Current Status and Challenges in CFD at the DLR Institute of Aerodynamics and Flow Technology

N. Kroll, C.-C. Rossow
DLR, Institute of Aerodynamics and Flow Technology

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DLR Institute of Aerodynamics and Flow Technology

Mission

Develop and apply aerodynamic and aeroacoustic technologies:

- Drag reduction by laminar flow and active flow control concepts
- Advanced high-lift systems
- Integration of high-lift and propulsion systems in A/C design
- Development of novel aircraft configurations offering potentially higher efficiency and less community noise

Approach / Tools

- Complementary use of numerical and experimental simulation techniques
- Development and validation of numerical methods (TAU, PIANO)
- Multidisciplinary analysis and optimization in close cooperation with other DLR research institutes

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Overview

- Current Prediction Capabilities – Selected Topics
- Future - The Virtual Aircraft
- Challenges and Activities
- Conclusion

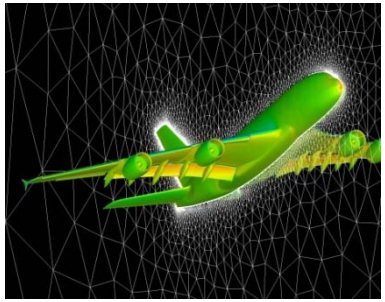
Overview

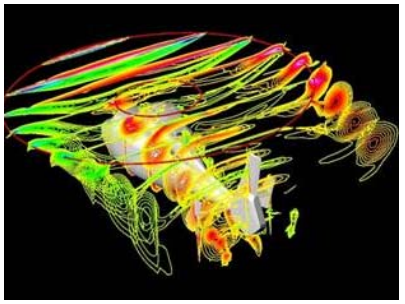
- Current Prediction Capabilities – Selected Topics
  - TAU-Code
  - High Lift
  - Optimization

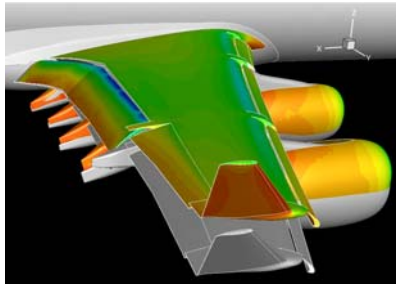
CFD Solver TAU

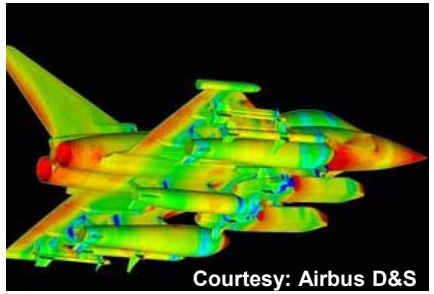
Reynolds-averaged Navier Stokes Code

- Unstructured, overlapping grids, adaptation
- Finite Volume method 2nd order
- Advanced turbulence models, e.g. RSM
- Hybrid RANS/LES
- Linear, adjoint solver
- Interfaces for multidisciplinary coupling, e.g. FlowSimulator
- Continuous verification & validation efforts

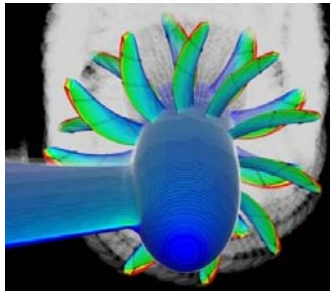


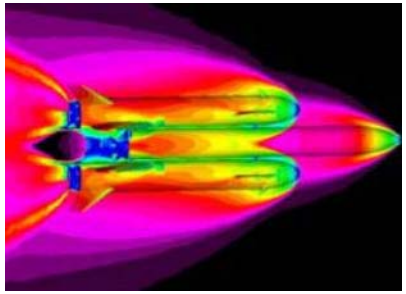






- Applied in European aircraft industry, e.g. Airbus, Airbus D&S, Airbus Helicopter, RRD, …)
- Research platform for European universities and research organizations





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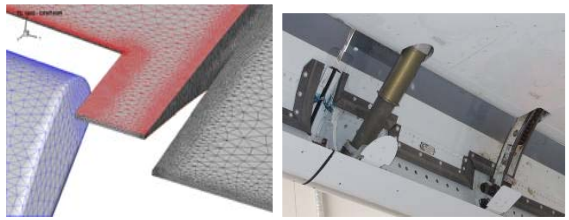
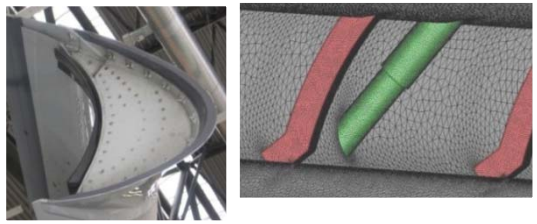
Current Prediction Capabilities

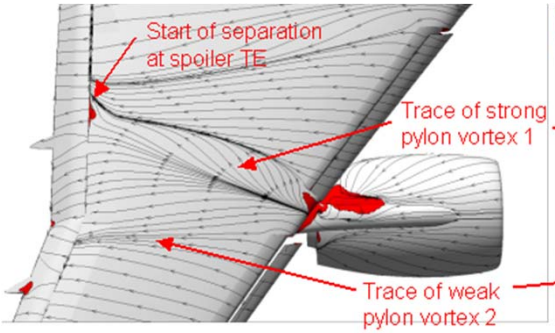
High-Lift Aerodynamics

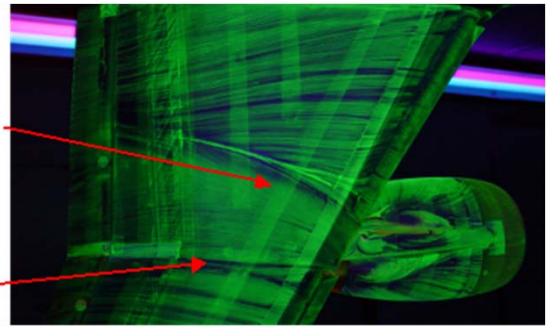




Pilot applications

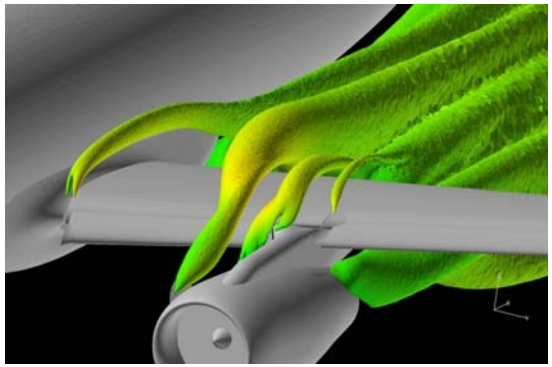
- Full aircraft configuration
- Full geometrical complexity
- Validation
  (wind tunnel & flight tests)
- Fluid/structure coupling
- Stall maneuver

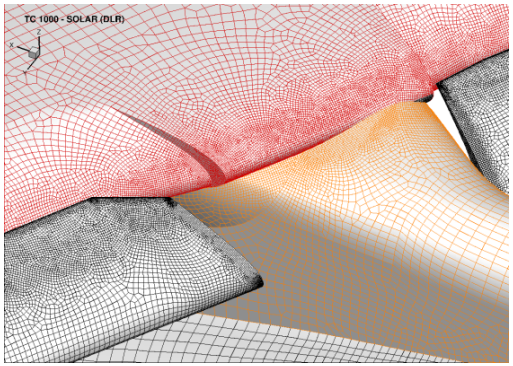




CFD sensitivity studies

- Influence of physical modeling
  (SA, RSM, transition)
- Grid sensitivities





Flow separation control

Design of high-lift devices

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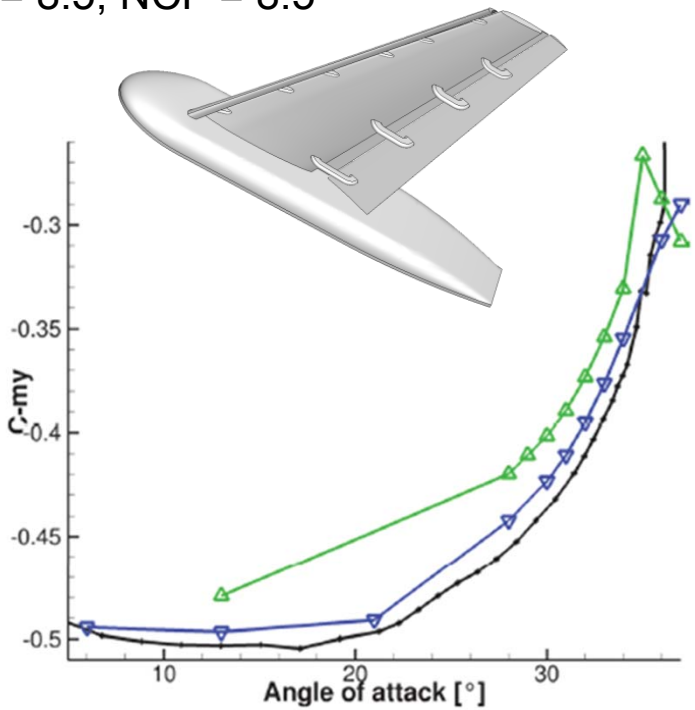
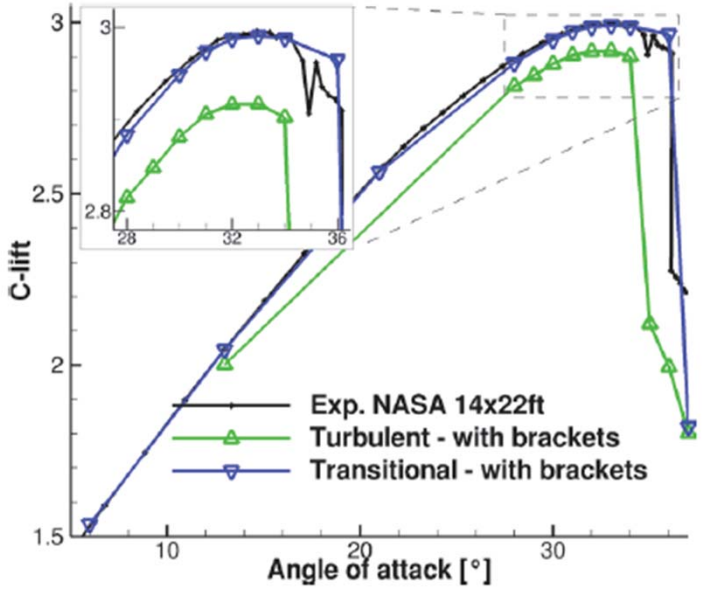
Current Prediction Capabilities

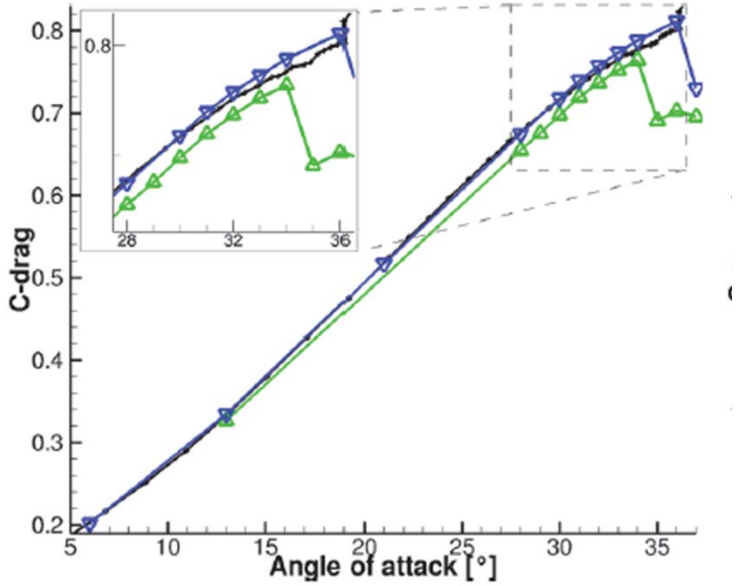
High-Lift Aerodynamics

NASA TRAP Wing

- M = 0.2, Re = 4.3×10^6, a = 6 - 36°
- SA turbulence model
- Transition prediction, e^N-method
  NTS = 8.5, NCF = 8.5







N. Krimmelbein, S. Crippa, 2012

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Current Prediction Capabilities

High-Lift Aerodynamics

Flow Separation Control for High-Lift Systems

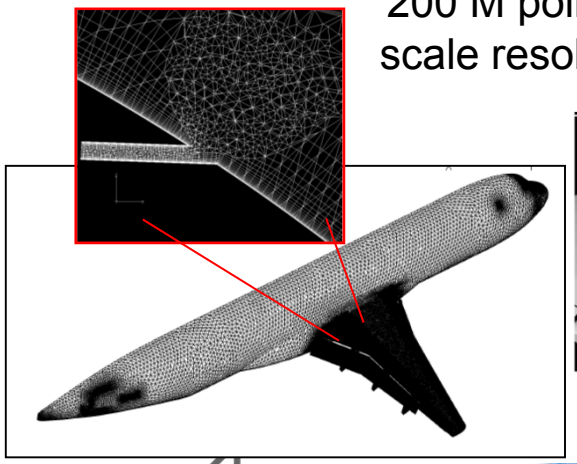
- Enhancement of lift coefficient with active flow control (AFC) (e.g. periodic excitation)

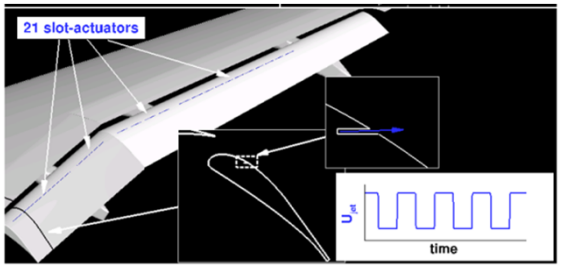
Requirements on CFD

- Resolution of local flow features essential for assessing the capabilities of AFC
- Prediction of influence of AFC-parameter variation and their global effects on A/C

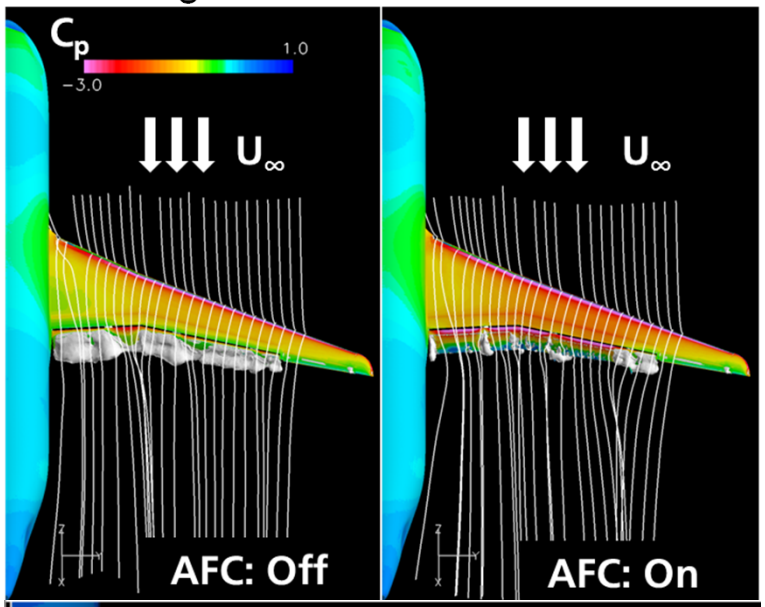
Application

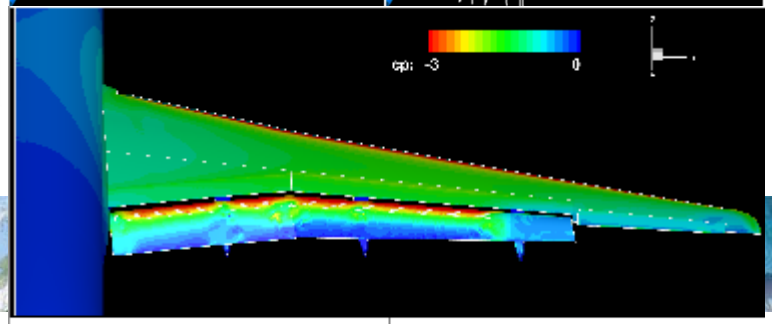
- 3D high-lift wing/body-configuration
  with 21 actuators (at high actuation velocities)
- URANS simulation on grid with 30 million points
- **Future**: Full range of actuator velocities:
  200 M points (URANS)
  scale resolving simulation





V. Ciobaca, J. Wild, 2013





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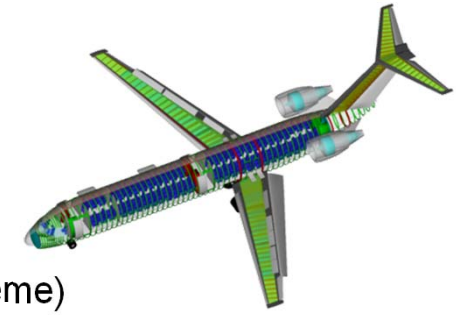
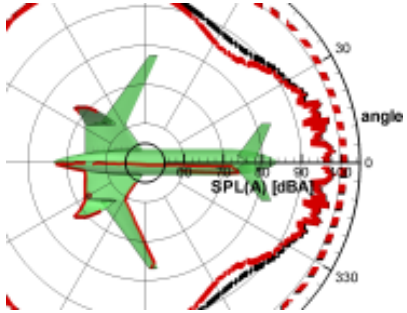
Current Optimization Capabilities

Aerodynamic/Multidisciplinary Design & Optimization

Preliminary Aircraft Design

- Numerical system for overall aircraft design on pre-design level (TIVA/VAMP)
- Central aircraft data model CPACS (Common Parametric Aircraft Configuration Scheme)





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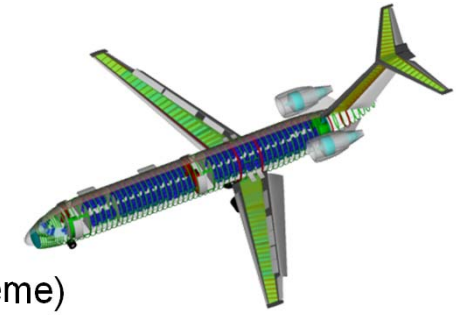
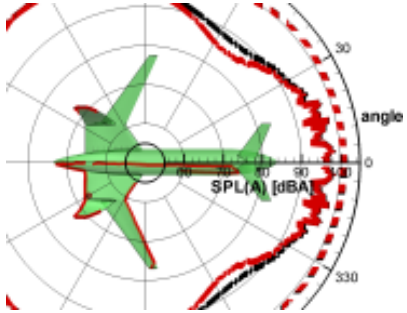
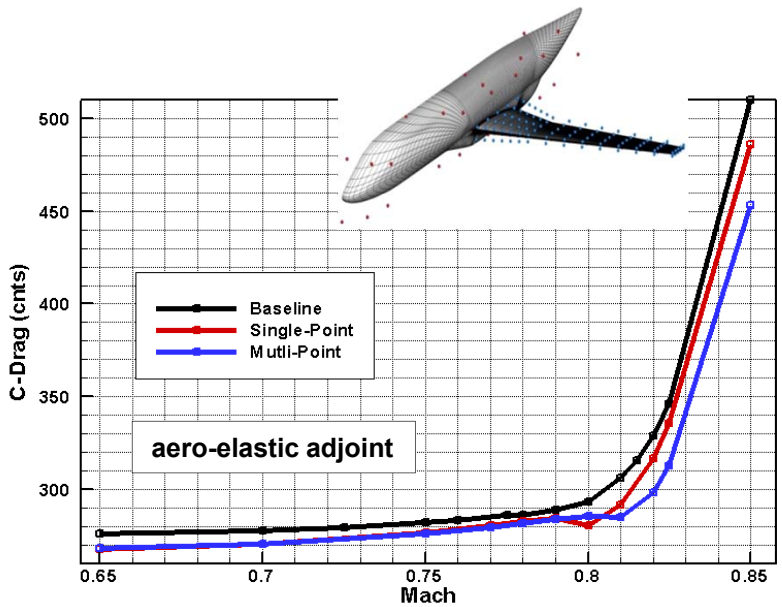




RANS-based Aerodynamic Optimization

- Gradient-free, adjoint-based, surrogate-based optimization strategies



M. Abu-Zurayk, 2013

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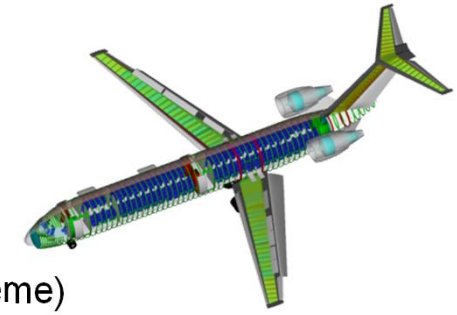

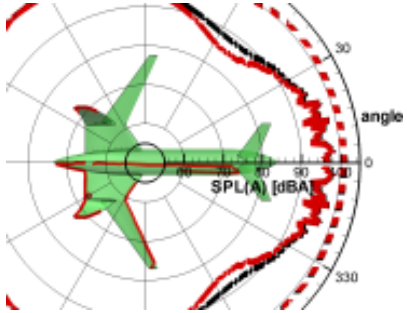

RANS-based Aerodynamic Optimization

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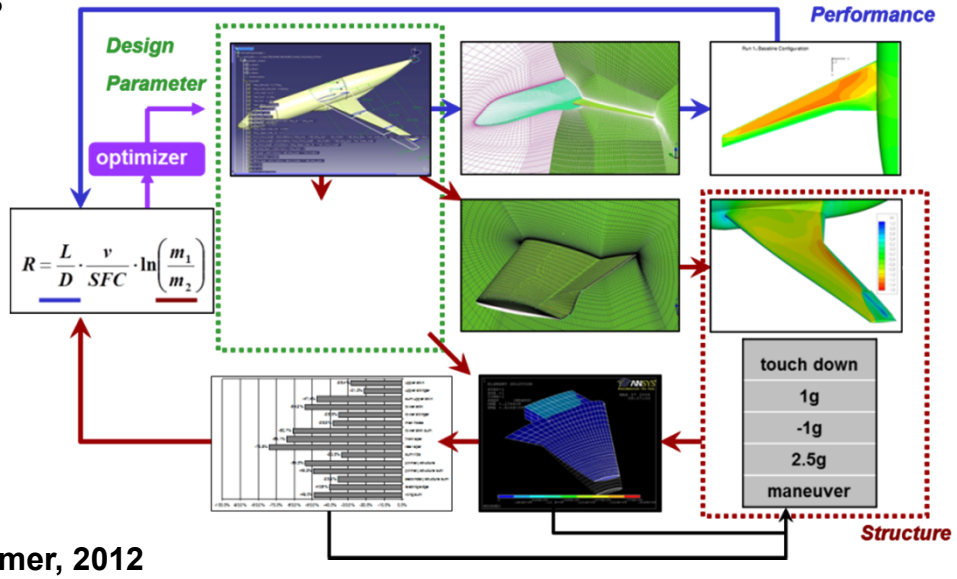
RANS-based MDO

- High-fidelity methods (aerodynamics & structure)
- Low number of parameter and load cases
- High manual setup time & computational costs



A. Ronzheimer, 2012

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Overview

- Current Prediction Capabilities – Selected Topics
- Future - The Virtual Aircraft

Towards the Virtual Aircraft

Motivation & Strategic Objectives

Need for DLR Virtual Aircraft Software Platform

- Support industrial and research activities in Germany
- Full knowledge of all Flight Physics aircraft properties relevant for design & certification
- Trade-off between disciplines for technology evaluation
- Identify future options for HPC based aircraft design
- Enhance and maintain aircraft design capabilities in DLR

Major and collaborative effort of DLR research institutes in aeronautics

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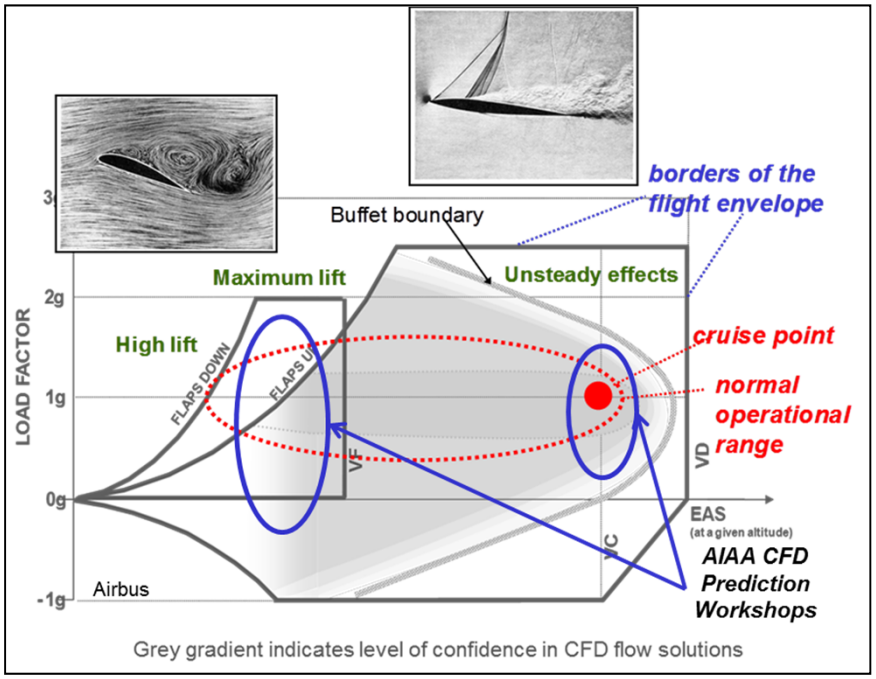
Towards the Virtual Aircraft
Challenges & Capability Needs

Simulation of Flight Envelope

- Separated flows
- Transition laminar/turbulent
- Unsteady effects
- Multidisciplinary simulations



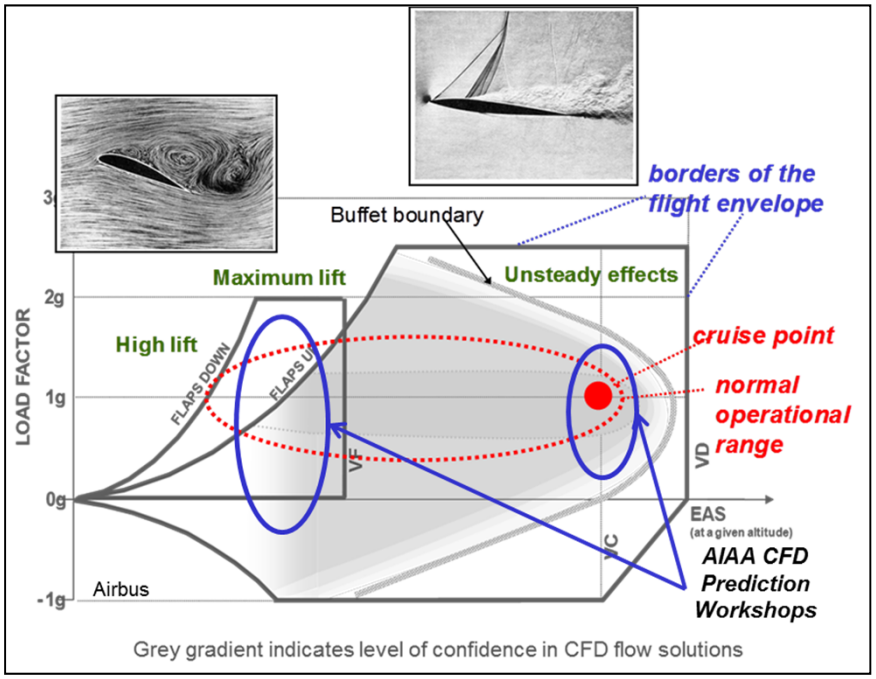
Towards the Virtual Aircraft
Challenges & Capability Needs

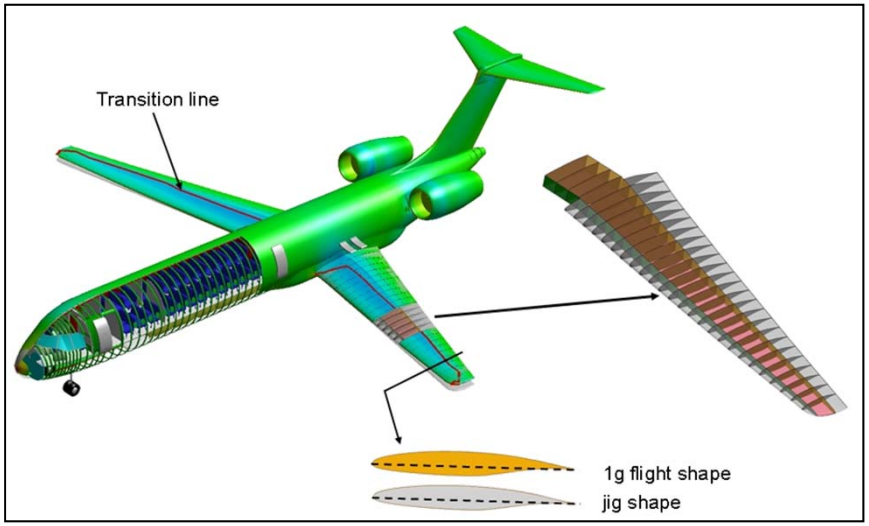
Simulation of Flight Envelope

- Separated flows
- Transition laminar/turbulent
- Unsteady effects
- Multidisciplinary simulations

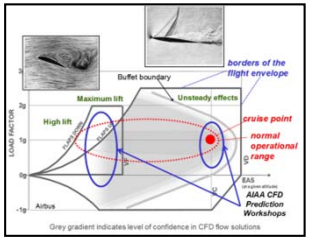
Aircraft Optimization

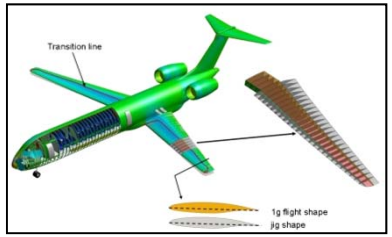
- Link of preliminary and “detailed” simulation / optimization capabilities
- High-fidelity for relevant disciplines
- Large number of design parameters
- Identification of realistic & relevant load scenarios for structural lay-outs (metal, CFRP)
- Representation of relevant system properties (mass, volume, performance, energy)





Towards the Virtual Aircraft
Challenges & Capability Needs





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Physics

- Modeling
- Validation

Numerics

- Robustness
- Accuracy
- Adaptivity
- Maintainability

HPC

- Applicability
- Efficiency

MD

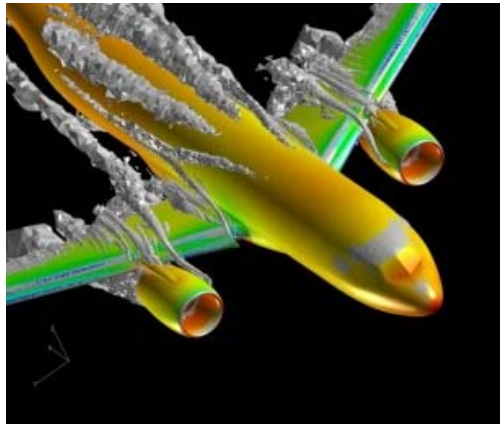
- Integration
- Optimization

Overview

- Current Prediction Capabilities – Selected Topics
- Future - The Virtual Aircraft
- Challenges and Activities
  - Physical Modeling
  - CFD-Solver
  - HPC-Capability
  - Multi-Disciplinary Simulation

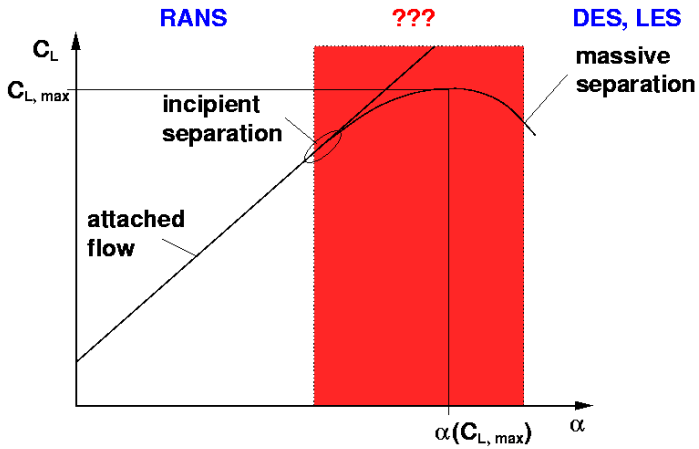
Physical Modeling

Numerical Analysis of Full Flight Envelope



Four development lines:

1. Reynolds stress models (RSM)
   - As standard RANS approach for any kind of configuration (including highly complex industrial configurations)
2. Scale resolving simulations (SRS)
   - Targeted application for specific components of aircraft or military configurations
3. Turbulence modelling improvements
   - Targeted experimental (physical & numerical) investigations for specific flow phenomena
4. Transition prediction and modeling
   - Necessary condition for accurate results of turbulence models within the full flight envelope



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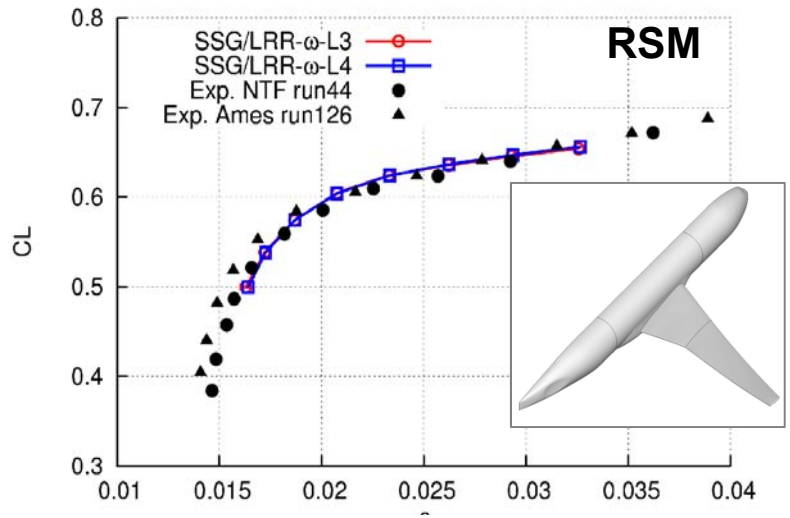
Physical Modeling

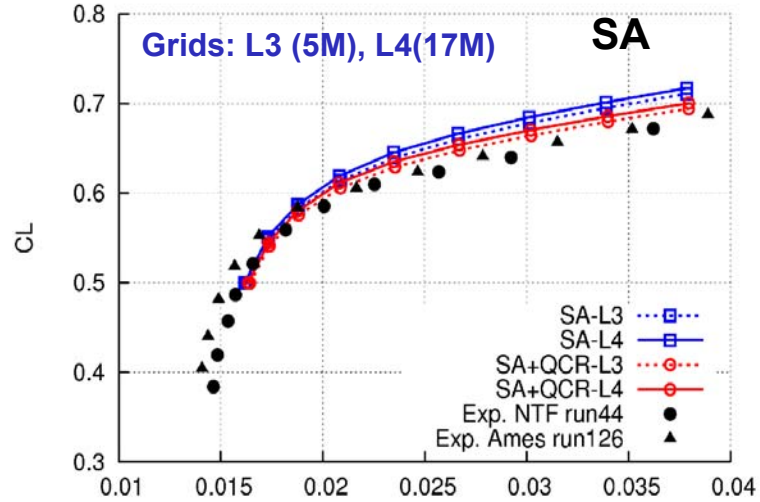
Differential Reynolds Stress Models

DRSM in TAU

- SSG/LRR-ω model (standard model)
  - Based on Menter's BSL ω-equation
  - Exact transformation to g=1/sqrt(ω)
- e^h-JHh-V2 model
  (Jakirlic-Hanjalic model, extension by U. Braunschweig)

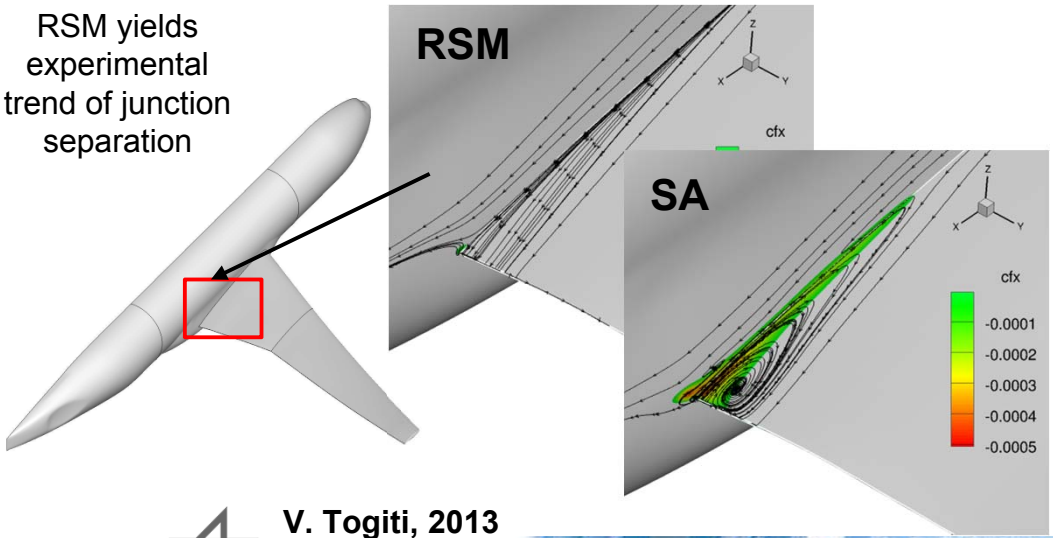
Wing-body configuration (DPW-5)
Re=5x10^6, M=0.85





Idealized drag coefficient

RSM yields experimental trend of junction separation



V. Togiti, 2013

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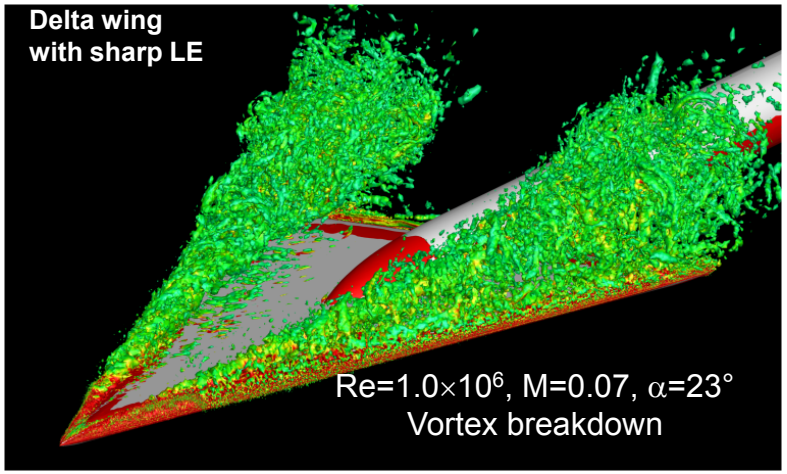
Physical Modeling

Scale Resolving Simulations

Basic approach in TAU

- Hybrid RANS/LES (DES, DDES, IDDES)
  - Coupled with SA or k-ω type RANS models
  - Standard numerical algorithms
  - **Target:** massive separation outside boundary layer

Iso-Q contours coloured with vorticity

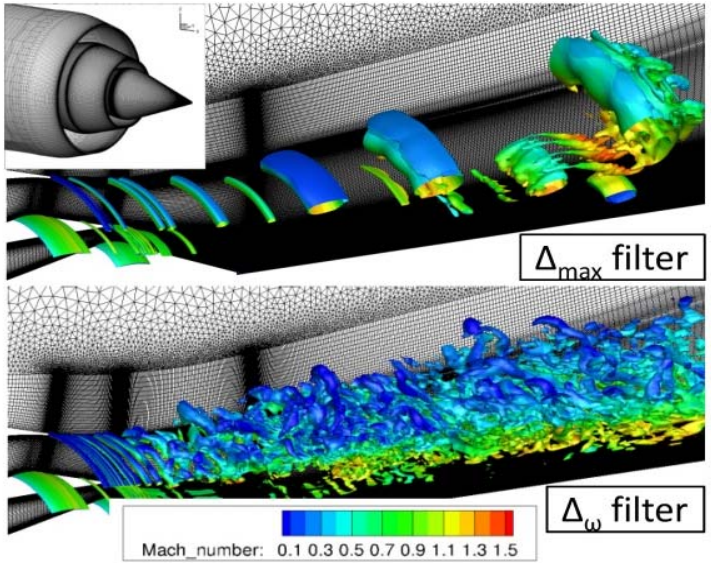


Extended approach

Target: small incipient separation

- Low dissipation & low dispersion scheme
- Algebraic RANS/LES sensor (ADDES) for boundary layer and separation detection
- Synthetic turbulence for forcing of fluctuation
- Improvement of LES scale
- SRS approaches based on RSM

Transonic nozzle jet flow



A. Probst, 2014

Δ_{ω}: vorticity orientation included

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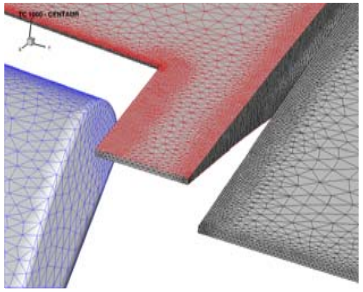
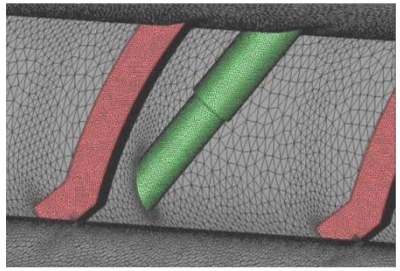
CFD Solver

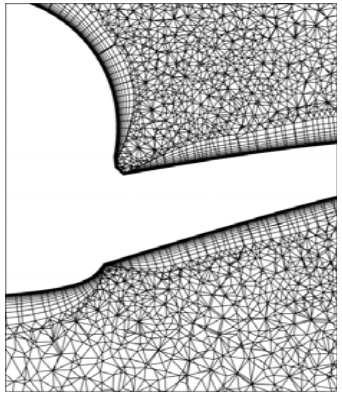
Goal: Secure Quality of CFD for Virtual Aircraft Requirements

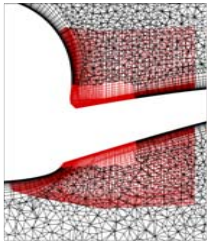
Applicability and accuracy

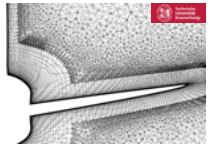
- Fully automatic grid generation for complex configurations requires
  - Unstructured grids

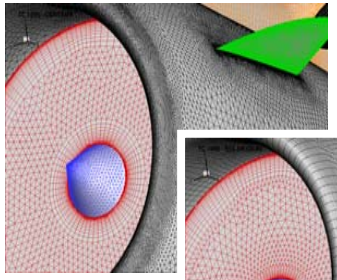


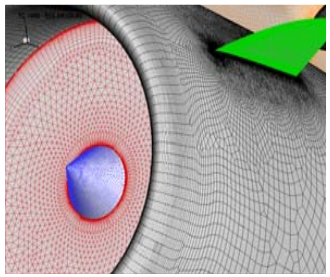












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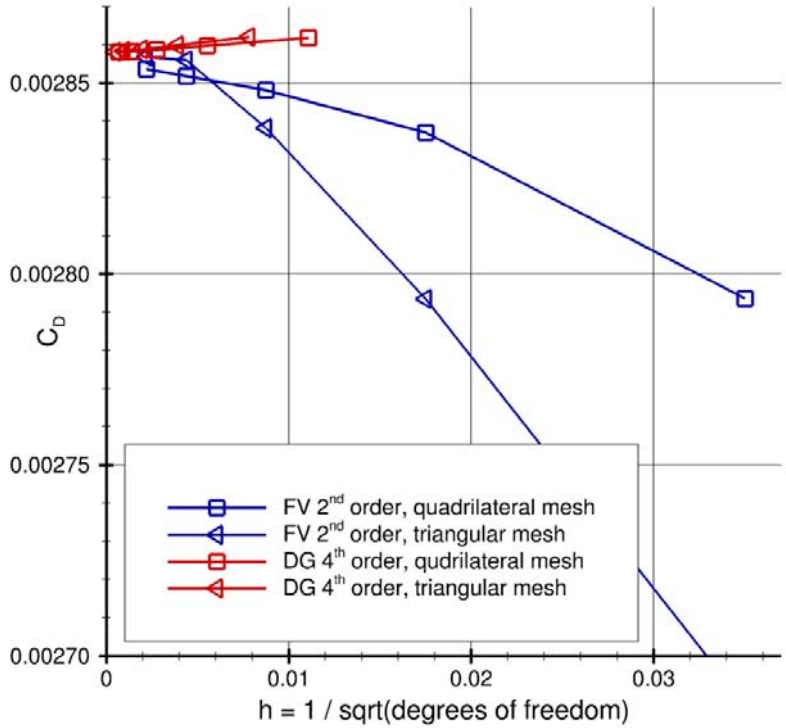
CFD Solver

Goal: Secure Quality of CFD for Virtual Aircraft Requirements

Applicability and accuracy

- Fully automatic grid generation for complex configurations requires
  - Unstructured grids
  - Accurate spatial discretization scheme for given element type



turbulent flat plate, M=0.15, Re=5M

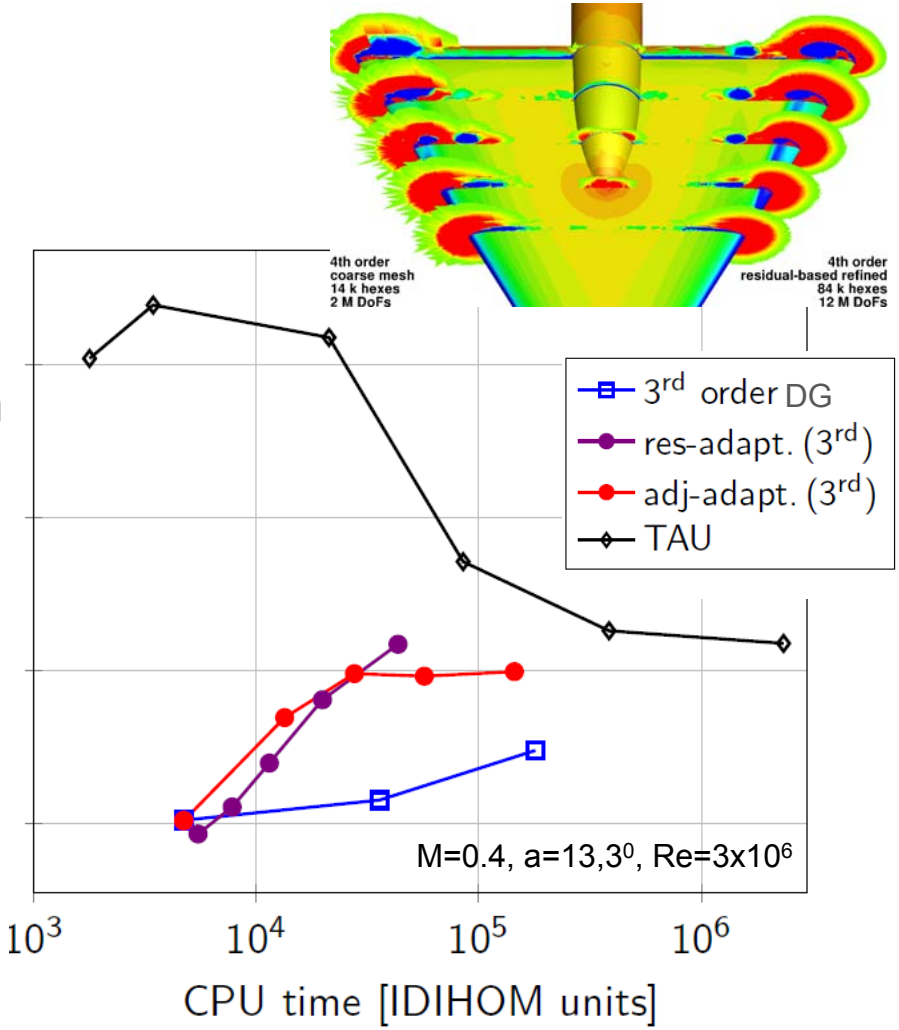
DLR

CFD Solver

Goal: Secure Quality of CFD for Virtual Aircraft Requirements

Applicability and accuracy

- Fully automatic grid generation for complex configurations requires
  - Unstructured grids
  - Accurate spatial discretization scheme for given element type
  - Robust and reliable local grid adaptation
  - High-order discretization
    - Flow interactions
    - Scale-resolving simulations



R. Hartmann, 2013

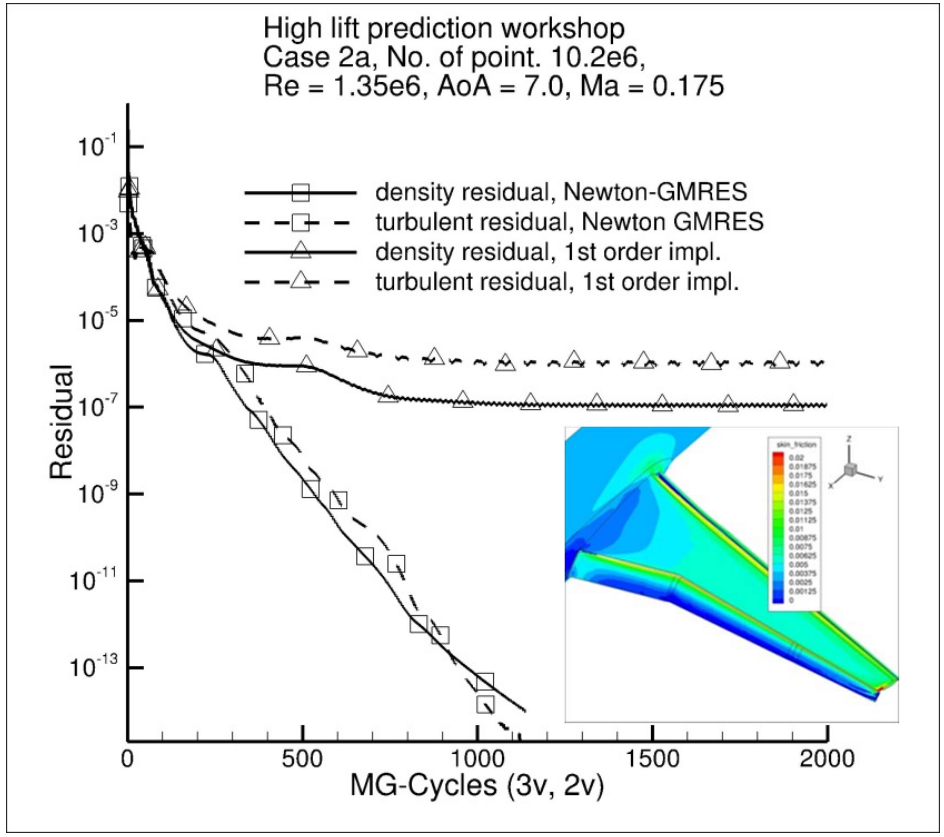
CFD Solver

Goal: Secure Quality of CFD for Virtual Aircraft Requirements

Robustness and efficiency

- Agglomerated multigrid for complex applications
- Implicit algorithms
  - Consistent derivatives of all solver components
  - Integration of advanced turbulence models (RSM)

SA turbulence model



S. Langer, 2013

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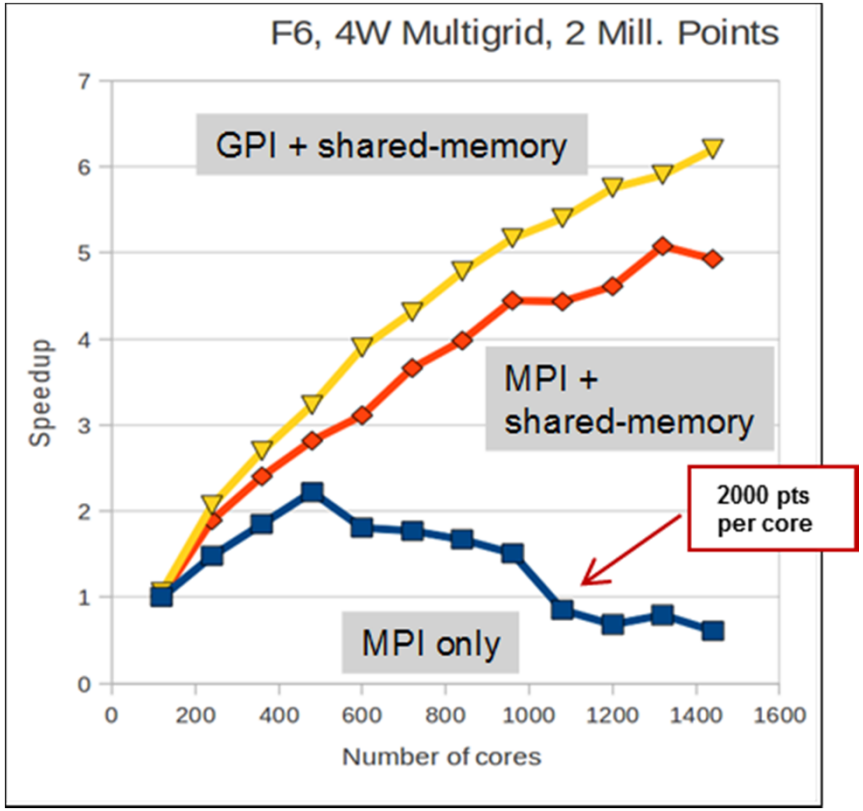
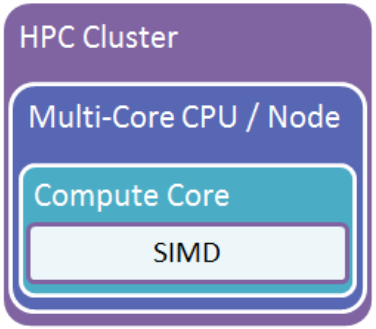
CFD Solver

Goal: Secure Quality of CFD for Virtual Aircraft Requirements

Robustness and efficiency

- Agglomerated multigrid for complex applications
- Implicit algorithms
  - Consistent derivatives of all solver components
  - Integration of advanced turbulence models (RSM)
- Parallel efficiency





J. Jägersküpper, 2012

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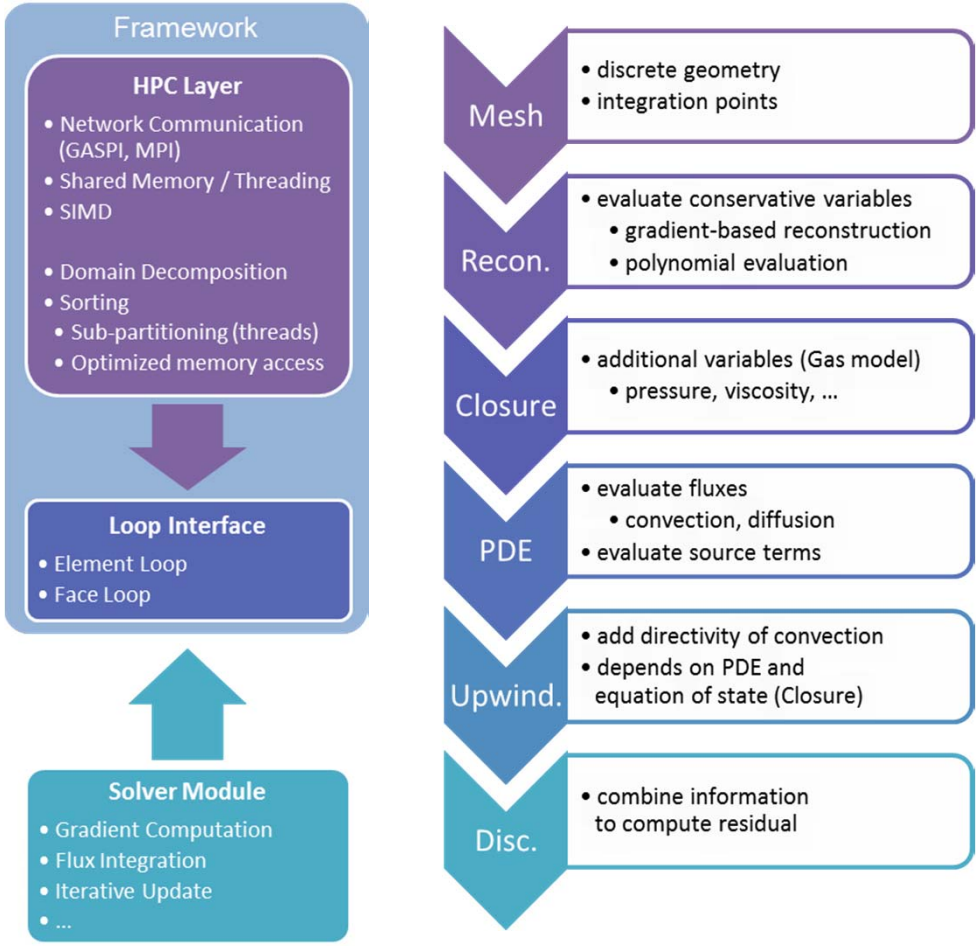
DLR Next Generation Solver

Goal: Secure Quality of CFD for Virtual Aircraft Requirements

- Full exploitation of future HPC systems
- Consolidation of current DLR CFD solvers
- Flexible building blocks
- Basis for innovative concepts & algorithms e.g. high-order-finite element discretization, adaptivity, …
- Seamless integration into multidisciplinary simulation environment
- State-of-the-art software engineering methods (C++11, templates)



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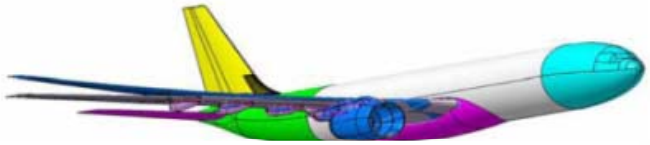
Multidisciplinary Optimization

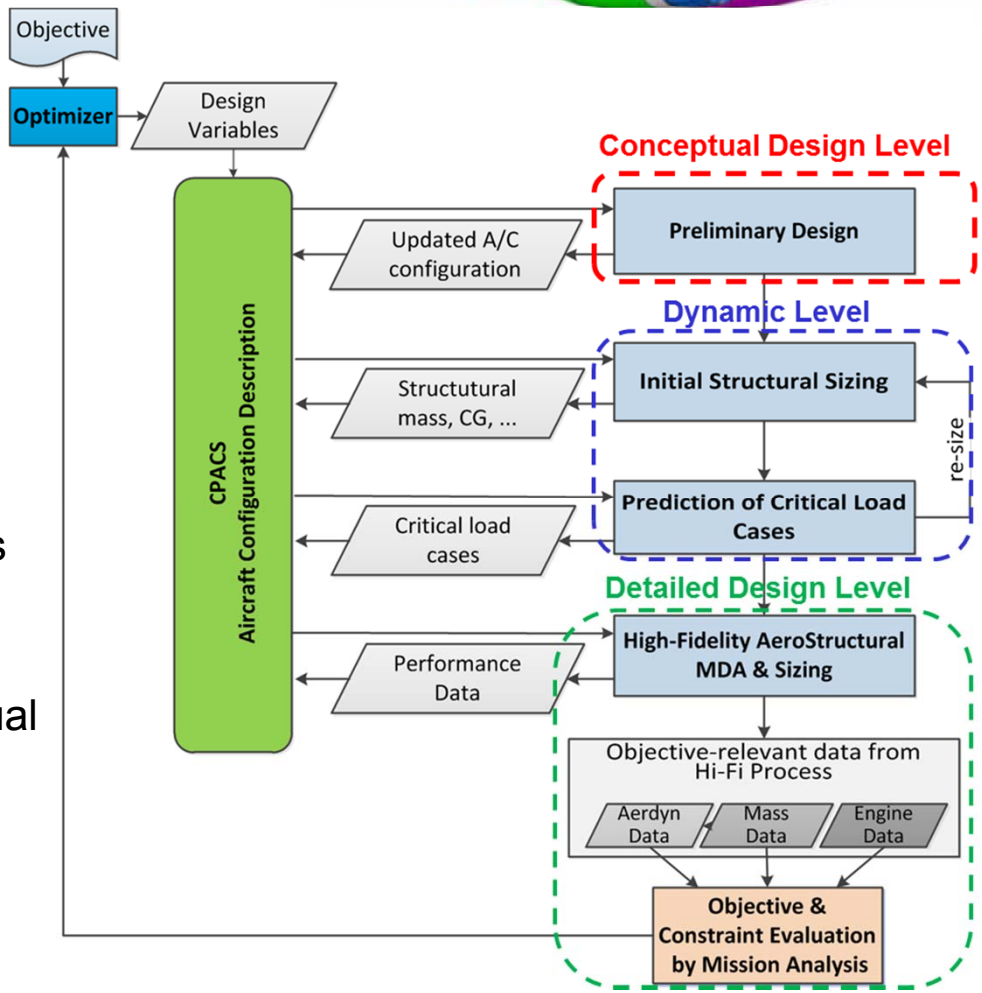


Goal

- MDO of complete A/C based on high-fidelity methods

Approach

- Aircraft description CPACS
- Multi-level procedure
  - Low-fidelity methods for overall aircraft design
  - Fast methods for identification/ computation of critical load cases
  - High-fidelity methods for aerodynamics and structure
  - Consistent stream from conceptual to detailed design
- Parallel software platform for hi-fi
- Interactive workflow management



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Multidisciplinary Optimization

Loads Prediction

Challenges

- Huge number of load cases
- Entire flight envelope

Status

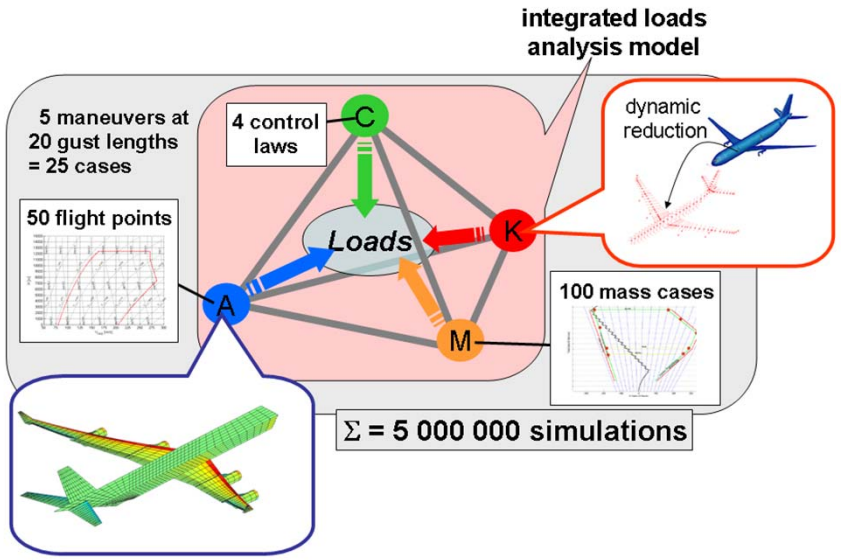
- Low-fidelity methods

Objective

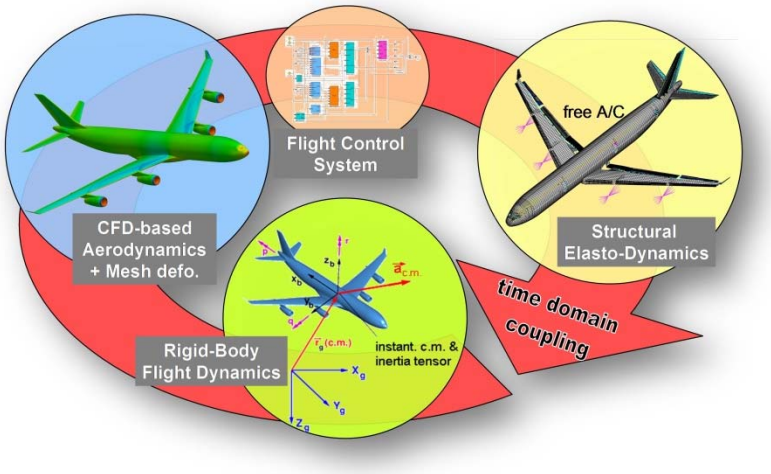
- Improve maneuver and gust loads analysis based on high-fidelity information

Approach

- High-fidelity multidisciplinary maneuver simulation (selected cases)
- Reduced order models
  - Based on high-fidelity data
  - Correction of low-fidelity methods



Courtesy of DLR Institute of System Dynamics and Control, T. Kier



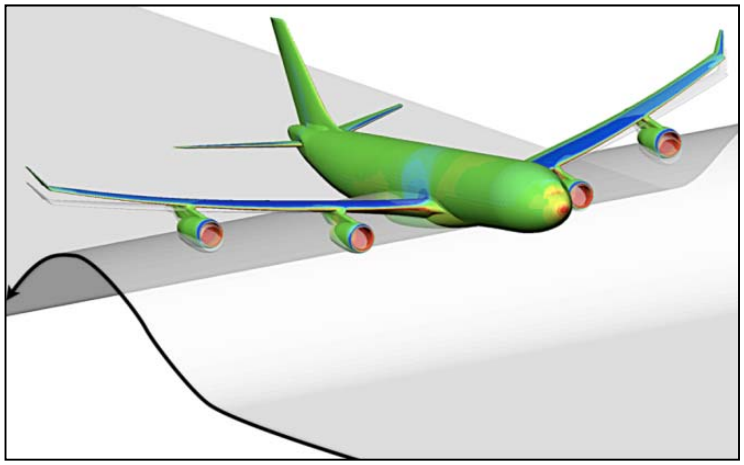
Multidisciplinary Optimization

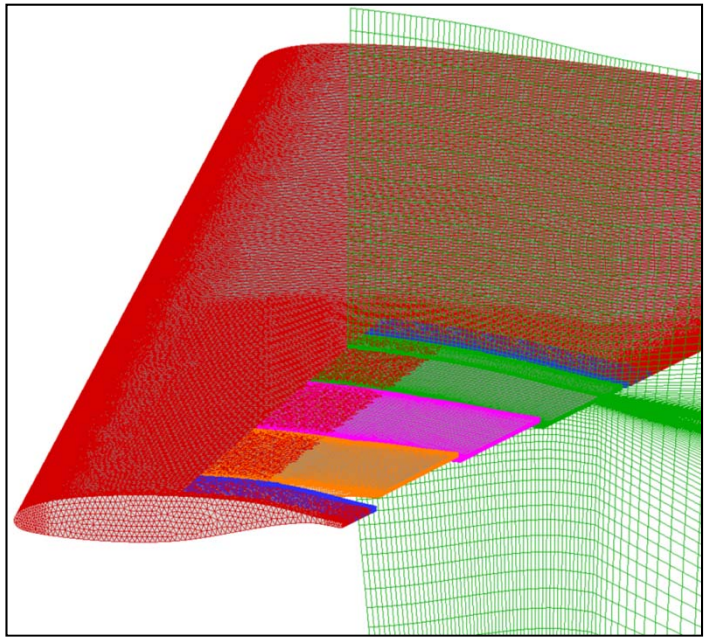
Loads Prediction

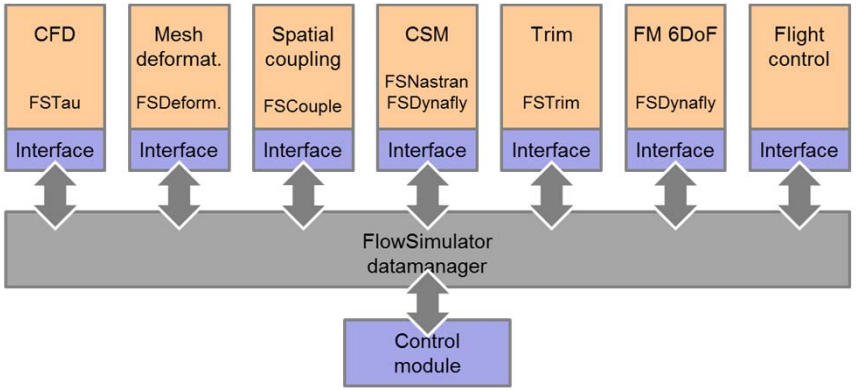
Analysis of maneuver loads based on high-fidelity methods

Activities

- Coupling of disciplines (CFD, CSM, FM)
- Integration of flight control
- Modelling / meshing of control surfaces
- Parallel simulation backbone
- Comparison / quantification of different levels of disciplinary and multidisciplinary fidelity







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Multidisciplinary Optimization

Loads Prediction

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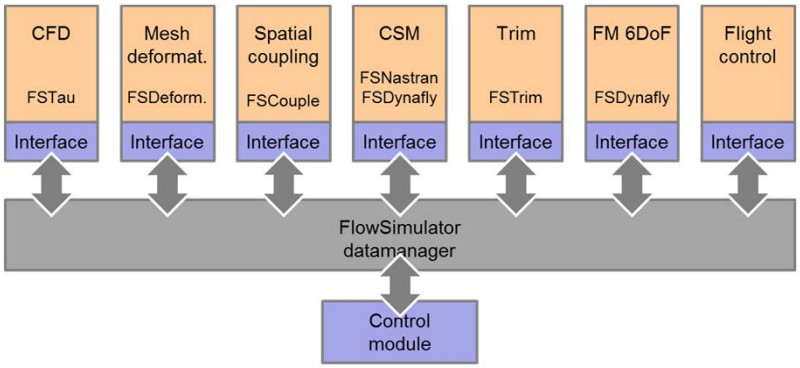
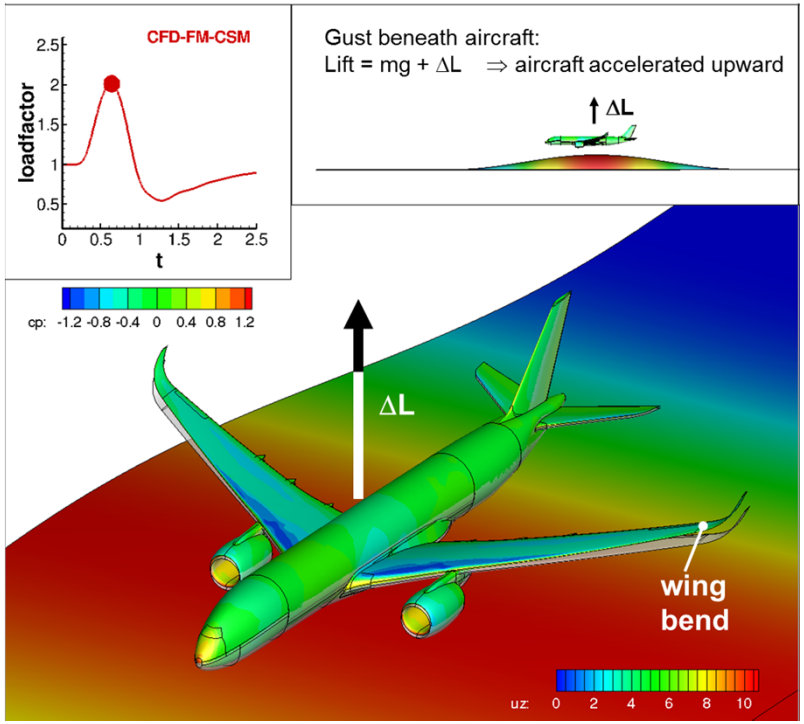
Example

- Gust loads
  - Vertical gust
  - M=0.836, Re=86x10^6, gust: 12m/s





L. Reimer, M. Ritter, 2014,

Cooperation with Institute of Aeroelasticity

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Multidisciplinary Optimization

Loads Prediction

Analysis of maneuver loads based on high-fidelity methods

Activities

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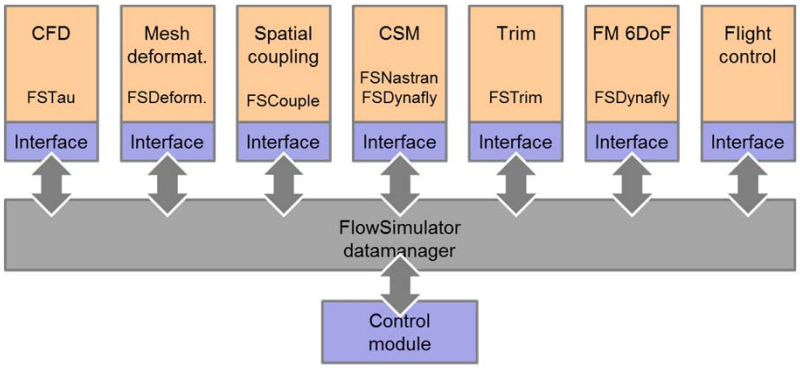
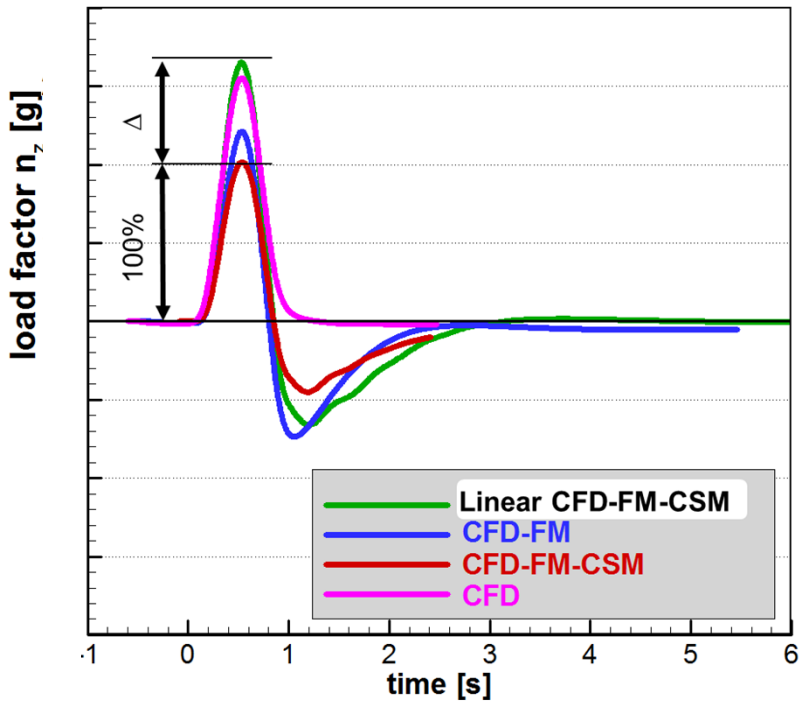




L. Reimer, M. Ritter, 2014

Cooperation with Institute of Aeroelasticity

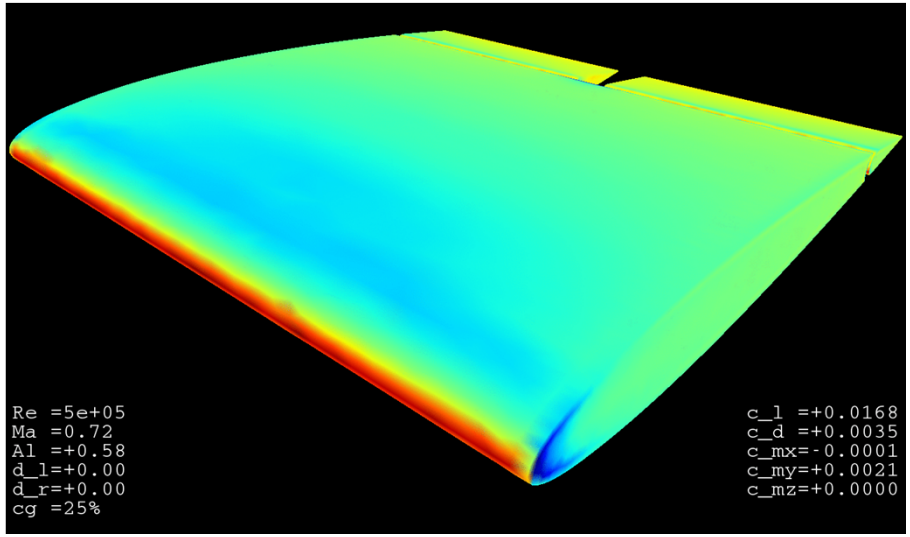
Multidisciplinary Optimization

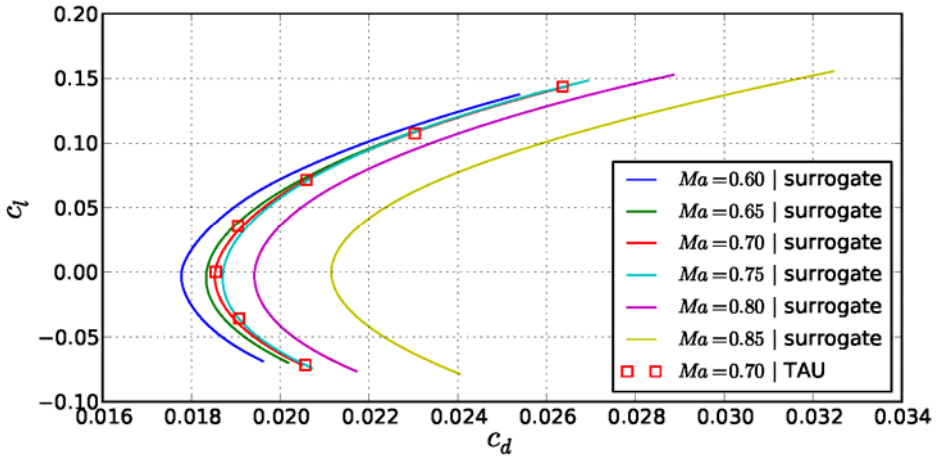
Loads Prediction

POD-ROM based on 5 parameters
Real time prediction of distributed loads & forces

Hi-Fi CFD Based ROM

- Development of efficient methods to construct parametric models for static & dynamic aero loads prediction based on high-fidelity methods
- Correction methods for aeroelastic applications





POD-ROM based on
1.960 **CFD solutions**

Re	0.5e6, 1.0e6, 3.0e6
Ma	0.6, 0.7, 0.8, 0.85
α	-2.0°, 0.0°, 2.0°, 4.0°
δ_l	-8°,-5°,-2°,0°,2°,5°,8°
δ_r	-8°,-5°,-2°,0°,2°,5°,8°

Trimmed polar + loads (surface distribution)
M=0,7, Re=1.0×10^6
250s for 700 trimmed polar points

N. Karcher, 2014

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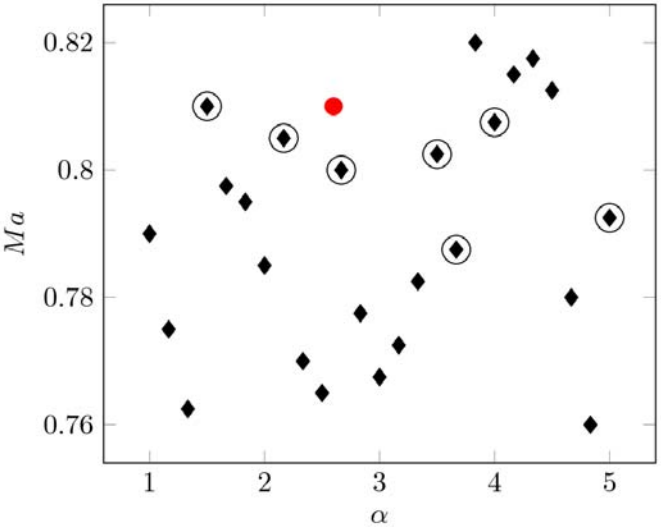
Multidisciplinary Optimization

Loads Prediction

Grid: 237,373 points, Euler computations

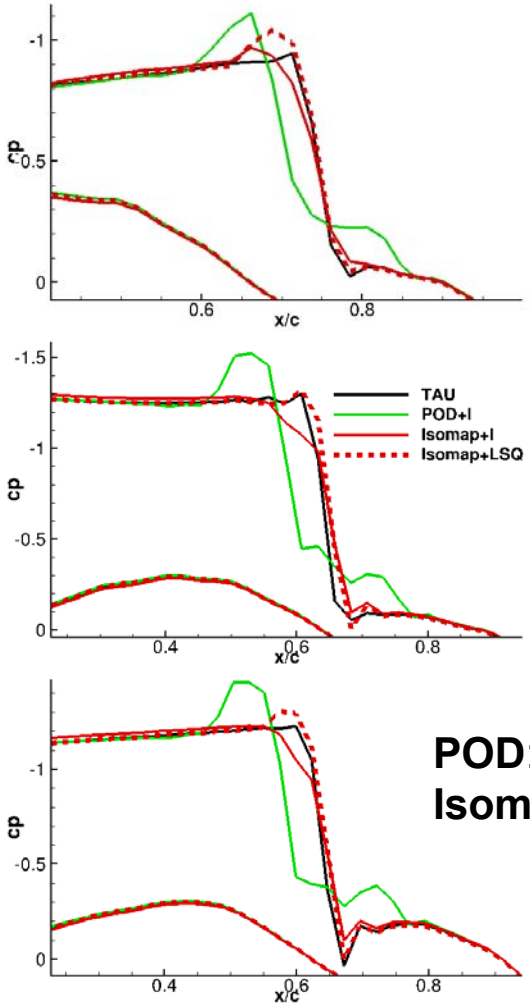
Hi-Fi CFD based ROM: Isomap

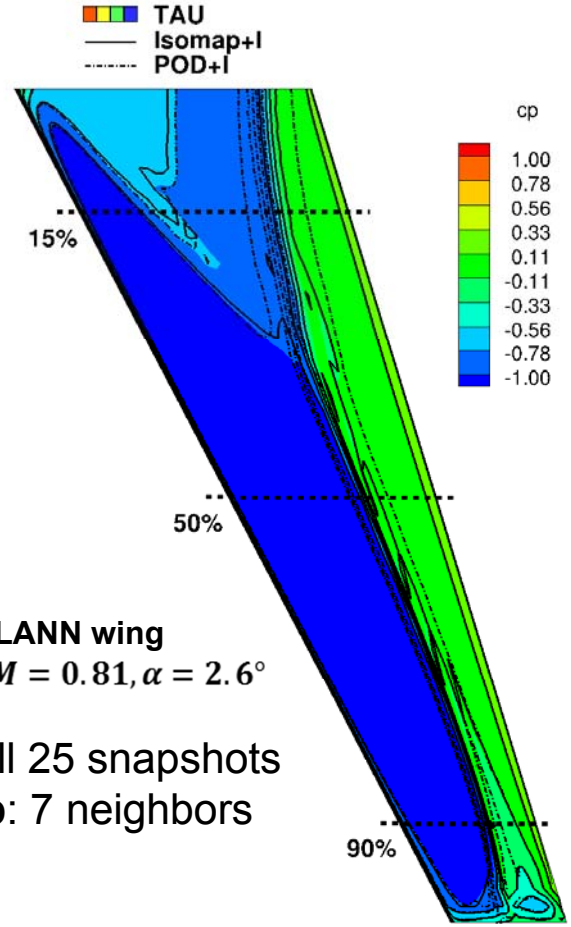
- Manifold learning method
- Reduction of high-dim data while preserving geodesic pairwise distances
- Coupled with interpolation method for ROM construction



⊙ Nearest neighbors on solution manifold

● Prediction point (M=0.81, α=2.6°)





LANN wing

$M = 0.81, \alpha = 2.6°$

POD: all 25 snapshots

Isomap: 7 neighbors

T. Franz, 2014

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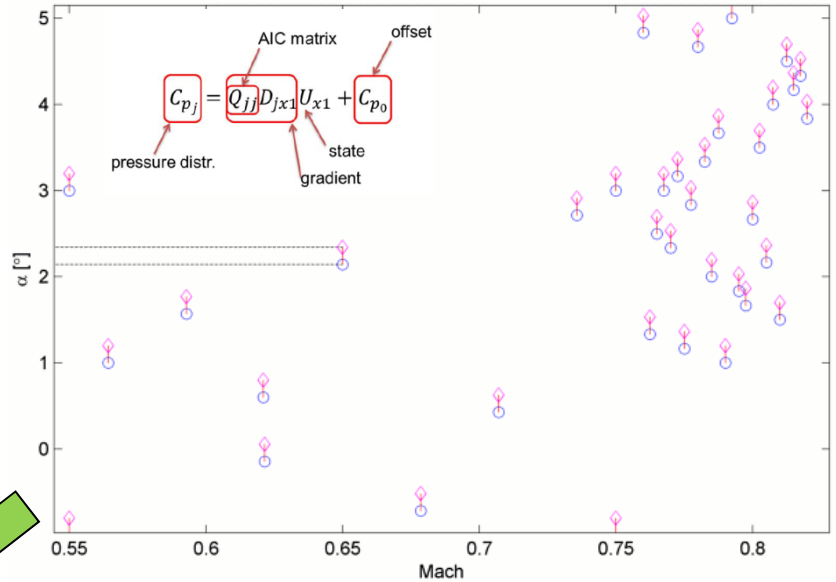
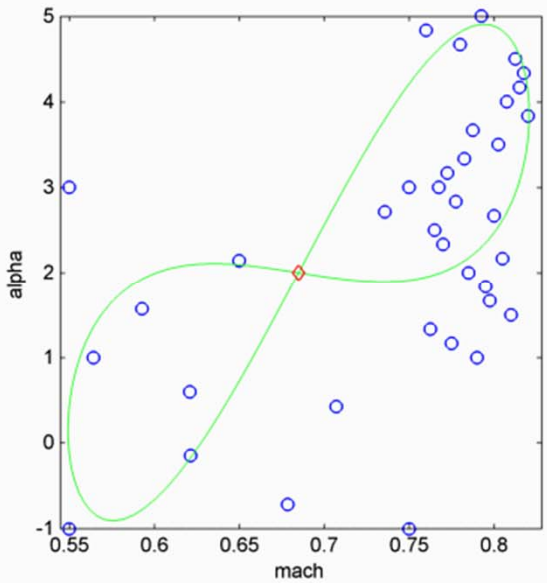
Multidisciplinary Optimization

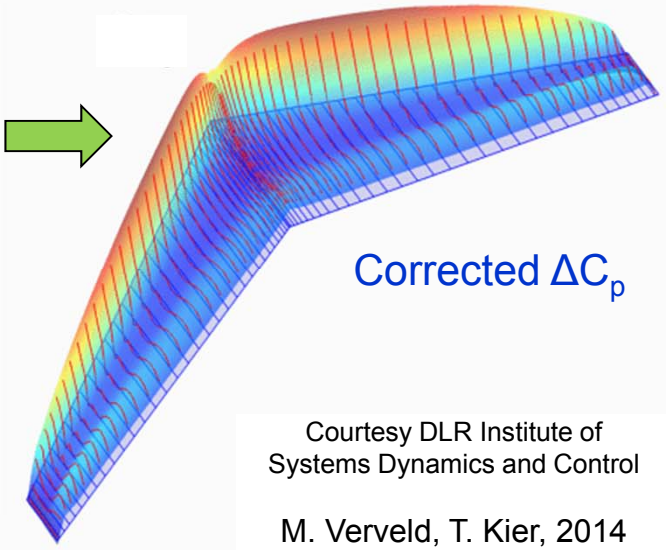
Loads Prediction

Hi-Fi corrections of low-fi methods

- Parametric POD-based ROM for steady surface C_p-distribution based on CFD, used to compute $dC_p/d\alpha$
- $dC_p/d\alpha$ and Cp used to correct unsteady DLM *(Doublet Lattice Method)*, mapping between CFD and DLM grid
- POD for AIC
- Extension to maneuvers







Courtesy DLR Institute of Systems Dynamics and Control

M. Verveld, T. Kier, 2014

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Conclusion

CFD-Challenges:

- Reliability: Improved Physical Modeling
- Applicability: Robustness with adaptable Accuracy
- Flexibility: Effective Adaptation to HPC Architectures
- Modularity: Integration of driving Disciplines

Generation of high quality grids for complex configurations still open issue

Technical Approach

- Dedicated calibration and validation experiments
- Next generation CFD solver
- Multi-level multidisciplinary simulation and optimization platform

Operational Approach

- DLR Project DIGITAL-X; DLR Guiding Concept “Virtual Product”
- LuFo Project HINVA, DLR Project LN-ATRA
- DLR research combined with partner activities (e.g. universities)

Acknowledgement

The authors would like to thank the DLR colleagues for providing the results shown here