drag optimization for 3-element airfoil
- take-off configuration ($M_\infty$=0.2, Re=3.52x$10^6$)

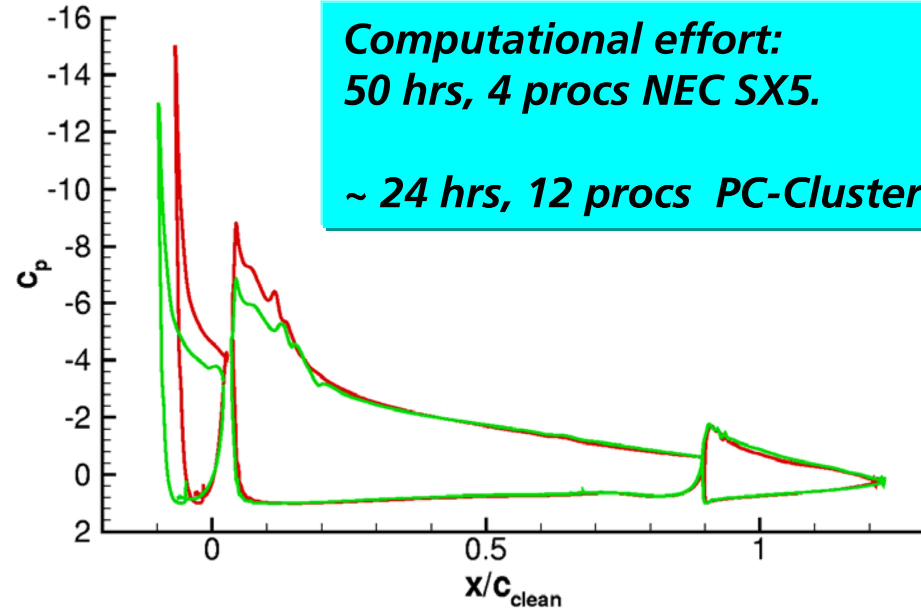
## Cost function:

- minimum drag with constant lift and constraint pitching moment

## Design parameters (12)

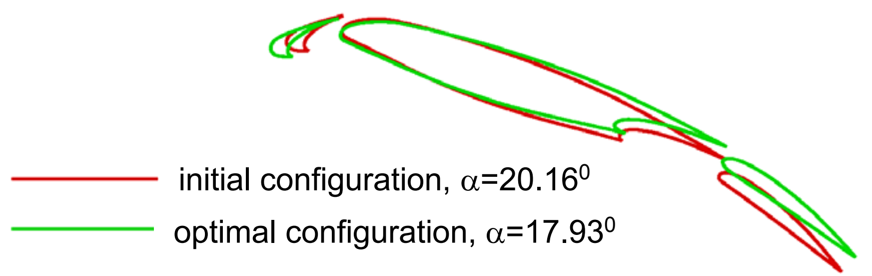
- element position & deflection
- element-size variations

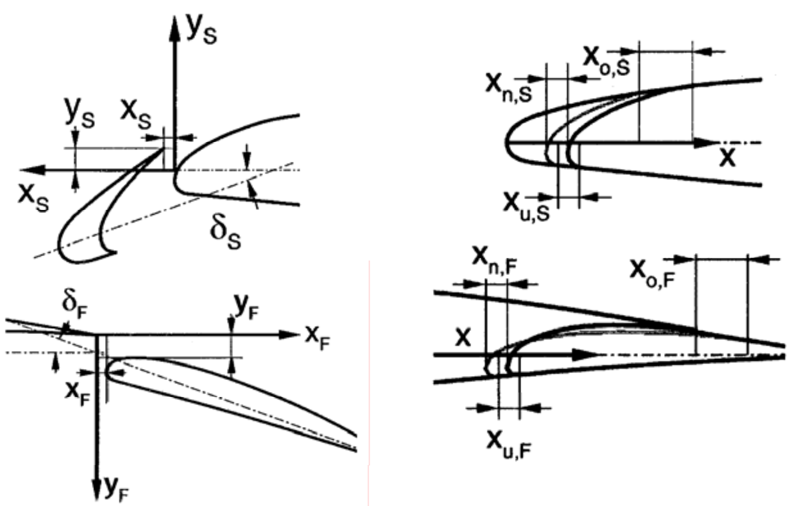
pressure distribution




***Computational effort:***
***50 hrs, 4 procs NEC SX5.***

***~ 24 hrs, 12 procs PC-Cluster***




Wild

# Aerodynamic Shape Optimization

## Requirements

- multi-point design, multi-objective optimization,
  multi-disciplinary optimization
- large number of design variables
- physical and geometrical constraints
- complex configurations
- parametrization based on CAD model
- meshing & mesh deformation techniques ensuring grid quality
- compressible Navier-Stokes equations
  with accurate models for turbulence and transition
- validated and efficient CFD codes
- efficient & reliable optimization algorithms

# Aerodynamic Shape Optimization

## Key elements

- Geometry parametrization
- Meshing & mesh movements methods
- Flow solver efficiency & accuracy
- Optimization techniques
- Multi-disciplinary optimization
- Optimization process chain
- Verification & Validation

# National Project MEGADESIGN (2003-2007)

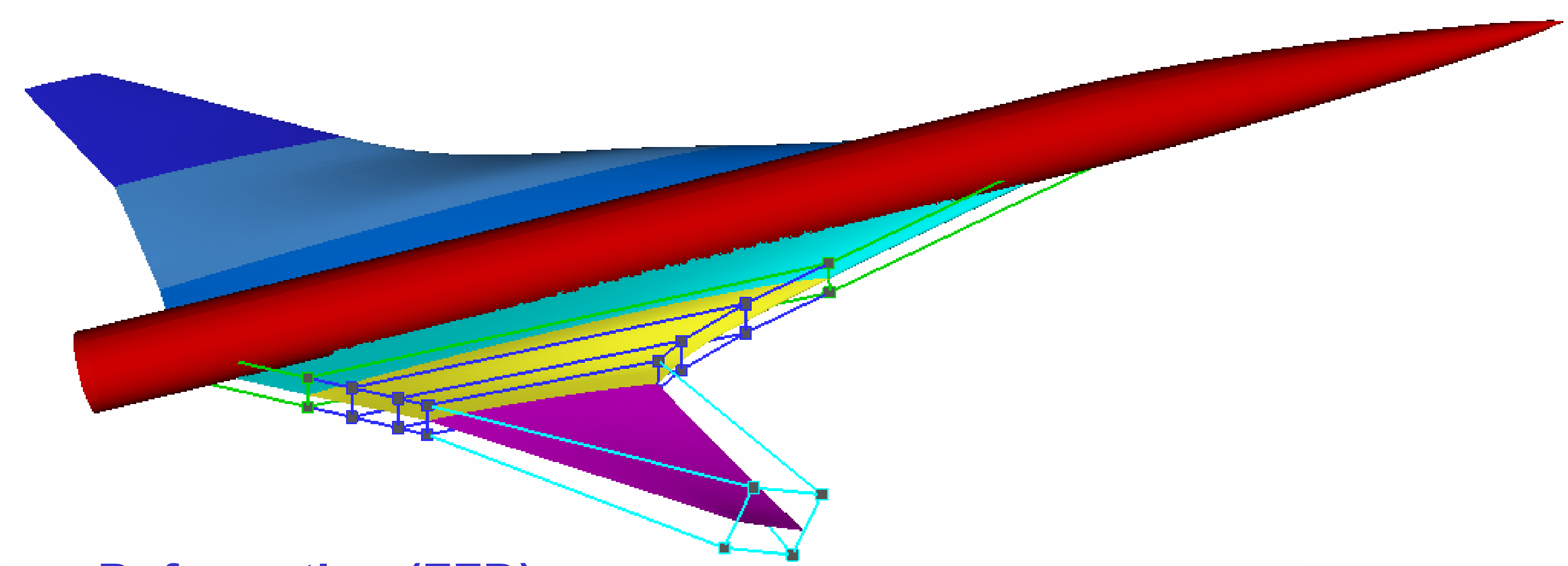
## Main objectives

- Improvement of aircraft shape optimization tools
- Establishment of numerical shape optimization within industrial aircraft design process
- Concentration of activities & resources from DLR, universities, aeronautical industry & SMEs

## Partners

- Airbus-G, EADS-M
- DLR
- CLE, *Fast*Opt, Synaps
- Universities of Aachen, Berlin, Braunschweig, Darmstadt, Trier

# Shape-Parameterization Using Freeform Deformation



## Freeform Deformation (FFD)

- parameterization of complex non parametric CAD-based shapes
- high flexibility in combination with grid generation techniques
- widely used for “Soft-Object Animation”

**Idea:**

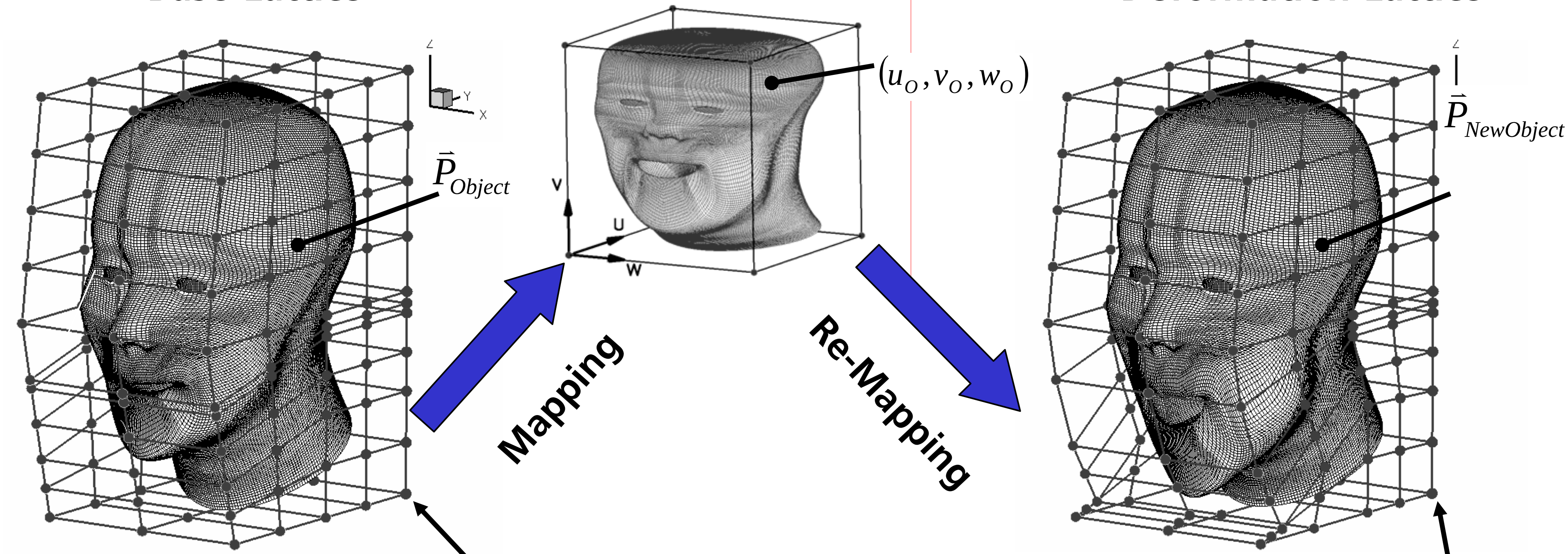
- use FFD as geometry modeler within aerodynamic shape optimization

Ronzheimer

# Freeform Deformation Technique *(Sederberg, Parry)*

DLR

**Base-Lattice** **Deformation-Lattice**




**Evaluate** $(u_O, v_O, w_O)$ **from:**

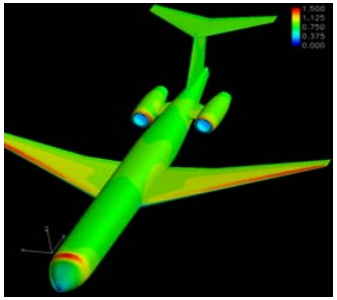
$$\vec{P}_{Object}(u_O, v_O, w_O) = \sum_{i=0}^{n_u} \sum_{j=0}^{n_v} \sum_{k=0}^{n_w} N_{i,m_u}(u_O) N_{j,m_v}(v_O) N_{k,m_w}(w_O) \vec{Q}_{i,j,k}$$

**Evaluate** $\vec{P}_{NewObject}$ **from:**

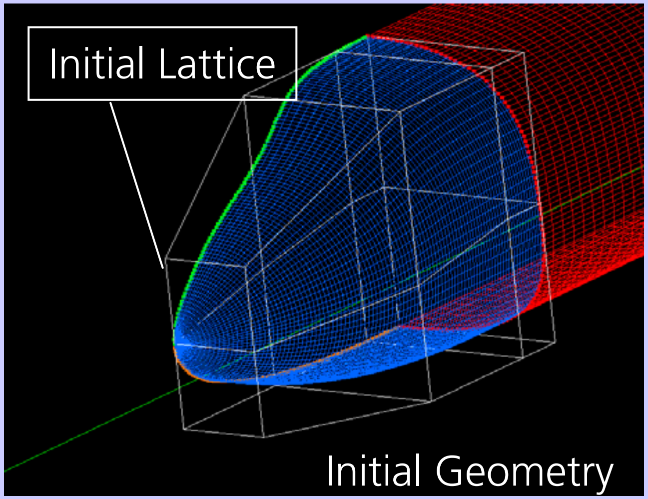
$$\vec{P}_{NewObject}(u_O, v_O, w_O) = \sum_{i=0}^{n_u} \sum_{j=0}^{n_v} \sum_{k=0}^{n_w} N_{i,m_u}(u_O) N_{j,m_v}(v_O) N_{k,m_w}(w_O) \vec{R}_{i,j,k}$$

B-Spline Base Functions: $N_{i,m_u}(u), N_{j,m_v}(v), N_{k,m_w}(w)$ B-Spline Control Poins: $\vec{Q}_{i,j,k}, \vec{R}_{i,j,k}$

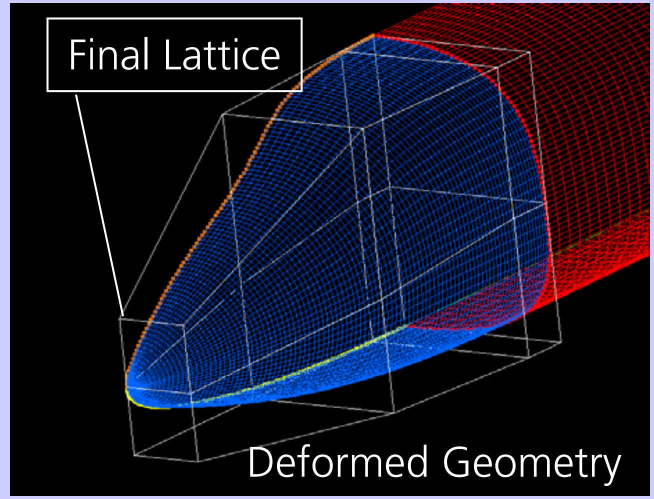
# Principle Steps of Freeform Deformation

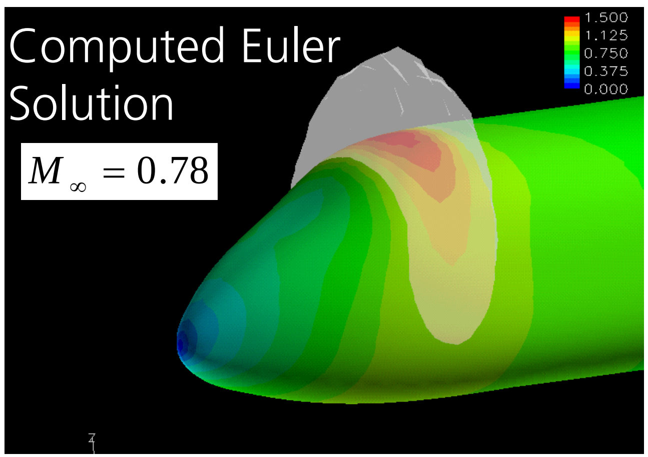


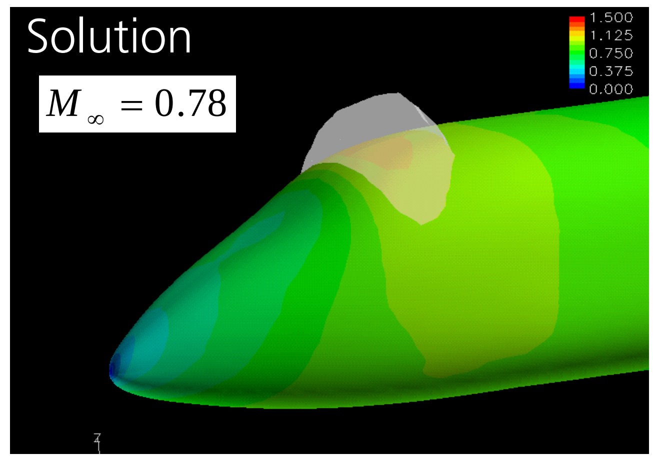
Mapping of Geometry into Initial B-Spline Volume




Re-Mapping of Geometry from Final B-Spline Volume

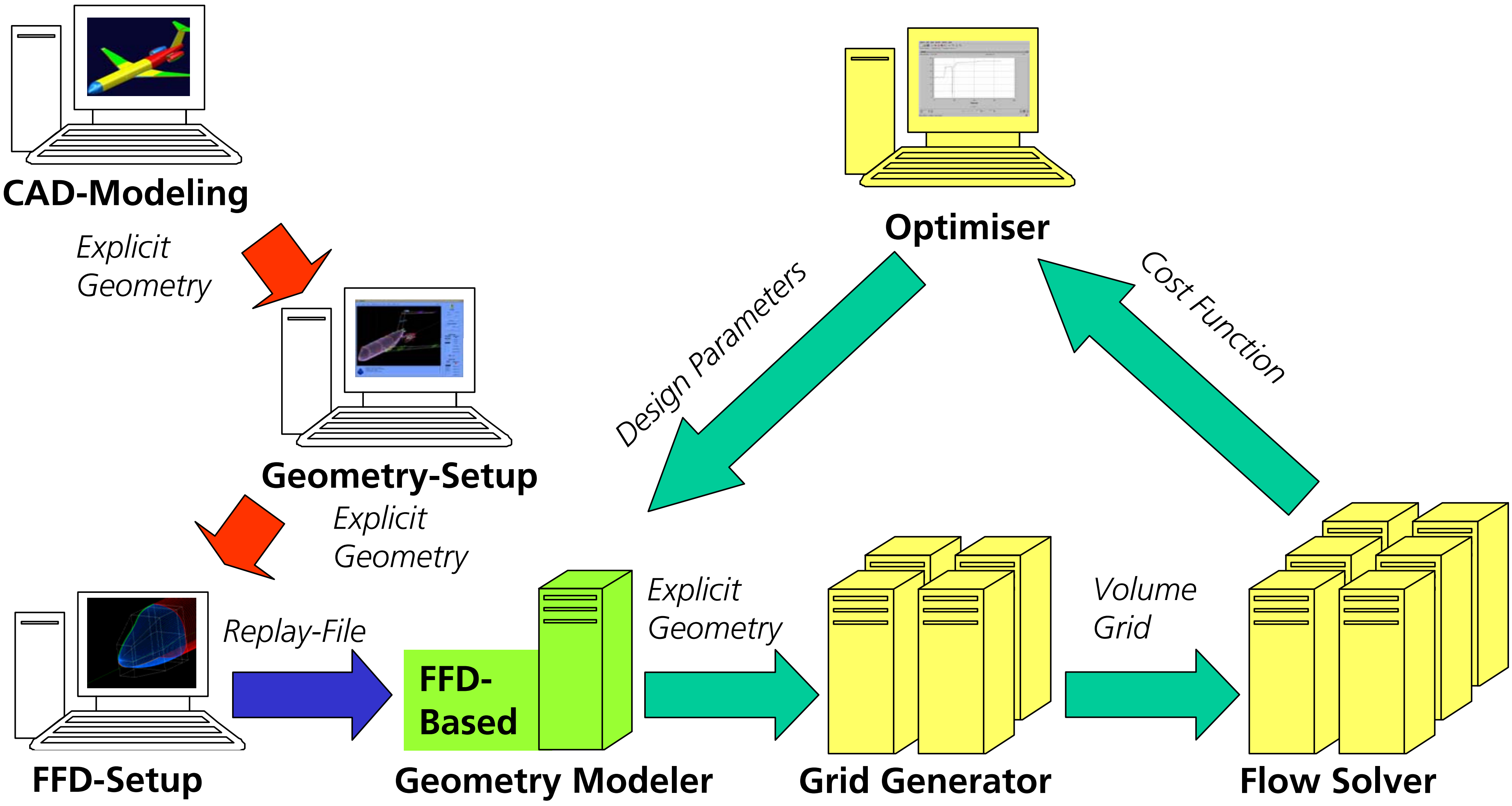


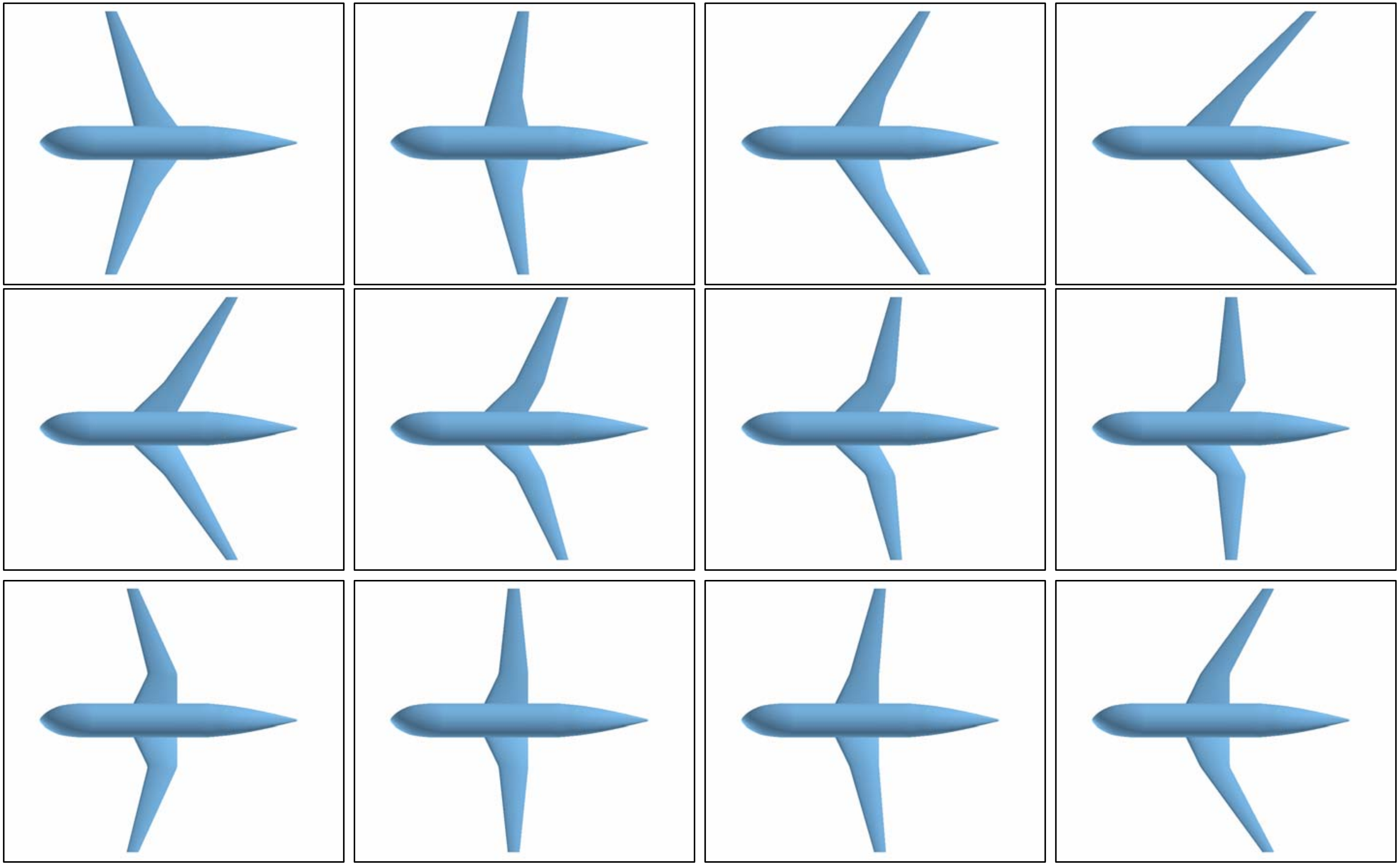

**Ronzheimer**

# Parametric CAD in Aerodynamic Shape Optimization




© Ronzheimer

# Example fro Freeform Deformation

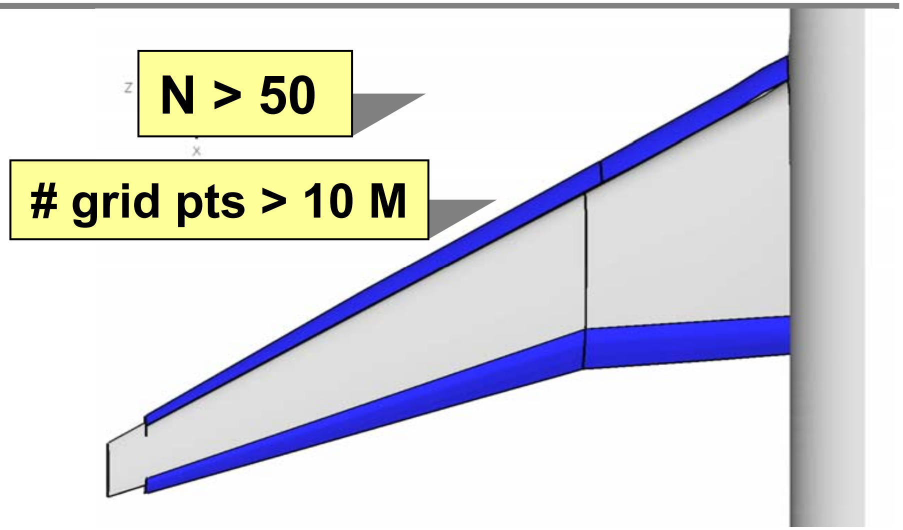


Ronzheimer

# Optimization algorithms

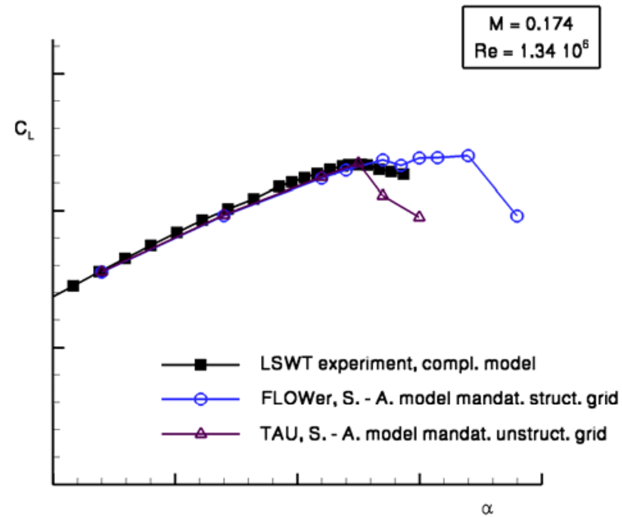
### Problem

- shape optimization in 3D requires large number N of design parameters
- high computational costs for each flow equations (Navier-Stokes)
- noisy cost functions
- constraints

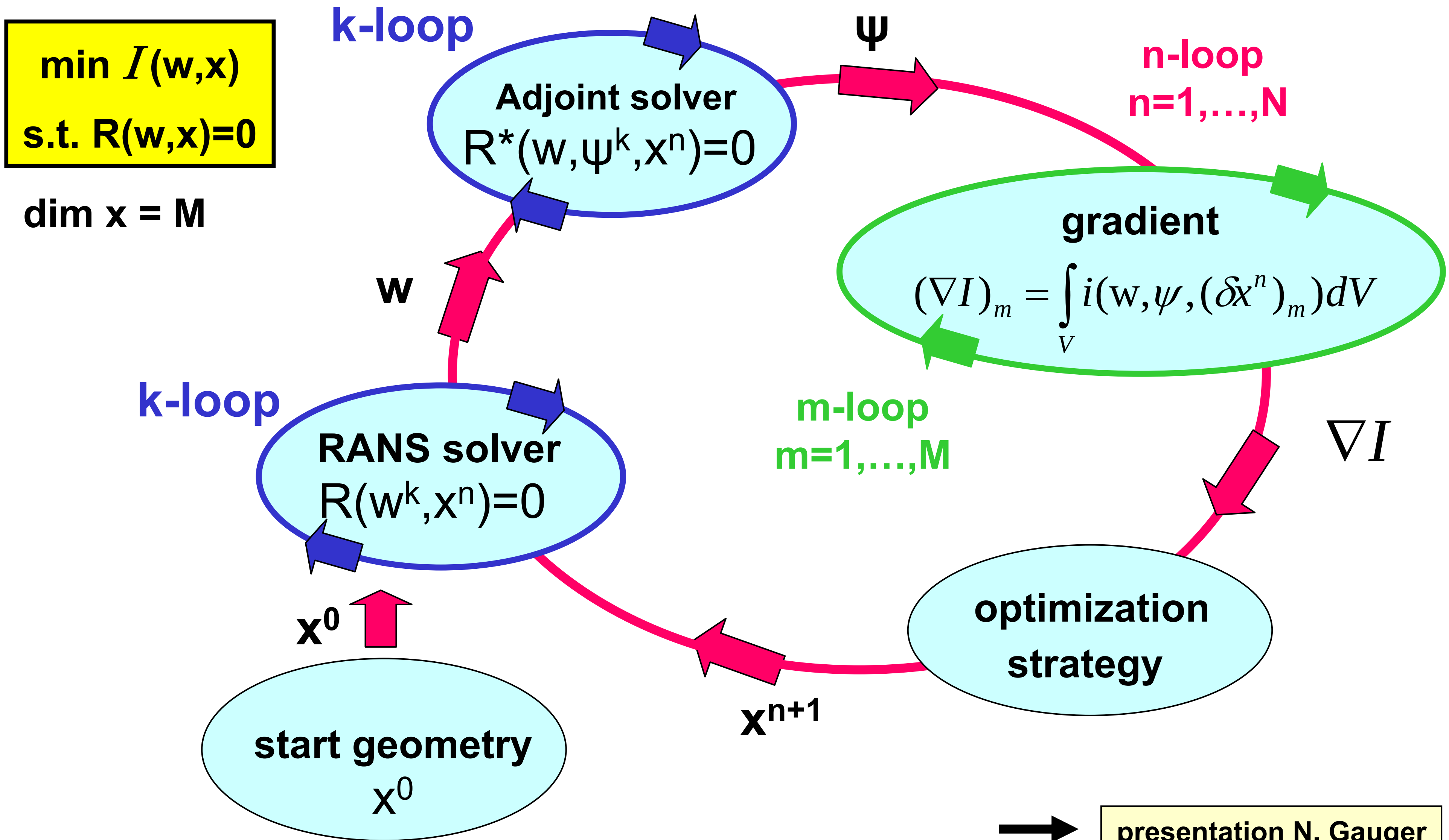



### Optimization strategies

- evolutionary strategies
- deterministic strategies
- gradient based strategies

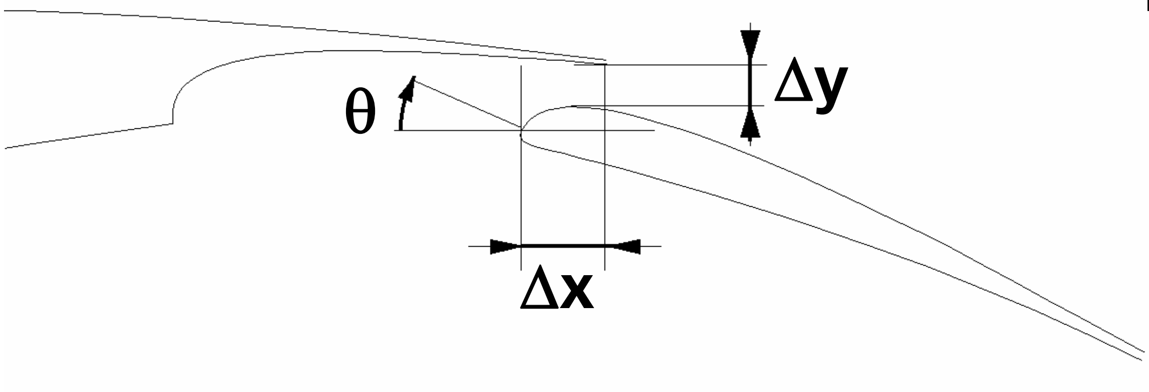


# Adjoint based Optimization



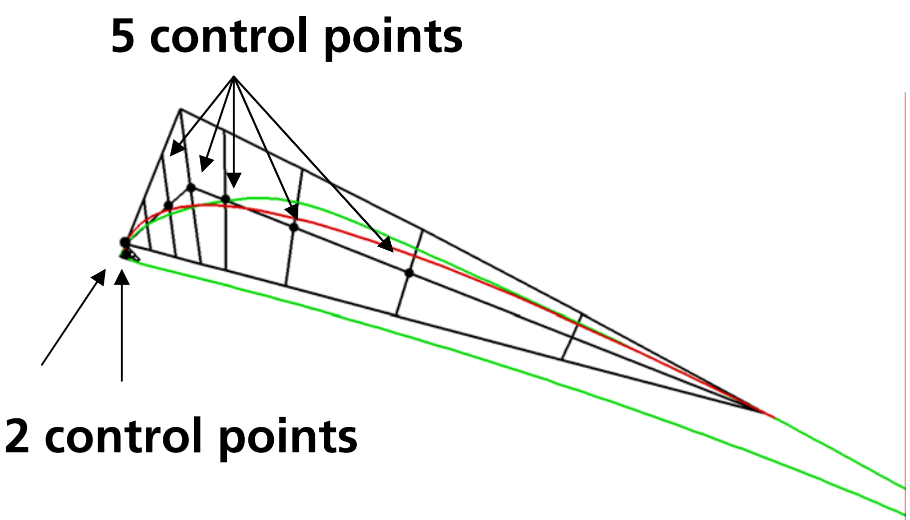

→ presentation N. Gauger

# Parameterisation (10 design parameters)




**Flap position and angle**

- Flap gap (Δy)
- Flap overlap (Δx)
- Flap angle (θ)

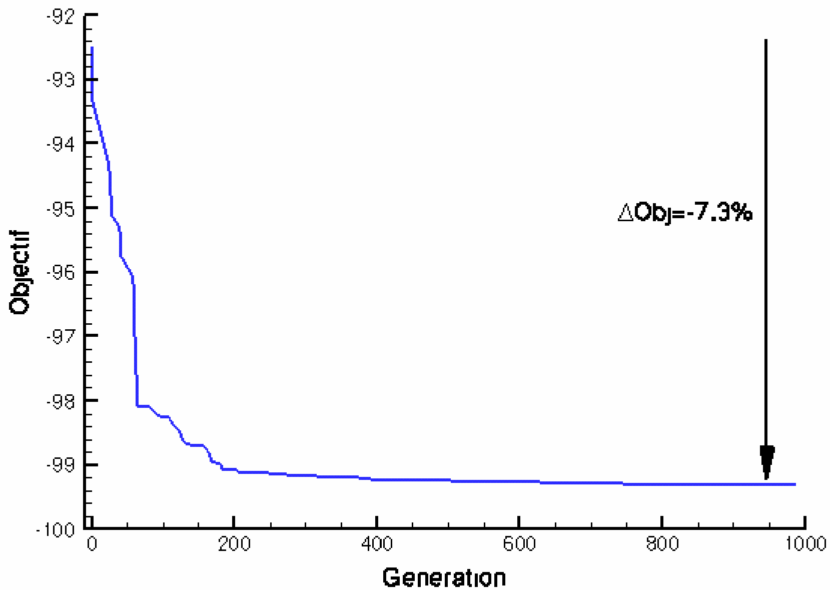


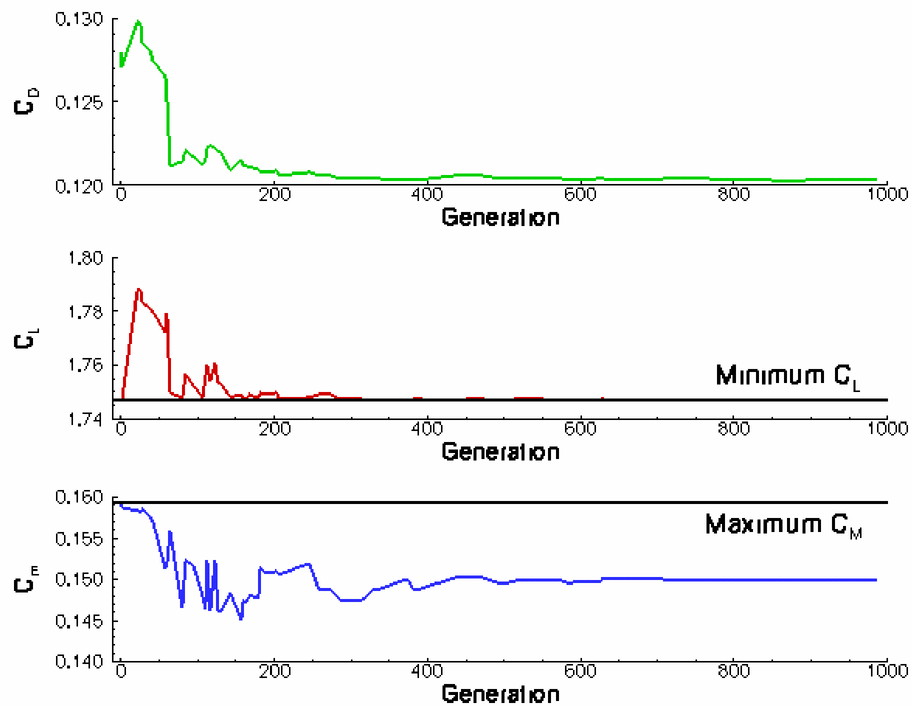

**Shape via Free Form Deformation**

- 5 design at the upper side
- 1 design at the lower side
- Nose position

# Differential Evolution (evolutionary algorithm)

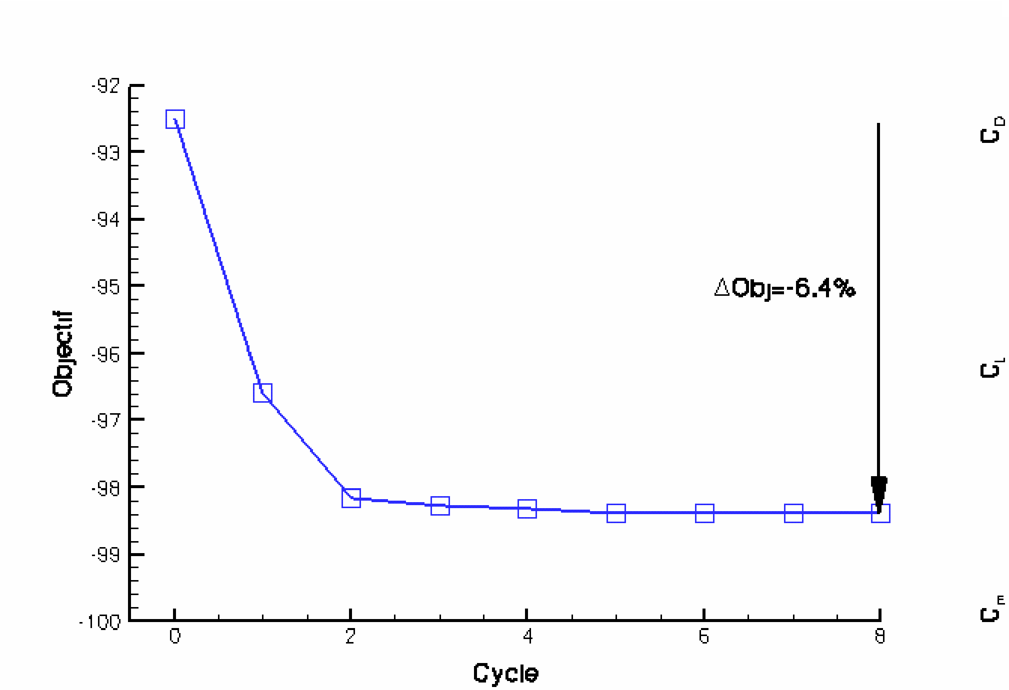
- 1000 generations, 10 individuals per generation (10.000 evaluations)
- Best solution after 964 generations ($\eta$=9.649)
  - 7.3% improvement
  - CD=0.940*CD(baseline) ; CL = CL(baseline) ; Cm<Cm(baseline)

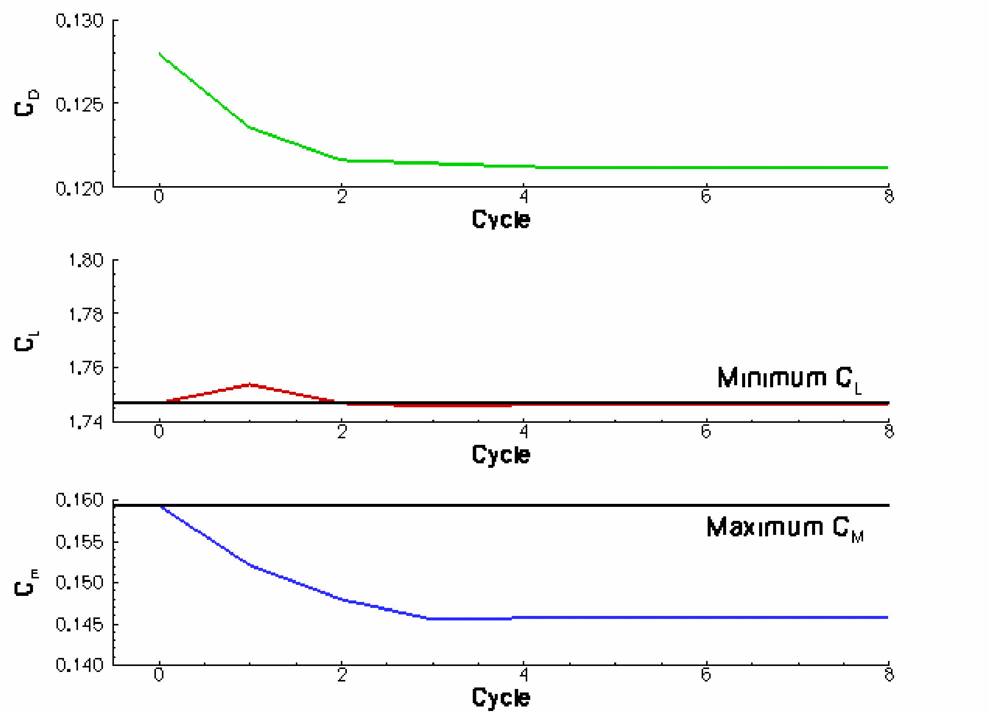


# Simplex (gradient free approach)

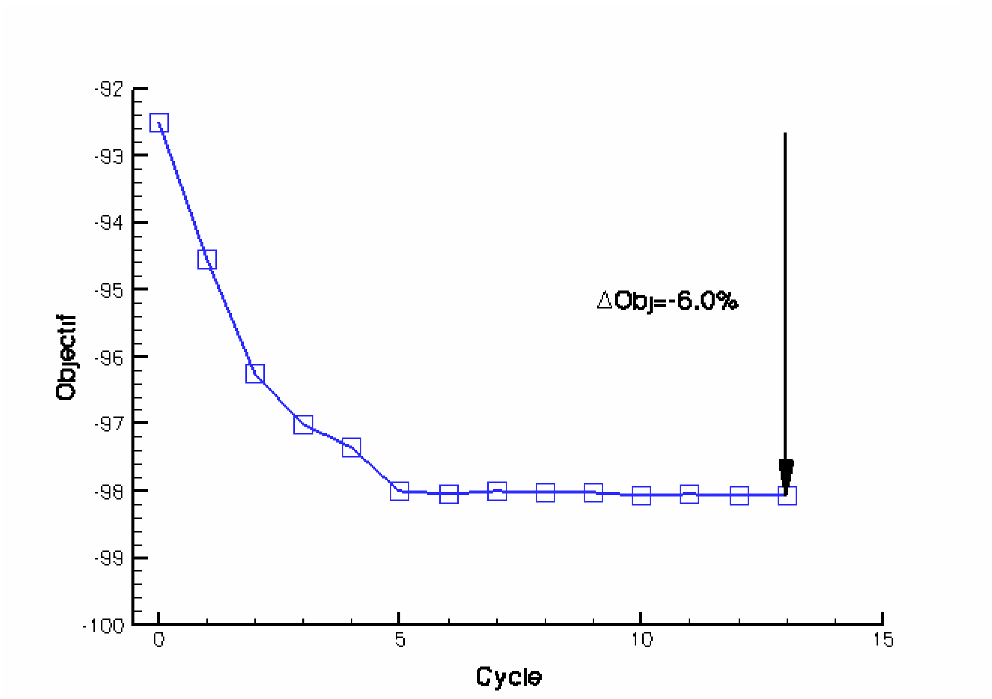
- 8 cycles (549 evaluations)
- Best solution after 8 cycles ($\eta$=514)
  - 6.4% improvement
  - CD=0.947*CD(baseline) ; CL = CL(baseline) ; Cm<Cm(baseline)

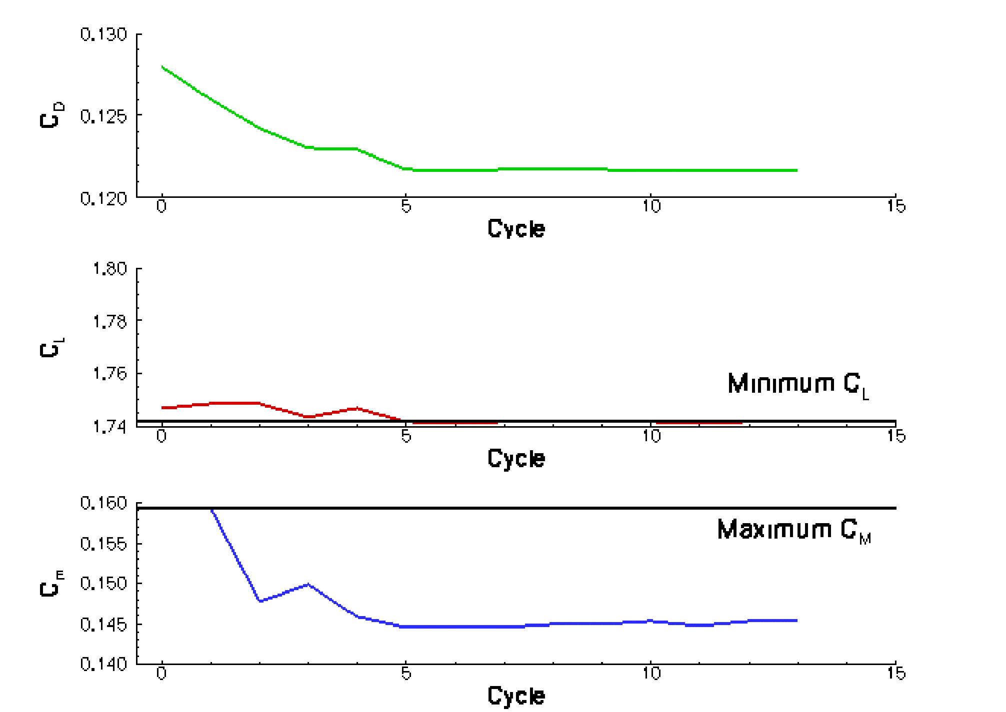


# Method of Feasible Directions (first order approach)

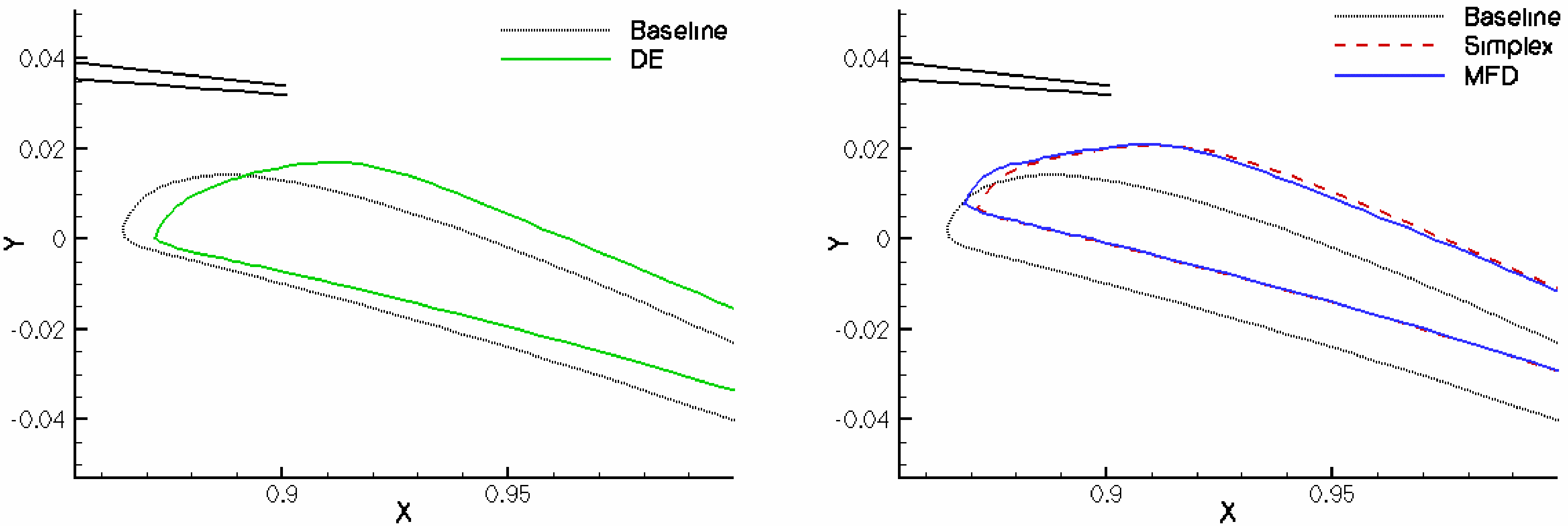
- 14 cycles (195 evaluations)
- Best solution after 12 cycles (η=180)
  - 6.0% improvement
  - CD=0.951*CD(baseline) ; CL = 0.997*CL(baseline) ; Cm<Cm(baseline)



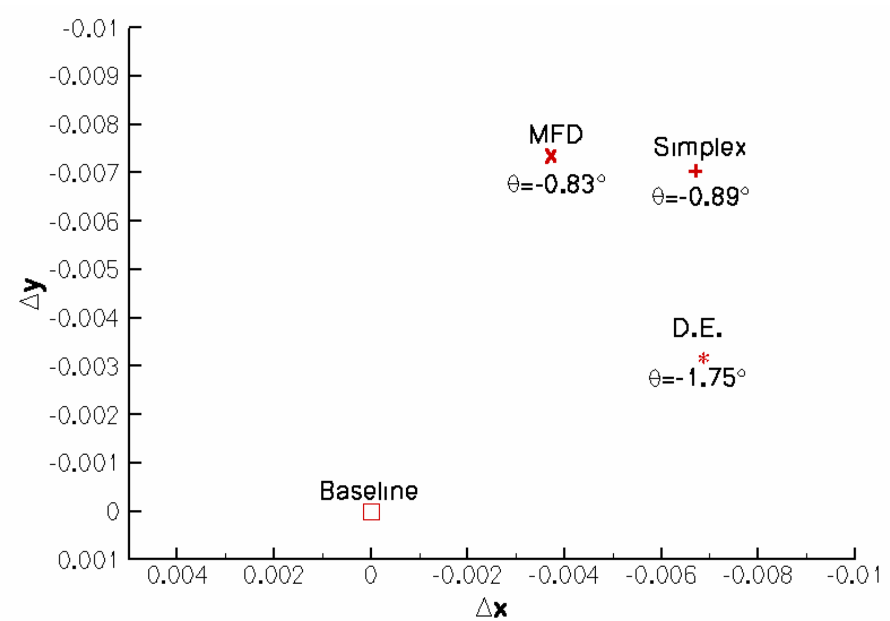



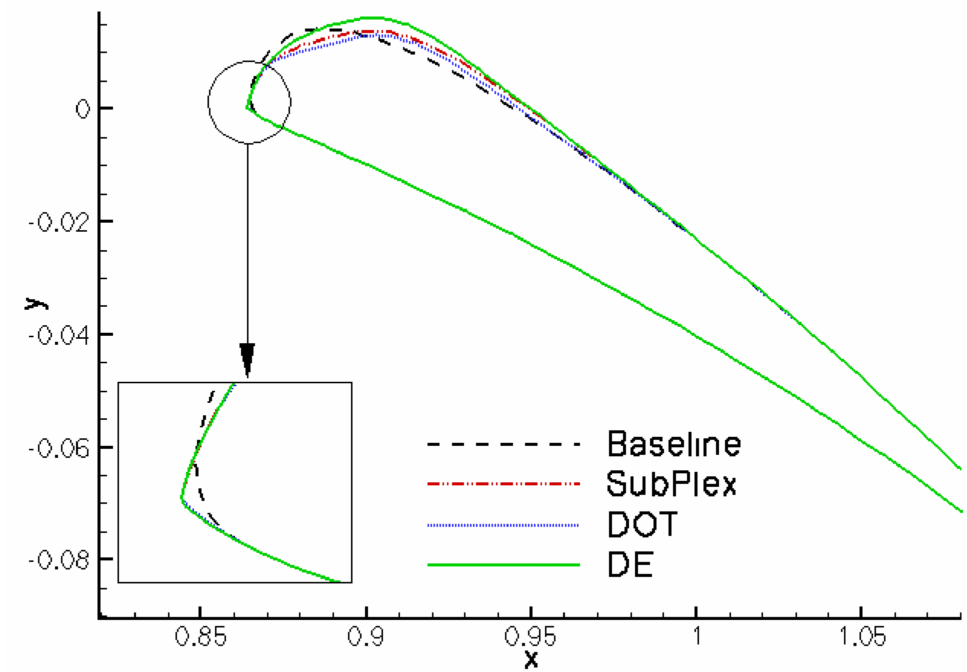
# Flap Design - position and geometry

- MFD and Simplex provide close results
- DE provides an other design



# Flap Design - position and geometry




- **With DE, flap mainly retracted (x direction)**
- **MFD and Simplex provide same gap (y direction)**
- **MFD and Simplex provide quite same shape**
- **Sharp nose obtained in all cases**

# Synthesis from the flap design with 10 design variables on the coarse mesh

## Differential Evolution

- provide the best optimum
- easy to use, robust, no extra operation from the user
- provide a complete database
- rather long to converge but easily scalable
  (180 wall clock hours on cluster of 5 computers)

## Simplex

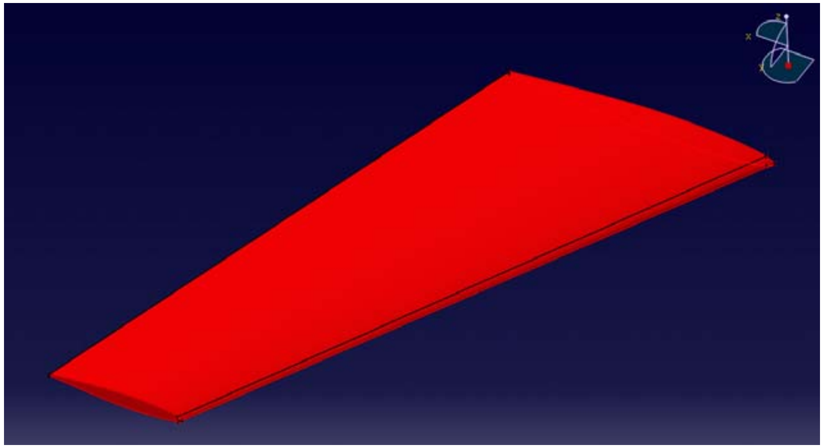
- easy to use and robust to noise
- faster than DE (61 wall clock hours on 1 pc)
- trap to local minimum

## MFD

- extremely fast (25 wall clock hours on 1 pc)
- lot of “try and error” to get a good optimization (scaling of the design variables)
- not robust (need accurate solution)
- trap to local minimum

# Multi-Objective Optimization - Example

## Shape optimization of wing plan form

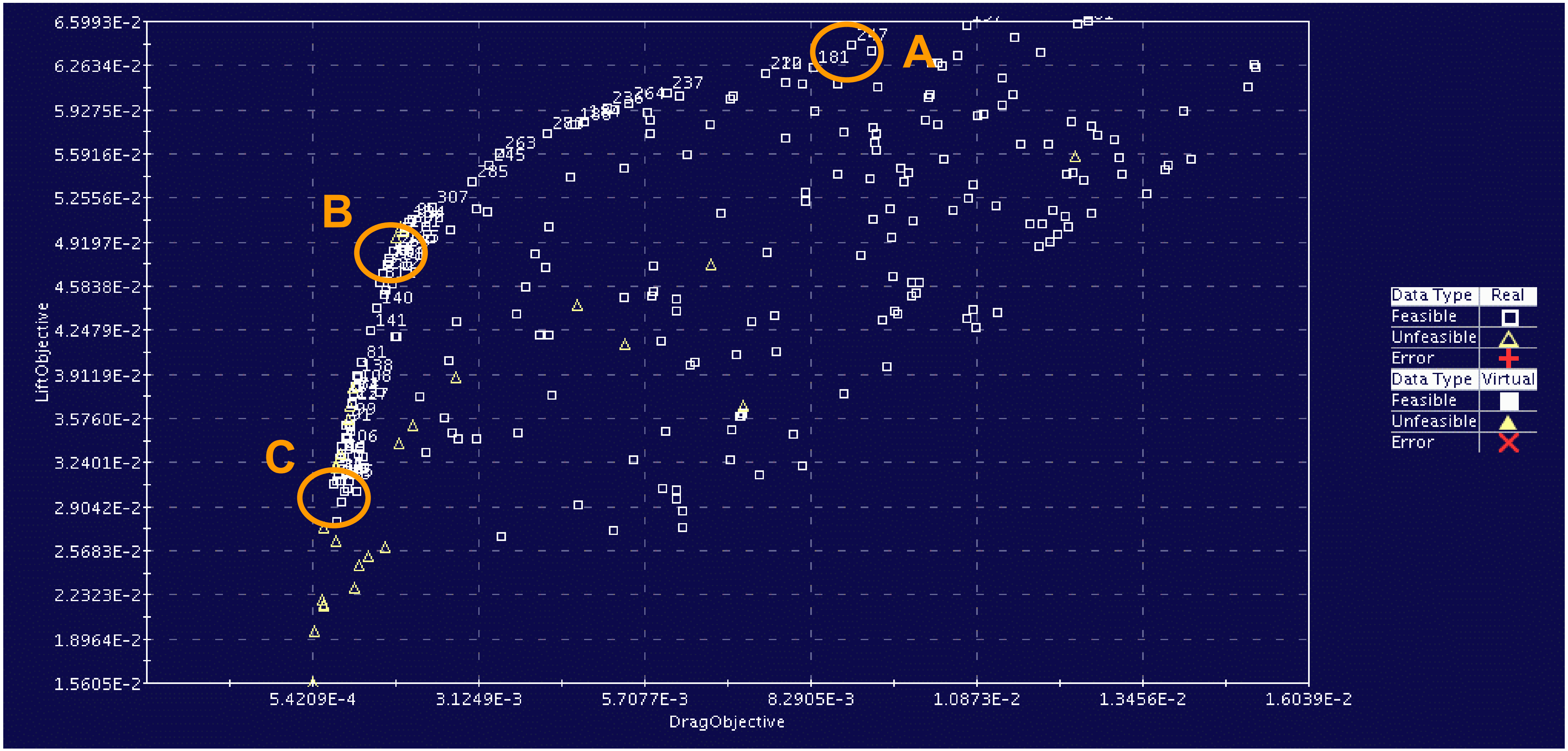


- flow condition: M = 0.85, a = 1°
- inviscid flow (Euler)
- computational mesh: 630.000 nodes
- multi objective optimization:
  - maximize lift and minimize drag
- design parameters:
  - sweep angle (range: -60° to +60°)
  - half span (range: 0.750 [m] to 1.250 [m])
  - aspect ratio (defined by const. wing plan area constraint)
  - taper ratio (range: 0.2 to 0.8)
- design constraints:
  - pitching moment restricted to range –0.025 to +0.0001

# Multi-Objective Optimization - Example

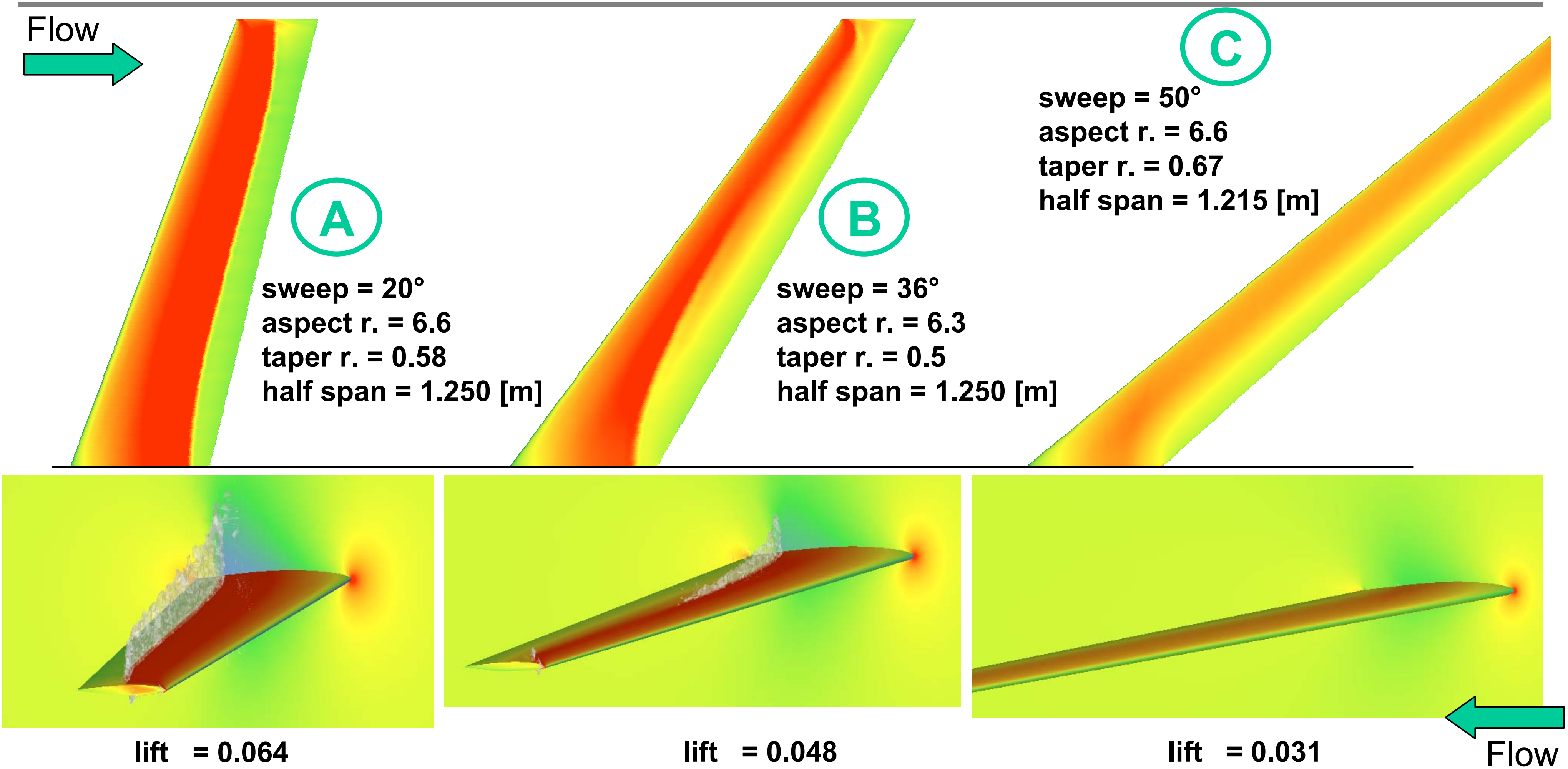
## Wing plan form optimization

Genetic algorithm




**Pareto Front**

# Multi-Objective Optimization - Example



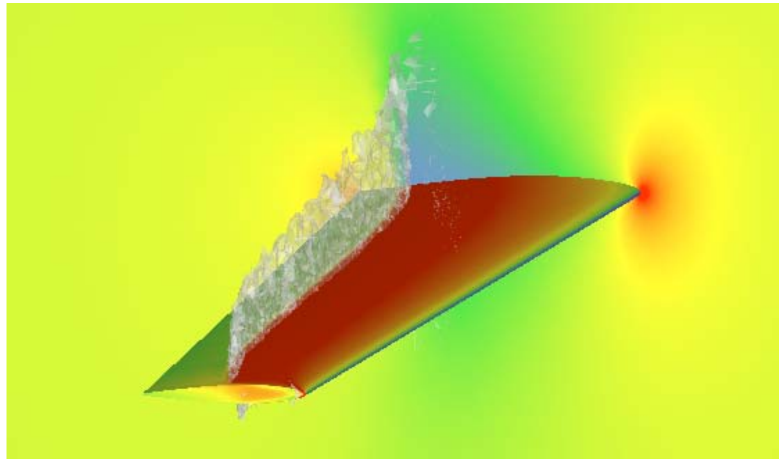

lift = 0.064
drag = 0.0089
moment = - 0.022
glide ratio = 7.2

lift = 0.048
drag = 0.0018
moment = - 0.025
glide ratio = 26.7

lift = 0.031
drag = 0.00087
moment = - 0.024
glide ratio = 35.6

EADS-M: Deister

# Multi-Objective Optimization - Example



## Shape optimization of wing plan form

## Computational effort:

- for one design evaluation:
  50 min (4 XEON 2.6 GHz processors)
  - complete mesh generation time: approx. 15 min.
  - complete flow simulation time: 35 min.
- 12 concurrent design evaluations using 4 processors each
- 30 design generations

- all together 360 design evaluations in less than 25 h

**but just 5 design variables and inviscid flow !**

**alternative strategies ?**

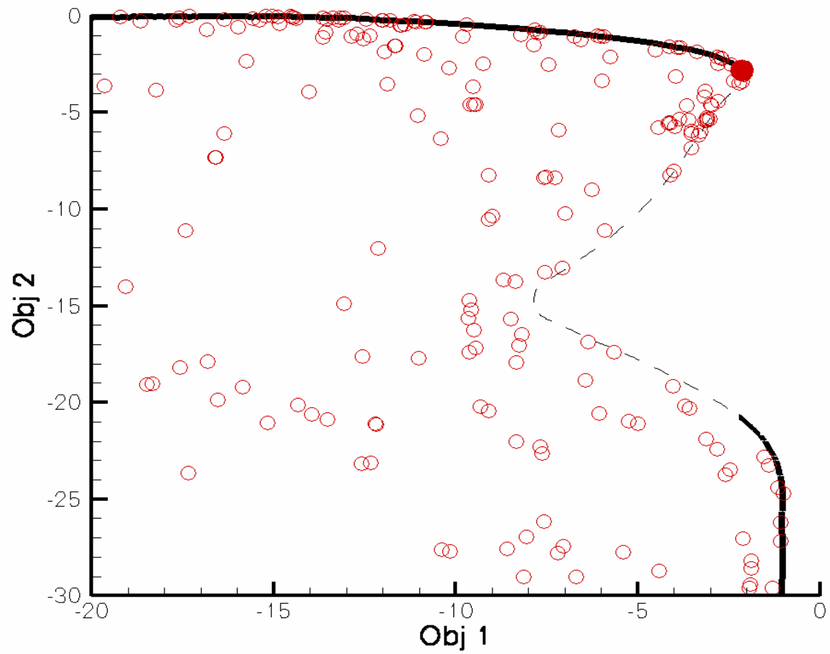
# Multi-Objective Optimization

## Academic test case: 2 objectives

**Multi-objective optimisation using Genetic Algorithm**

- **Latin Square DOE**
- **Population size of 64 individuals (i.e. 64 concurrent evaluations could be performed in parallel)**
- **6 generations**
- **383 evaluations**

**Almost the complete Pareto front is captured within a single run !**

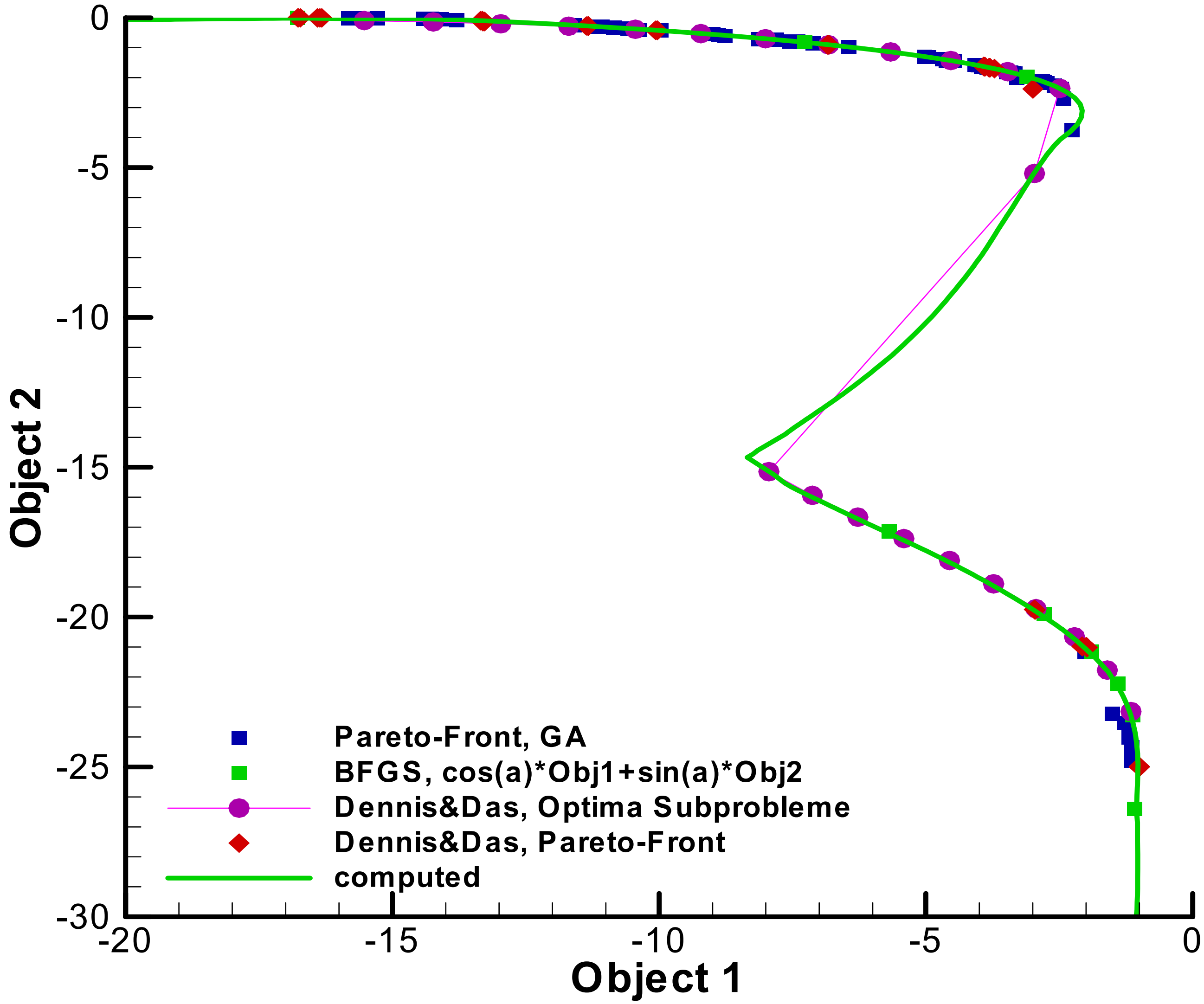


# Multi-Objective Optimization

## Academic test case

**Method of Dennis & Das**

**Pareto front is calculated through set of nonlinear constraint problems**



# Conclusion

- CFD mature tool for aerodynamic analysis of complex aircraft configurations
- aerodynamic optimization based on high fidelity CFD not yet fully exploited
  - large scale applications
  - lack of efficient and reliable optimization strategies
  - lack of suitable algorithms for geometric modeling
  - ….
- new innovative CFD algorithms and optimization strategies required
- focus on multi-objective optimization

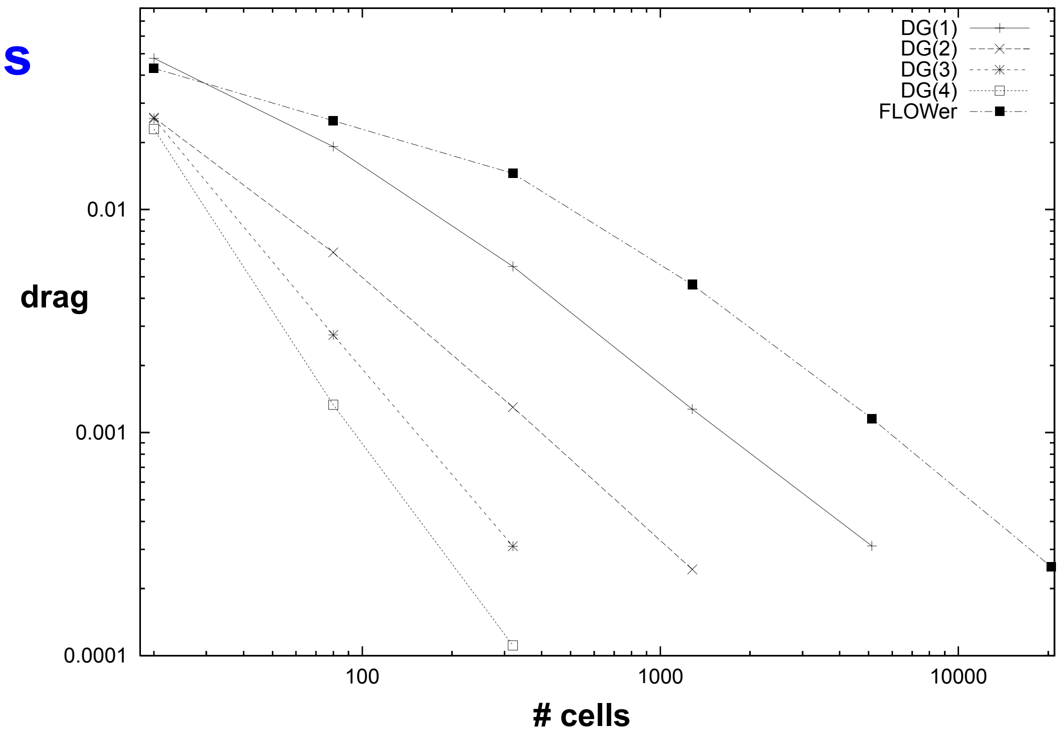
# Perspectives (1)

## Discontinuous Galerkin methods

- **higher order methods**
- **(h,p) refinement**

**Example**

- **NACA0012, subsonic**
- **inviscid computation**




grid convergence

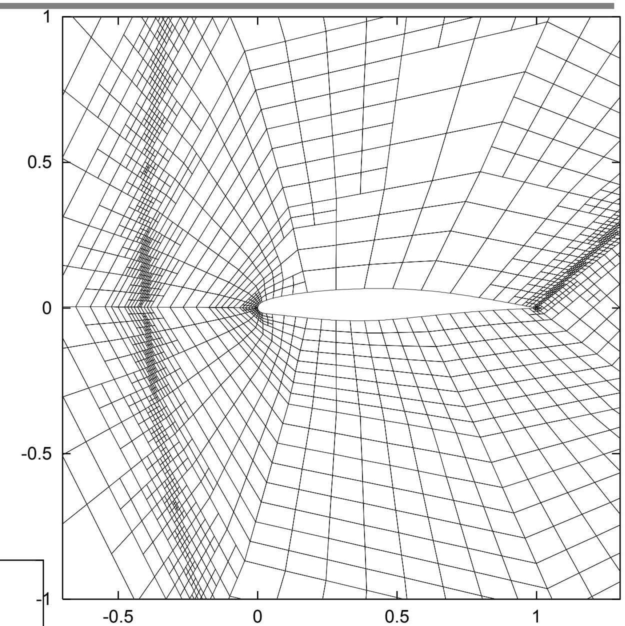
# Perspectives (2)

## Innovative grid adaptation

- **goal-oriented**
- **dual-weighted residual indicators (adjoint solution)**

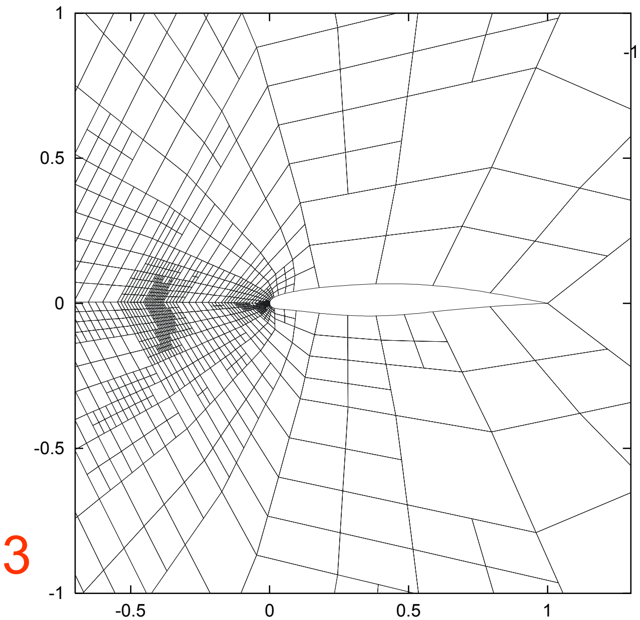
**residual indicator**

**13719 cells**
**$J(u) - J(u_h) = 0.035$**




## Example

- **BAC3-11 airfoil**
- **$M = 1.2$, $\alpha = 5^0$**
- **target:**
  **find pressure at leading edge to best accuracy**
  $J(u) = p(x_l)$
- Reference value: $J(u)=2.393$




**dual-weighted residual indicator**

**1803 cells**
**$J(u) - J(u_h) = 0.003$**