NIA CFD Research , Hampton Virginia, August 6-8, 2012

Digital-X: DLR's Way Towards the Virtual Aircraft

Norbert Kroll, Cord Rossow

German Aerospace Center (DLR)
Institute of Aerodynamics and Flow Technology

DLR (German Aerospace Center)

Fields of Research

Aeronautics | Space | Energy | Transport

≈ 15% (activities, personnel, …)

≈ 85% (activities, personnel, budget, funding)

Defence&Security

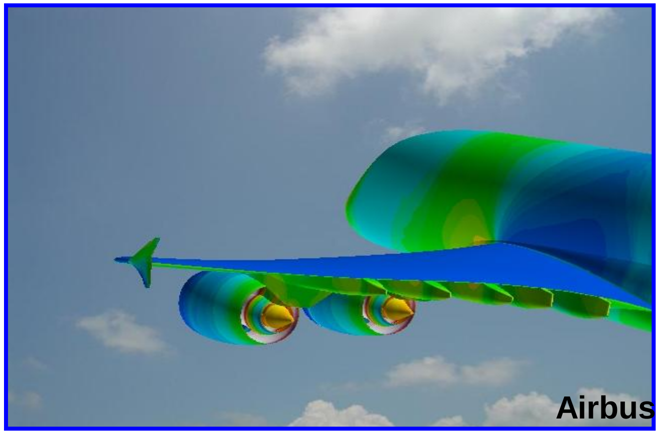
Cross-Function,
Inputs from the
4 Programms

- ~ 7000 employees
- 33 Institutes and facilities
- Turnover ca. 1.3 B€ *(2010)*
  - 745 M€ for research & development
  - **205 M€ for aeronautics**

Plus:
- Space Administration
- Project Management Agency

Outline

- Background & Motivation
- DLR’s Vision: Digital-X
  - Physical Modeling
  - CFD Solver
  - Full Flight Simulation
  - Multidisciplinary Optimization
- Summary



ACARE 2020 / Flightpath 2050

ACARE: Advisory Council for Aeronautics Research in Europe

Europe’s Vision for Aviation

- Maintaining Global Leadership & Serving Society’s Needs

Goals *(relative to typical aircraft in 2000)*

- CO_2 emissions reduced by 75%
- NOx emissions reduced by 90%
- 65% reduction in perceived aircraft noise

Consequence

- Heavy demands on future product performance
- Step changes in aircraft technology required
- New design principles mandatory

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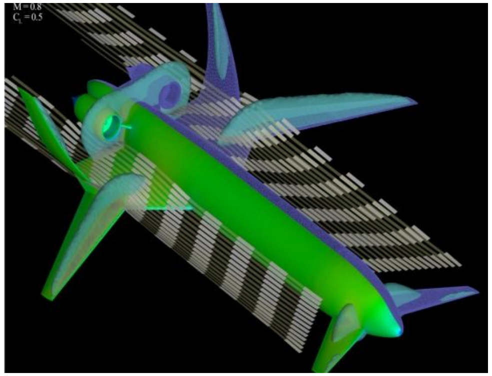
Numerical Simulation
Key Enabler for Future Aircraft Design

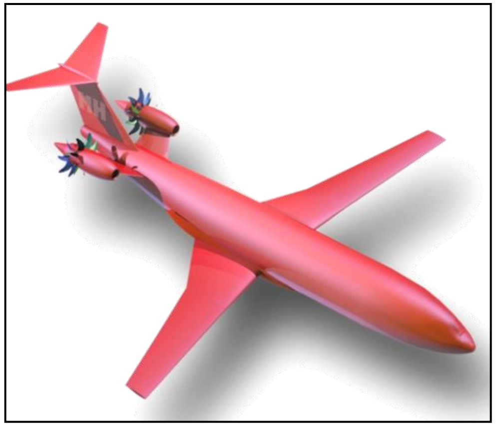
Future aircraft

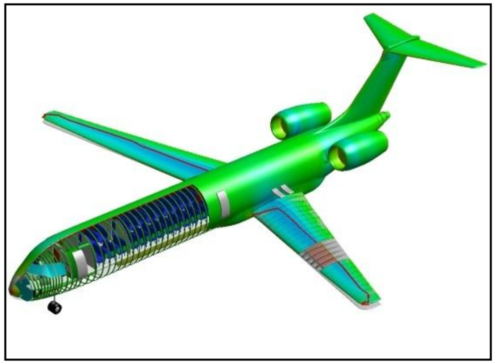
- Design may be driven by unconventional layouts
- Flight characteristics may be dominated by non-linear effects



High-fidelity methods indispensible for design & assessment of step changing aircraft

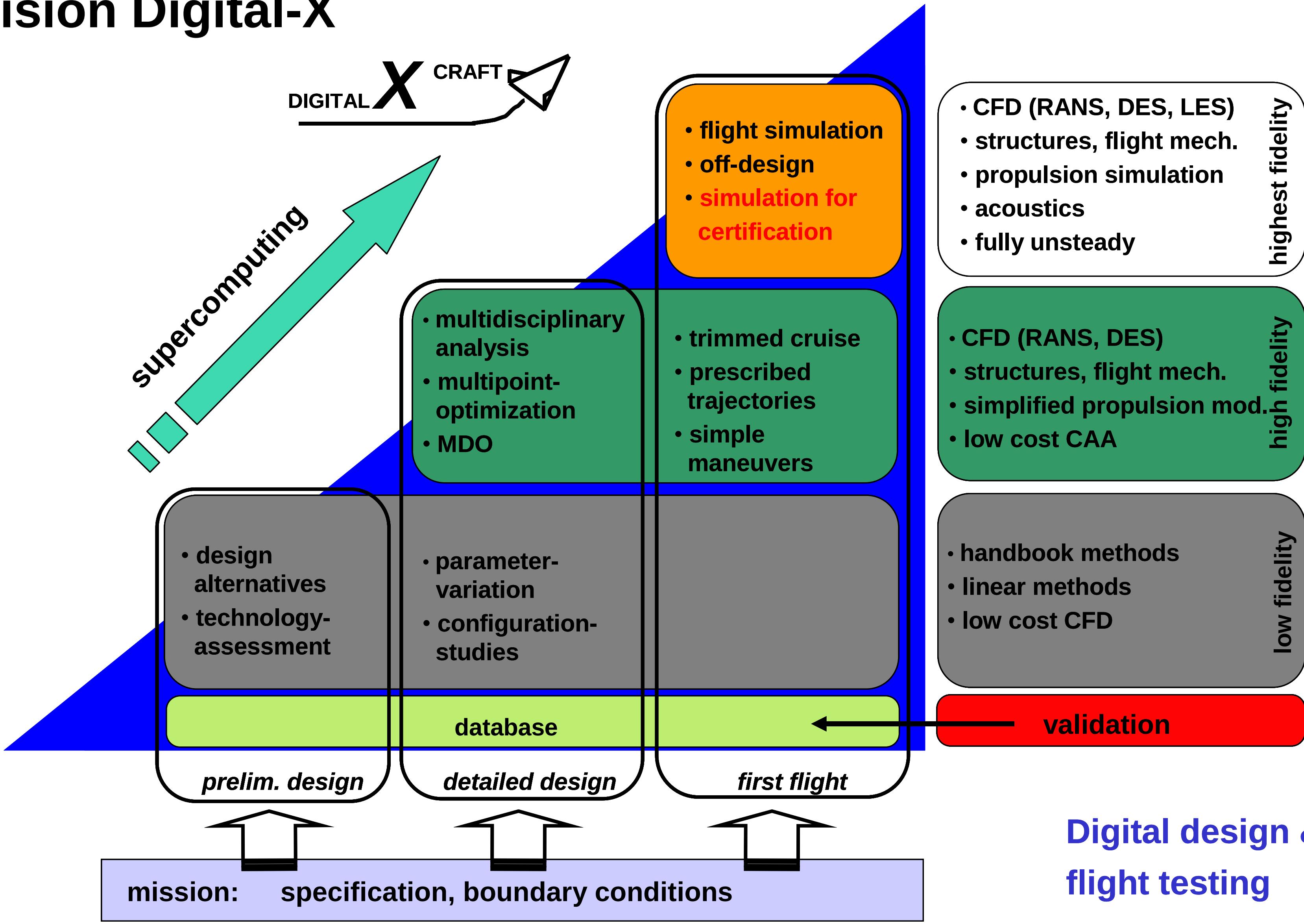
- Reliable insight to new aircraft technologies
- Comprehensive sensitivity analysis with risk & uncertainty management
- Best overall aircraft performance through integrated aerodynamics / structures / systems design
- Consistent and harmonized aerodynamic and aero-elastic data across flight envelope





Further improvement of simulation capability necessary

Vision Digital-X



Digital design & flight testing

2007

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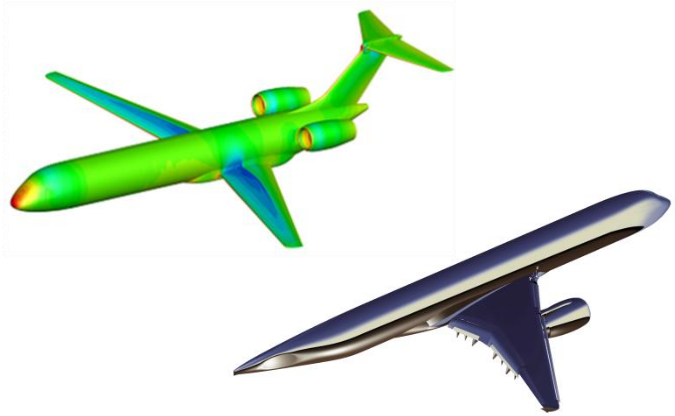
DLR Project Digital-X

Towards Virtual Aircraft Design and Flight Testing

Long term goals

- Development of an integrated software platform for multi-disciplinary analysis & optimization based on high fidelity methods
  - Integration of relevant disciplines



Short term goals *(1st phase 2012-2015)*

- Prototype of integrated software platform
- Demonstration of new capabilities using industrial relevant configurations

Main activities

- CFD solver improvement, reduced order modeling, maneuver simulation, MDO, uncertainty quantification, parallel simulation environment

Project partners

- 9 DLR institutes, Airbus associated partner
- Strong links to national research projects *(Federal Aeronautical Research Programme)* *(Cassidian, RRD, ECD, Universities of Braunschweig, Stuttgart, Aachen, Darmstadt, München, ..)*

DLR Project Digital-X

Towards Virtual Aircraft Design and Flight Testing

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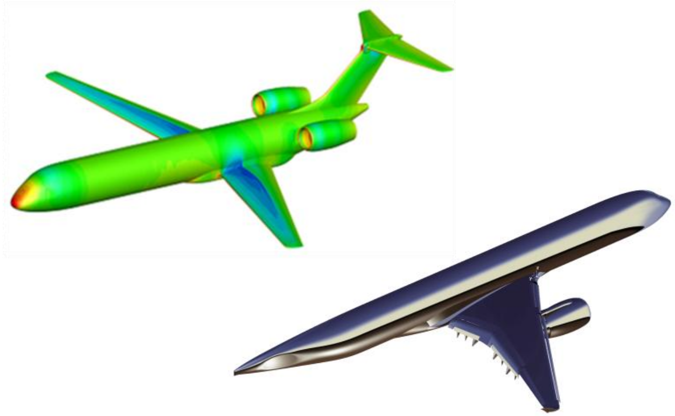

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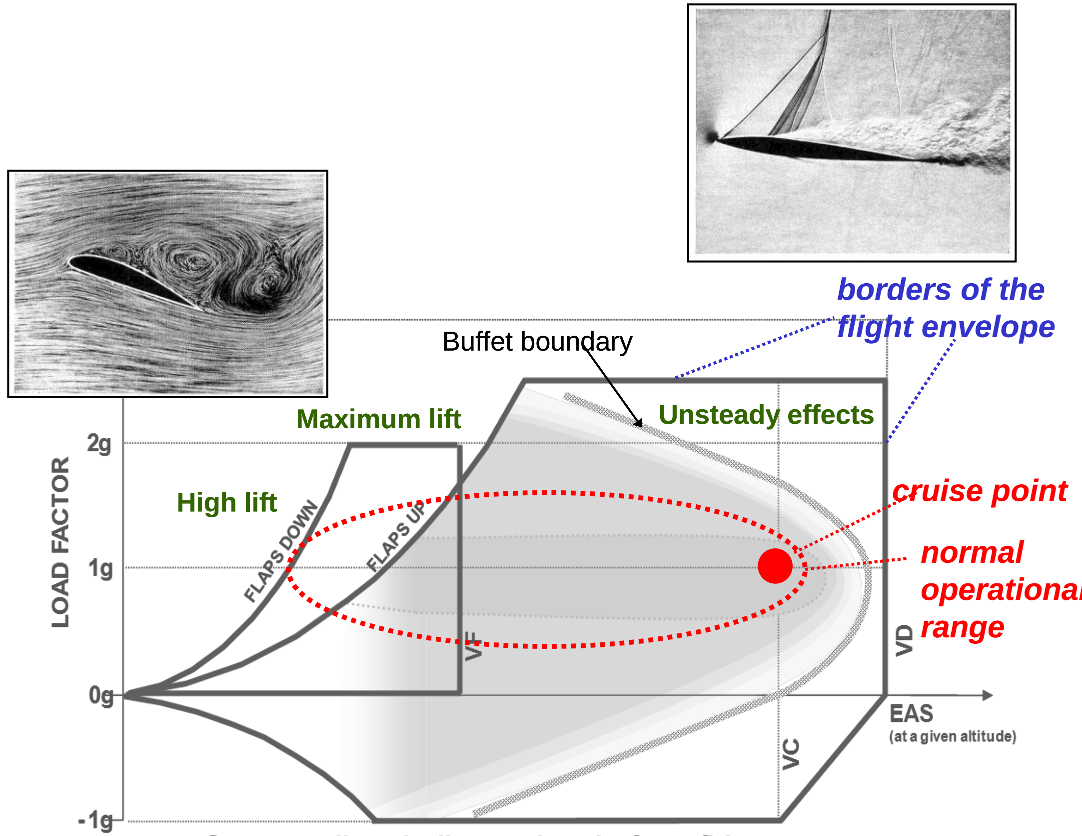
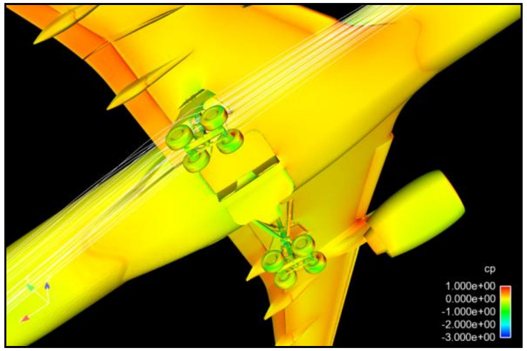
Digital Aircraft

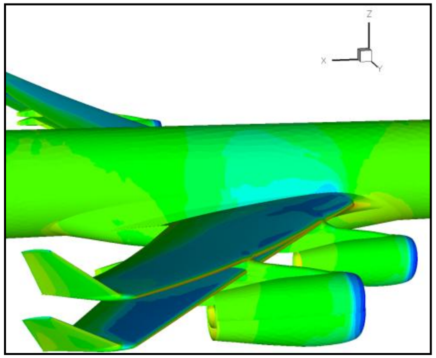
Challenges

- Simulation of full flight envelope
- Physical modeling of flows with separation
- Reliable & efficient CFD computations
  - Complete A/C
  - Complex flows
  - Huge number of cases (CFD for data)
  - Unsteady computations
- Coupling of all relevant aircraft disciplines
  - Maneuver simulation
  - Loads prediction
- Multi-disciplinary optimization



Grey gradient indicates level of confidence in CFD flow solutions

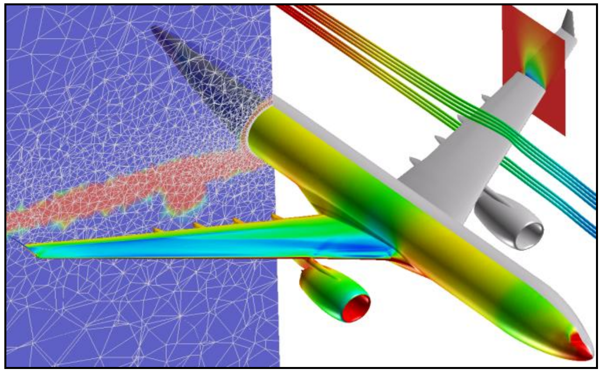




DLR CFD Codes

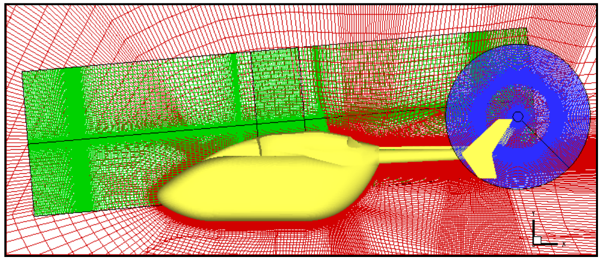
TAU-Code ***(Production code)***

- Unstructured hybrid meshes, overlapping grids
- RANS, hybrid RANS/LES
- Edge-based 2nd-order FV solver
- Grid re- & de-refinement
- Linear and adjont solver
- Hybersonic extension
- Incompressible version THETA



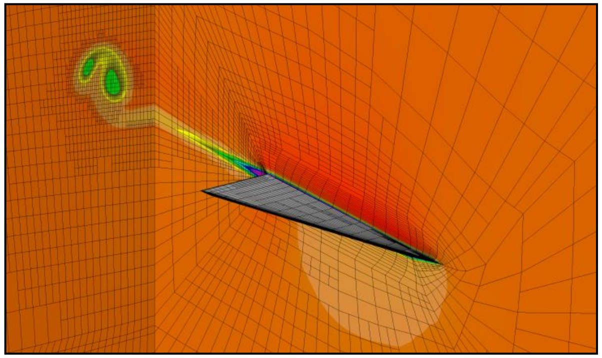
FLOWer-Code ***(For dedicated applications)***

- Block-structured 2nd-order FV solver
- Overlapping grids



PADGE-Code ***(Research Code)***

- Higher-order DG solver
- Unstructured mixed-element grids
- Isotropic & anisotropic hp-adaptation
- Reliable error estimator



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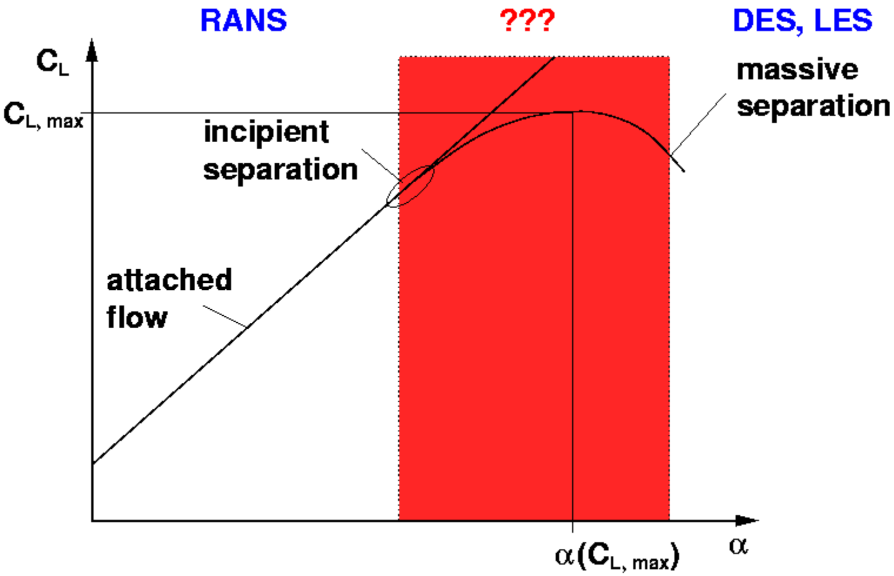
Physical Modeling

Challenge & Vision



CFD for off-design conditions

- Separation onset
- URANS vs. scale resolution
- Influence of transition

Vision: Unified model based on Reynolds Stress Transport for full flight envelope

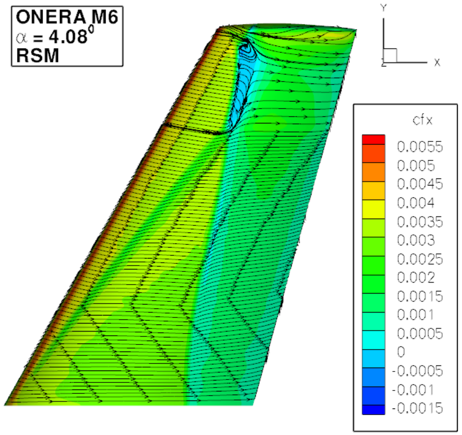
- For macroscopically steady & unsteady flows
- Effects of favorable and adverse pressure gradients on turbulence to be included
- Wide range of applicability (separation, free vortices)
- Automatic switch from URANS to scale resolving method, in cases where details of turbulent spectrum relevant
- Correct behavior at turbulence onset

Physical Modeling

Current Status (TAU-Code)

Differential Reynolds Stress Models (RANS)

- SSG/LRR-ω model
  - „Simple“ standard model
  - Based on BSL ω-equation (Menter)



Standard RSM in TAU

EU-Project FLOMANIA

- Speziale-Sarkar-Gatski model (SSG) as common model chosen
- SSG model relies on length scale variable ε

Aerodynamics

- Length scale variable ω is advantageous

Reynolds stress model based on ω

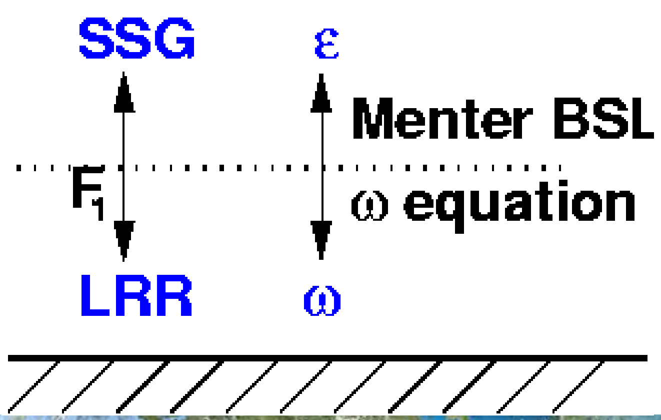
- Stress-ω model by Wilcox
  = Launder-Reece-Rodi model (LRR) without wall reflexion

Idea:

- Model combination by coefficient blending (according to Menter models)

⇨ SSG/LRR-ω model

- Far field: SSG + ε
- Near wall: LRR + ω
- Coefficients:
  Blending function F_1 by Menter
- BSL-ω-equation by Menter



Physical Modeling

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Differential Reynolds Stress Models (RANS)

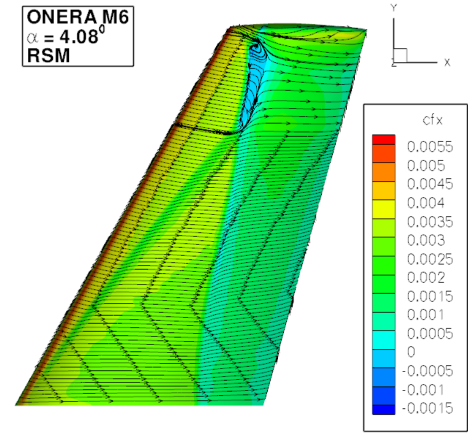
- SSG/LRR-ω model
  - „Simple“ standard model
  - Based on BSL ω-equation (Menter)
- JHh-v2 (Jakirlic-Hanjalic)
  - Advanced near-wall treatment
  - Based on homogeneous dissipation rate ε^h
  - Anisotropic dissipation

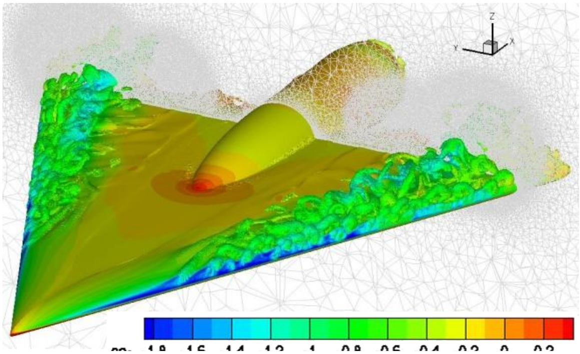
Scale resolving approaches

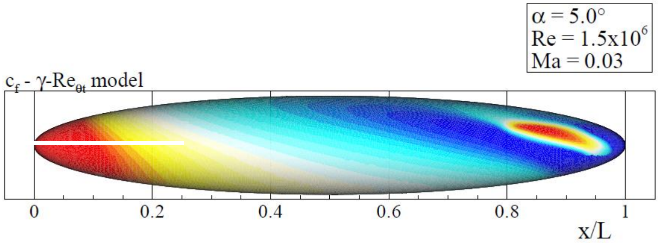
- DES (+ variants)
  - Based on various models
- Advanced URANS (SAS, PANS)
  - Based on SST model

Transition prediction

- e^N method
- Transport equation based model







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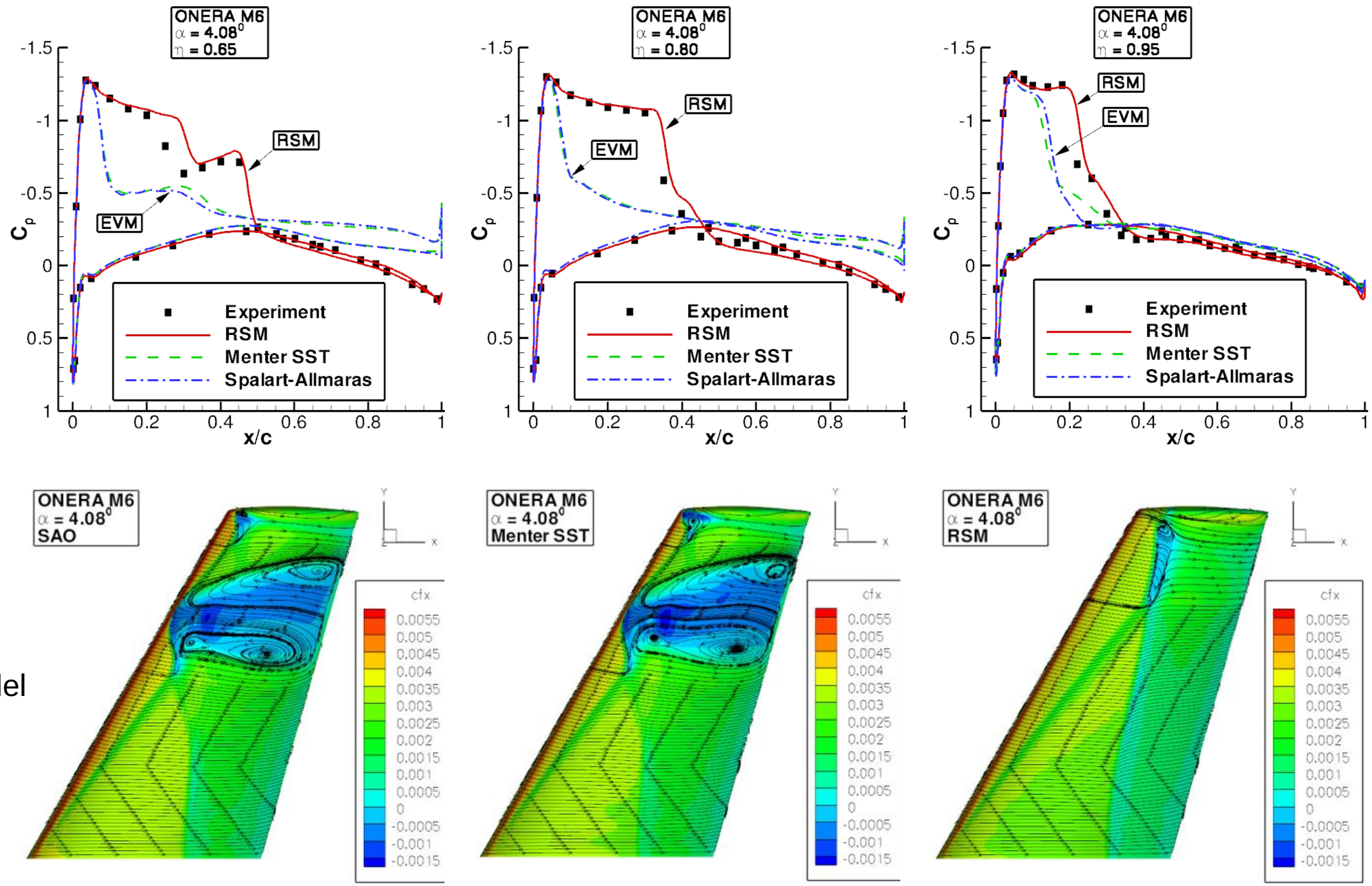
Turbulence Modeling

Application of Reynolds Stress Models to High-Speed Flow

ONERA M6 wing

- Shock-induced separation
- RSM delivers significantly better results compared to eddy viscosity models (EVM)

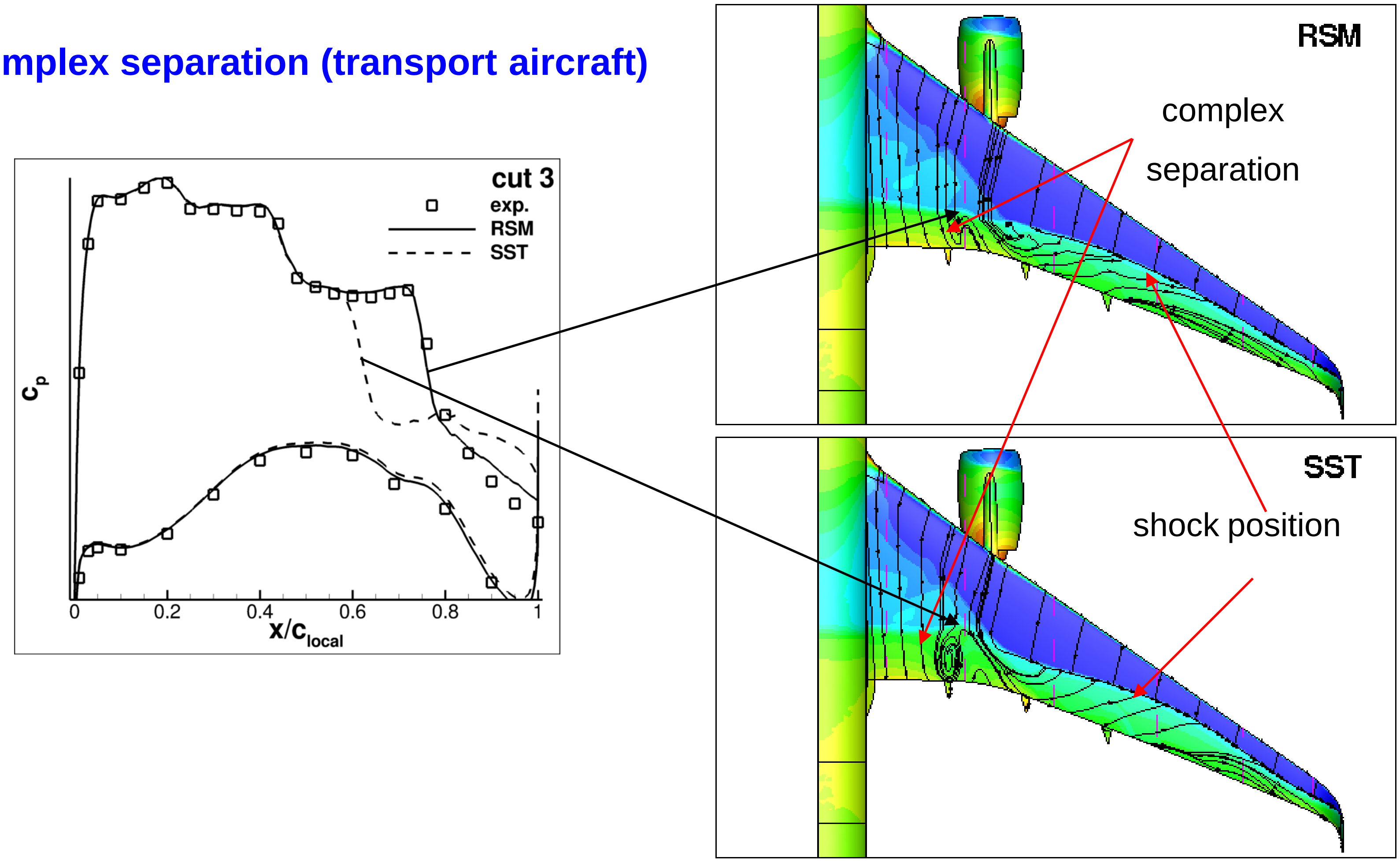


RSM: Reynolds Stress model
EVM: Eddy viscosity model

Turbulence Modeling

Application of Reynolds Stress Models to High-Speed Flow

Complex separation (transport aircraft)

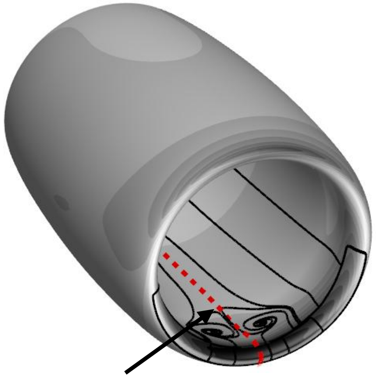


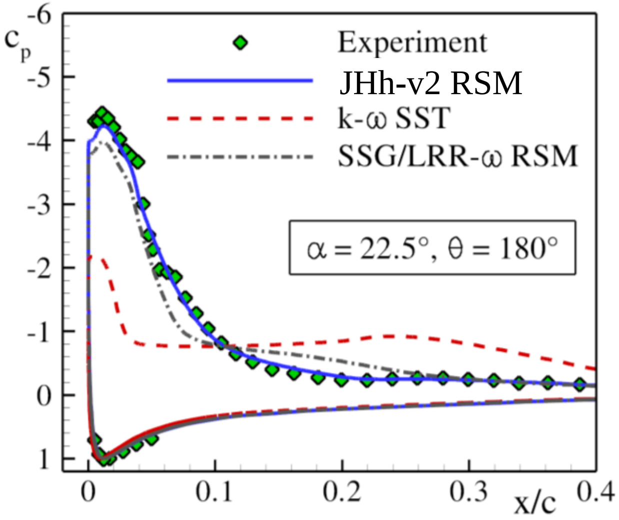
Turbulence Modeling

Application of Reynolds Stress Models

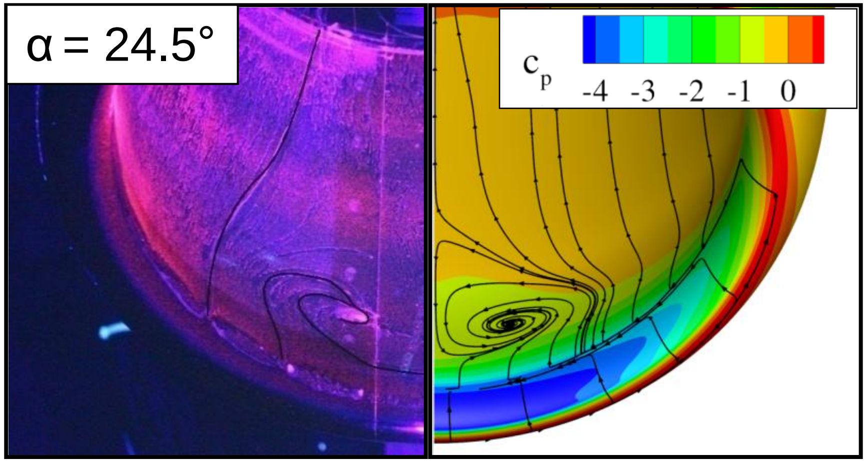
Stall characteristics (nacelle)

- $M = 0.15$, $Re = 1.3$ million
- URANS combined with e^N method
- Measured separation onset around $\alpha \geq 24°$
- Improvement by DRSM, in particular JHh-v2





Surface pressure in inlet symmetry plane



Oil-flow picture (left) and JHh-v2 RSM (right)

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Physical Modeling

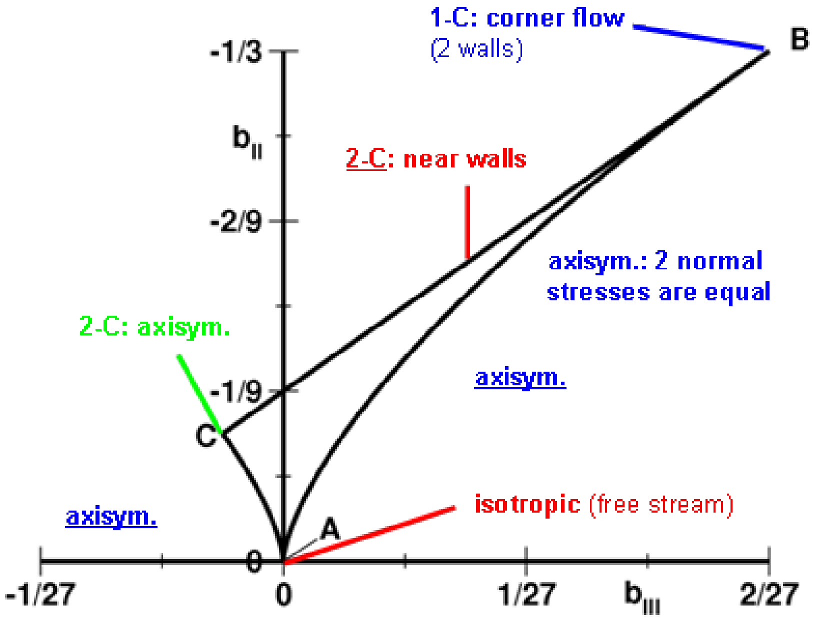
Activities / Perspectives - DRSM

Fundamental investigations

- Near-wall flow physics
- Effect of positive pressure gradients

Improved Reynolds Stress Modeling

- Non-linear re-distribution modeling
  - Analysis of physical constraints
  - Hierarchy in complexity
- Anisotropic dissipation modeling
  - Analysis of physical constraints
  - Focus on near-wall region
- Compressibility effects
  - Analysis of flow equations
  - Transfer of modeling principles
- Length scale equation
  - Maintain boundary layer characteristics
  - Enhance sensitivity to separation



Invariant map allows

- Systematic analysis of RSM
- Reduction of free parameters

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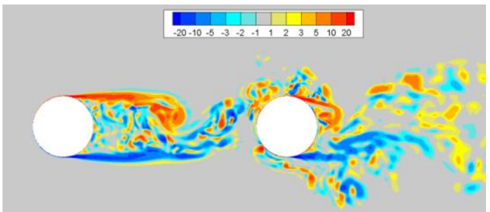
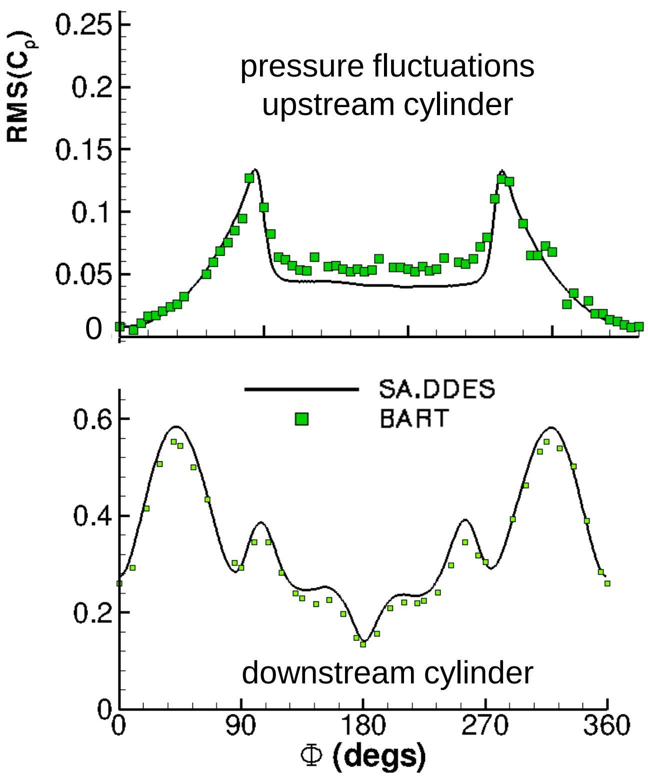
Turbulence Modeling

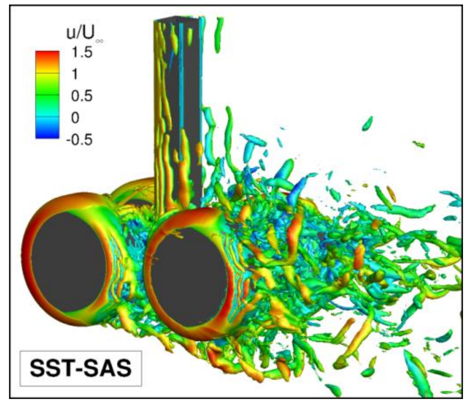
Status - Hybrid RANS/LES

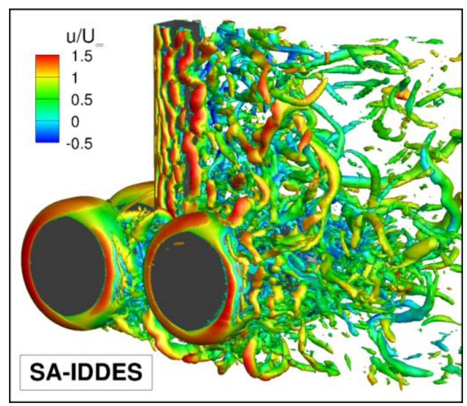
Tandem cylinder *(TAU-Code)*





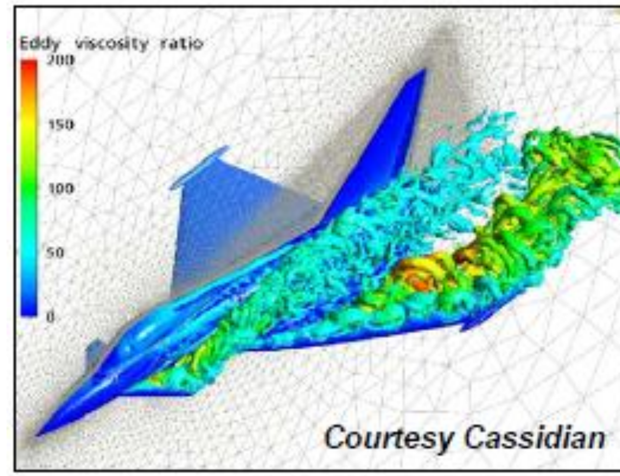
Simplified landing gear





DLR THETA-Code

FA-5 generic fighter at α=15°



EU project DESider, Springer book, 2009

DLR TAU-Code

Improvements required for prediction of incipient separation

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Physical Modeling

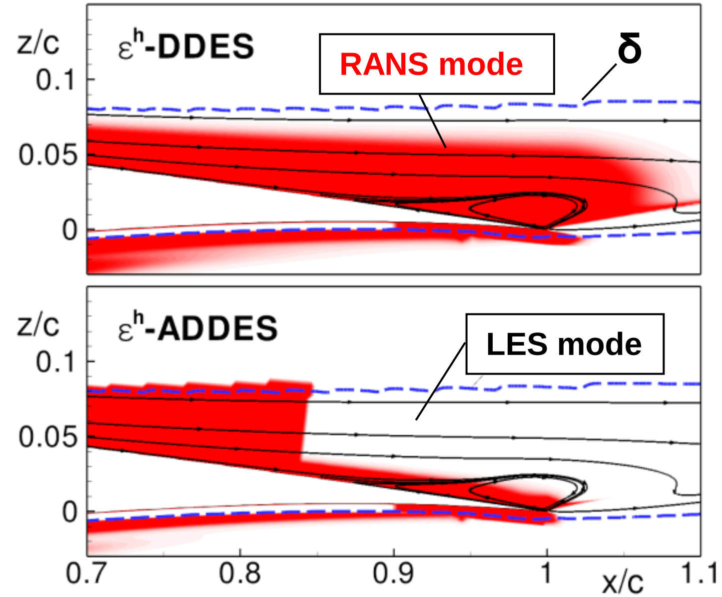
Activities / Perspectives - Scale Resolution

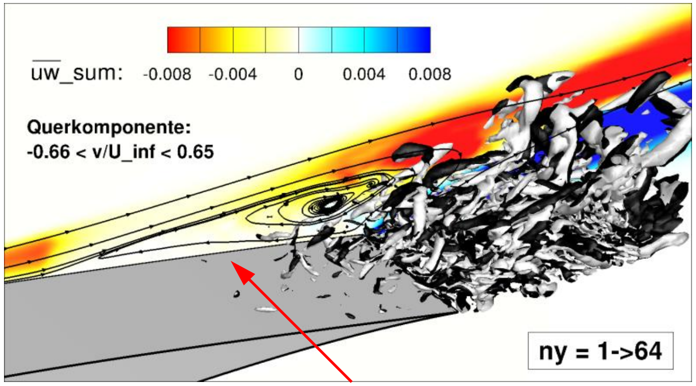
DRSM extension to scale resolution

- Coupling of existing approaches *(DES/DDES/IDDES, SAS, PANS)* with DRSM
- Onset of scale resolution
  - Definition of criteria (ADDES) (RANS/LES sensors based on boundary layer quantities)
  - Physical based forcing of fluctuations

LES

- Focus on studies concerning
  - Structured/unstructured grids
  - 2^{nd}-order/high-order methods





NO break-up into small scale structures above the surface at shallow separation

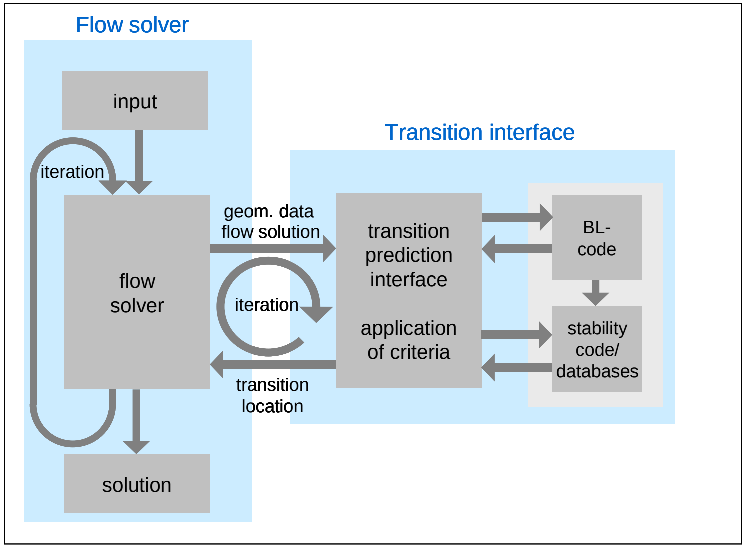
No forcing of fluctuations applied

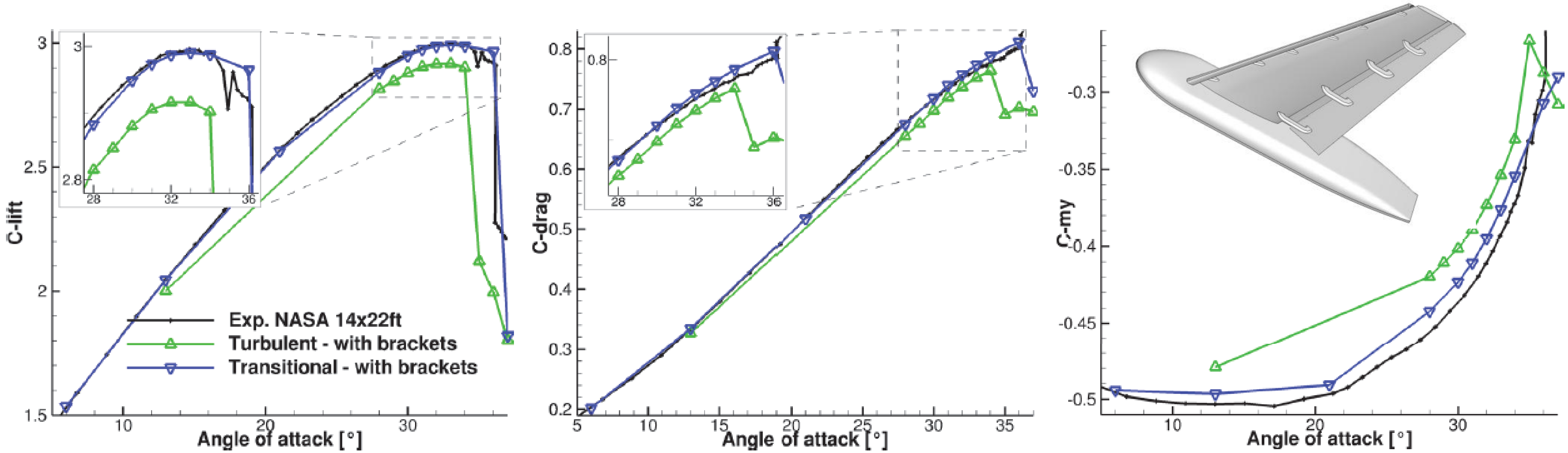
Transition Prediction

Status - e^N Method

NASA TRAP Wing

- M = 0.2, Re = 4.3 106, a = 6° - 36°
- NTS = 8.5, NCF = 8.5
- Transitional computations result in proper prediction of
  - Pitching moment
  - Stall characteristics





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Physical Modeling

Activities / Perspectives – Transition Prediction

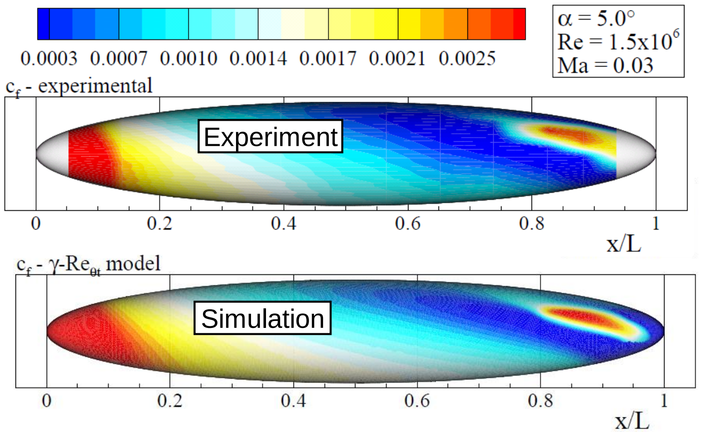
Correlation-based transition model γ-ReΘt

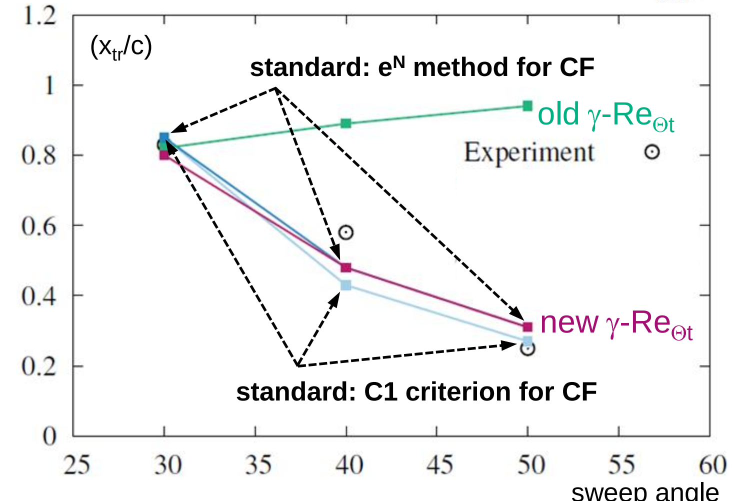
- Integral part of a flow solver
- Good results for a variety of flows dominated by streamwise transition mechanisms (2D+3D)
- Potential to be extended to flows dominated by Cross-Flow (CF) transition
- Potential for using transition prediction in adjoint-based optimization

Planned Activities

- Extension to CF instabilities on arbitrary 3D wings
- Calibration of the model functions, validation

Streamwise transition





CF transition for ISW

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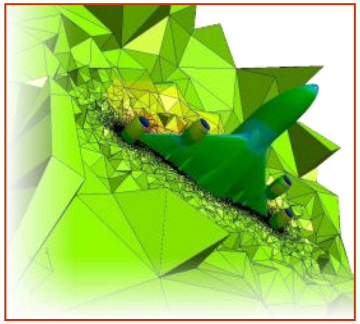
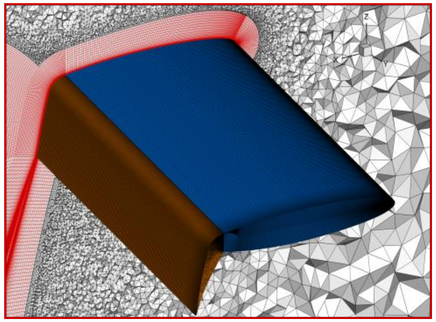
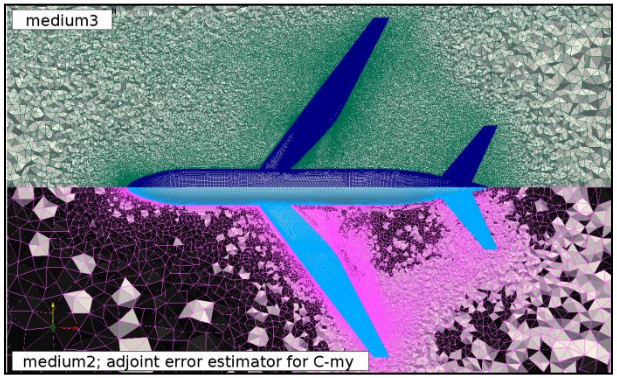
CFD Solver





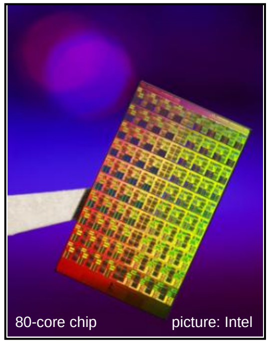
Challenge

- Accurate, efficient and robust / reliable solver for a given physical model



Aspects / issues

- Grid generation
- Adaptive mesh refinement
- Discretization issues
- Solution strategies
- Adaptation to novel hardware technique



Goal: **Layout and prototype realization of Next Generation Solver**

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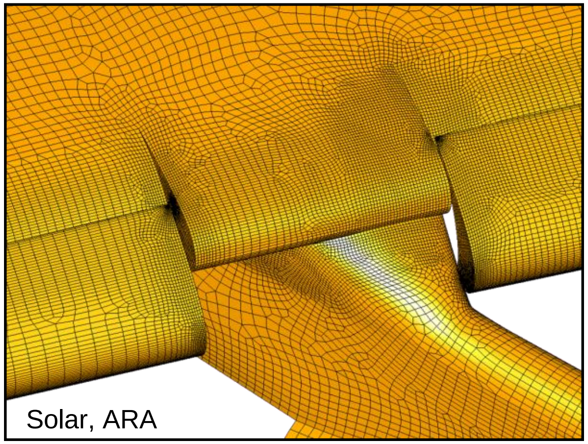
Grid Generation (Unstructured)

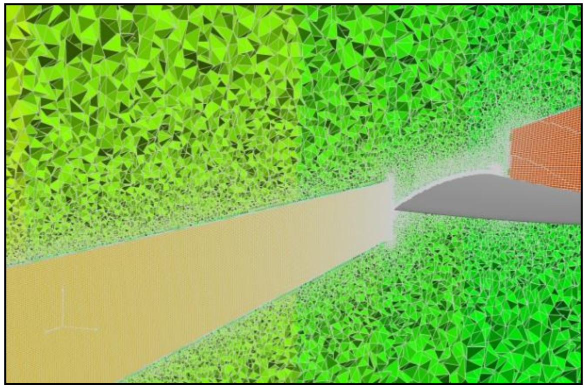
Requirement

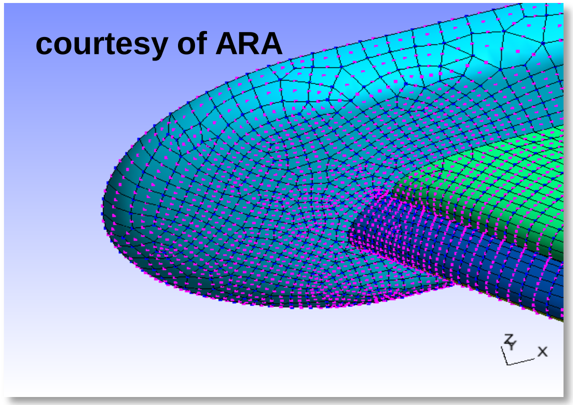
- **Direct control of grid quality for unstructured grids**

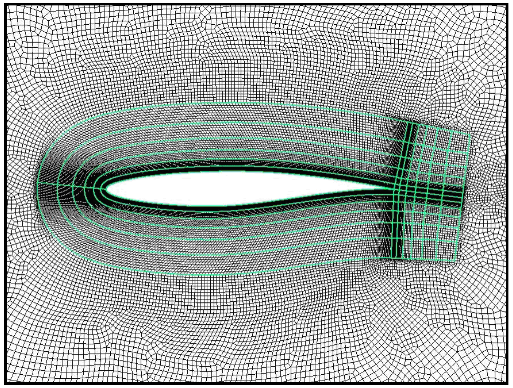
Vision

- Hex-dominant unstructured meshes
- Physical anisotropies reflected in mesh topology
  (boundary layers, high aspect ratio wings, rotor blades)
- Adapted wake and vortex resolution
- Cartesian mesh regions for general flow field resolution
- Support for overlapping mesh components (movables)
- Higher-order boundary representation


Solar, ARA


Centaur


courtesy of ARA


Hyperflex mesher, courtesy of Airbus

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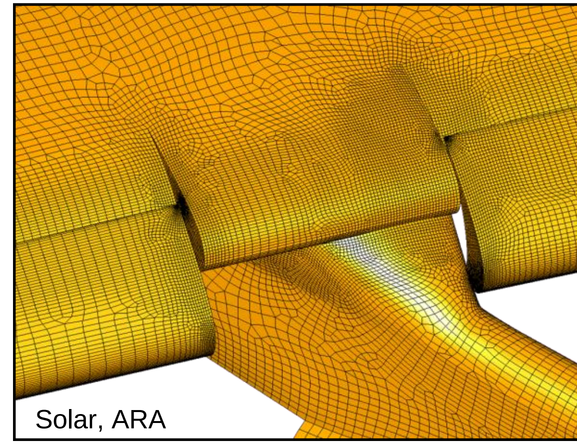
Approach

- Extensive evaluation of available software
- No major grid generation activities at DLR
- Co-operation with grid generation software vendors
  - Centaur (Centaursoft)
  - SOLAR / Hyperflex mesher (ARA/Airbus)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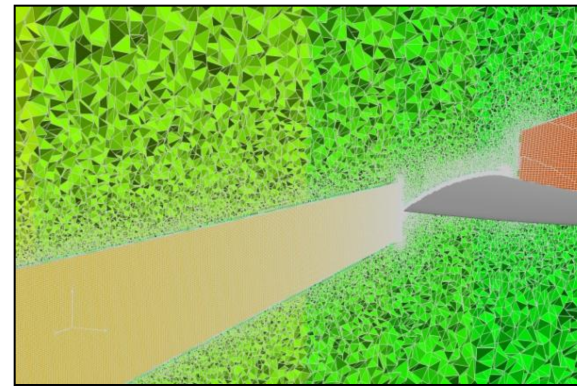
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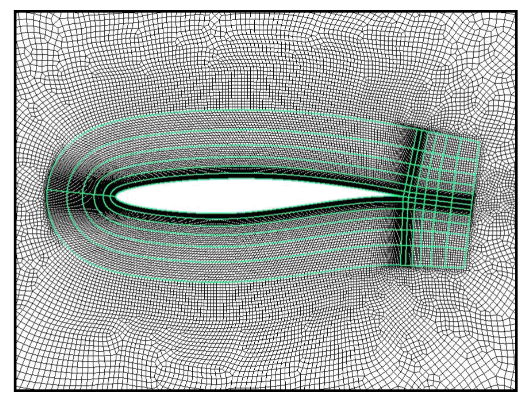
Hyperflex mesher, courtesy of Airbus

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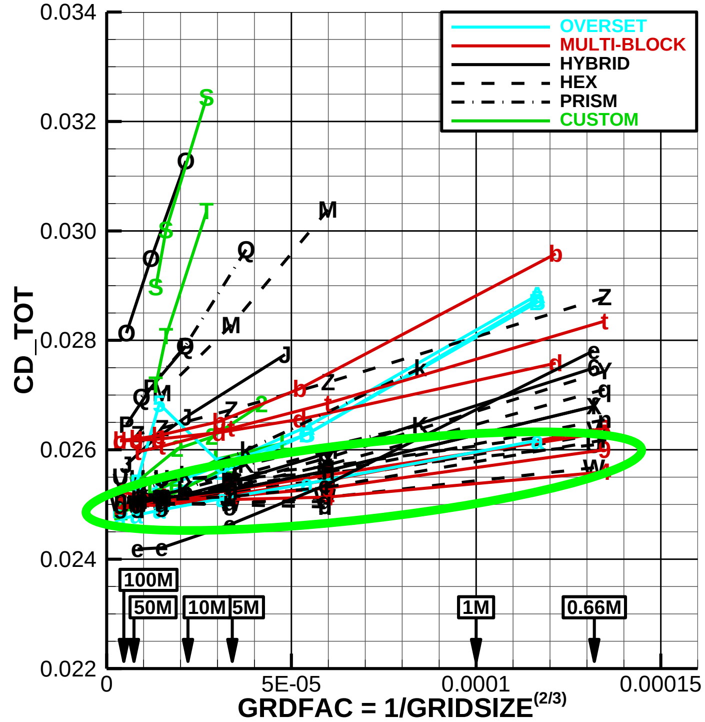
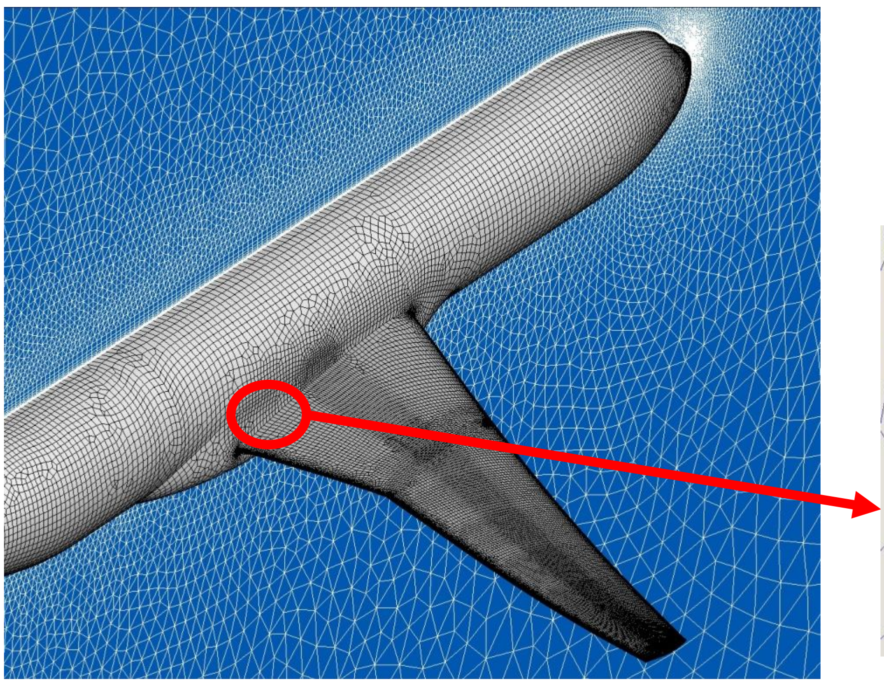
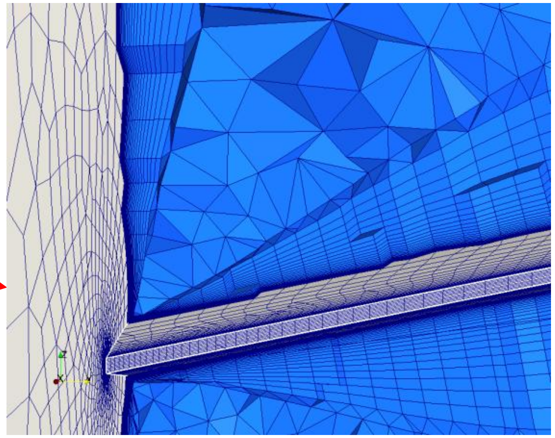
Grid Generation

Status / Current situation

- Hex-dominant grid families can deliver grid convergence similar to fully structured grids
- Limitations of adequate element quality in concave areas



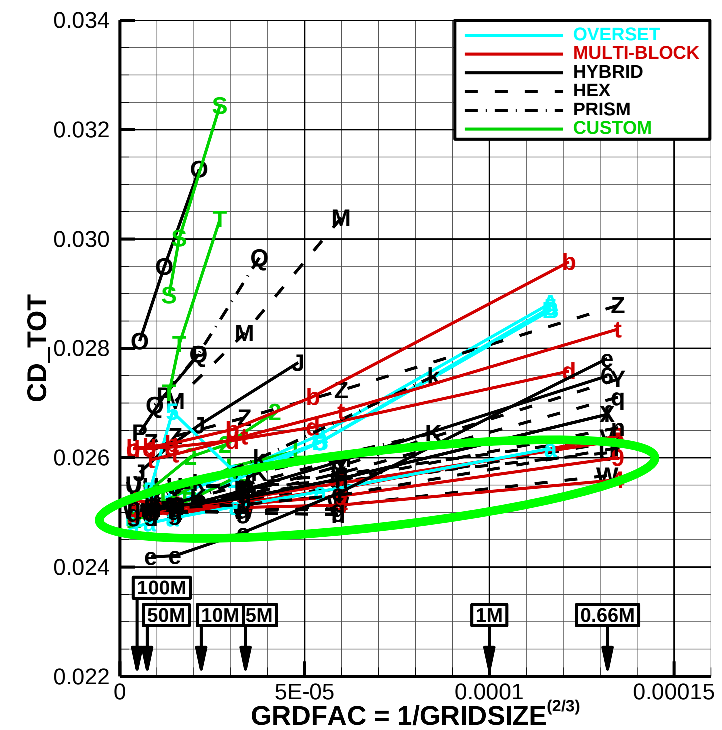




Wing Fuselage Corner
initial hex-dominant grid

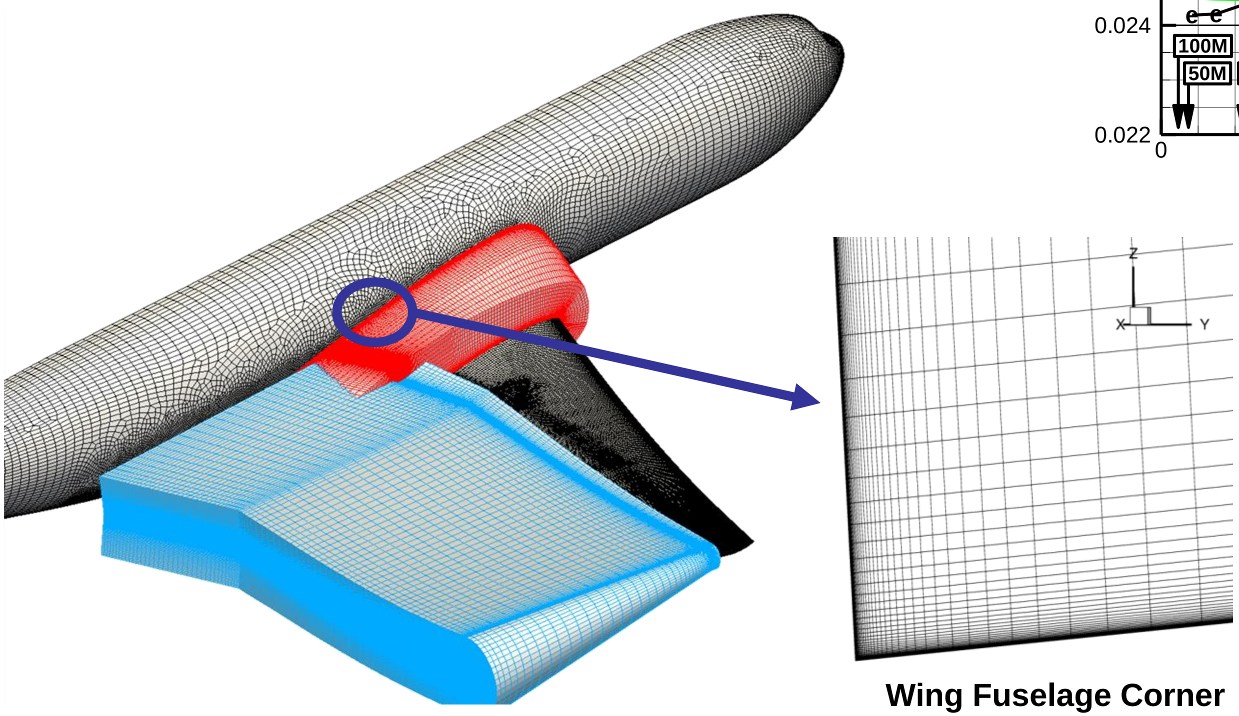
DLR

Grid Generation



Status / Current situation

- Hex-dominant grid families can deliver grid convergence similar to fully structured grids.
- Limitations of adequate element quality in concave areas



Wing Fuselage Corner overlapping block

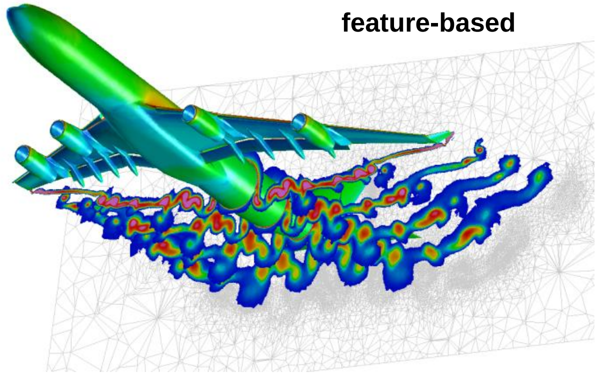
CFD Solver
Adaptive Mesh Refinement

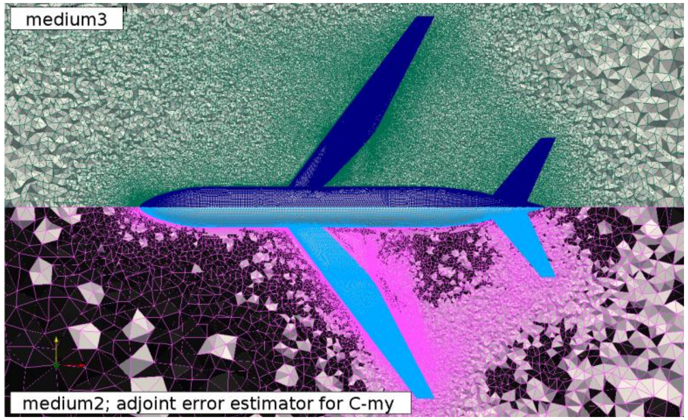
Status TAU-Code

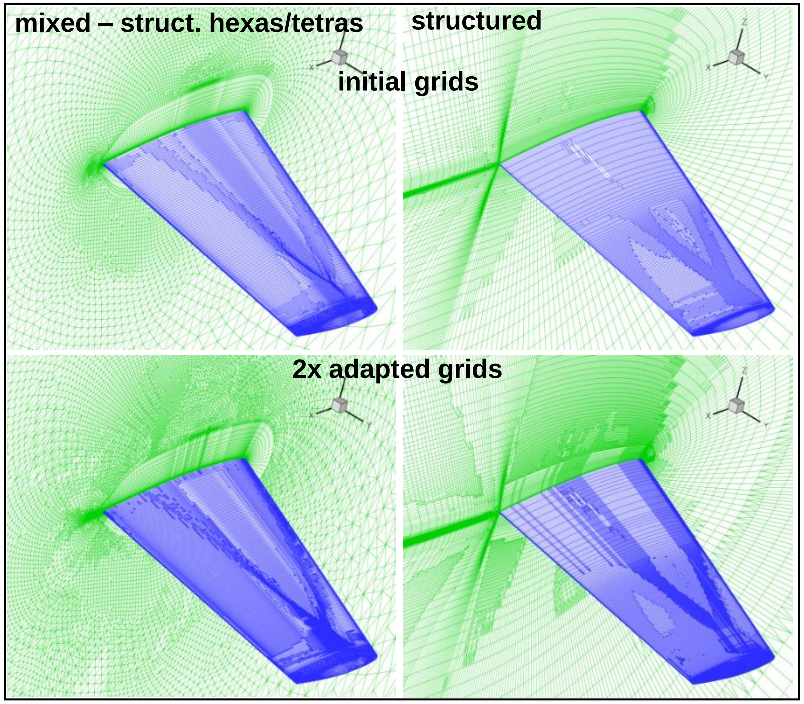
- Local re- & de-refinement of mixed meshes
- Feature-based & goal-oriented indicator
- Parallel implementation (MPI)

Open issues

- Grid refinement strategies retaining structured grid regions
- Isotropic element refinement in structured boundary layers
- Industrialization for turbulent flows around complex configurations
- Adjoint adaptation for unsteady applications



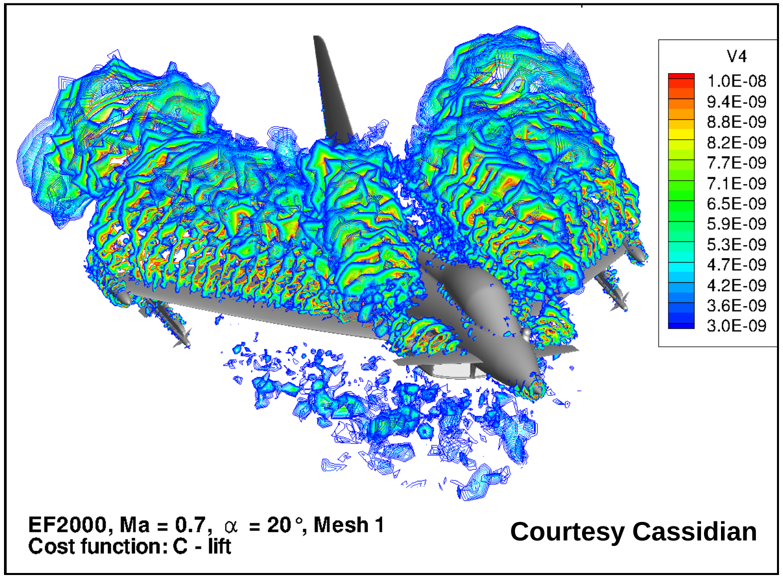


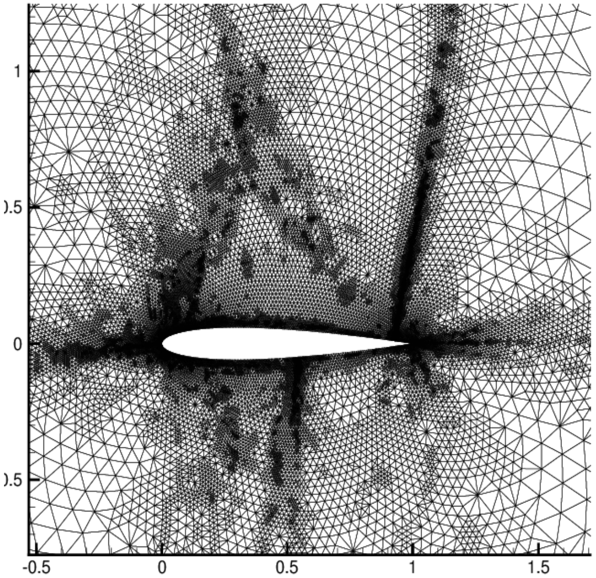


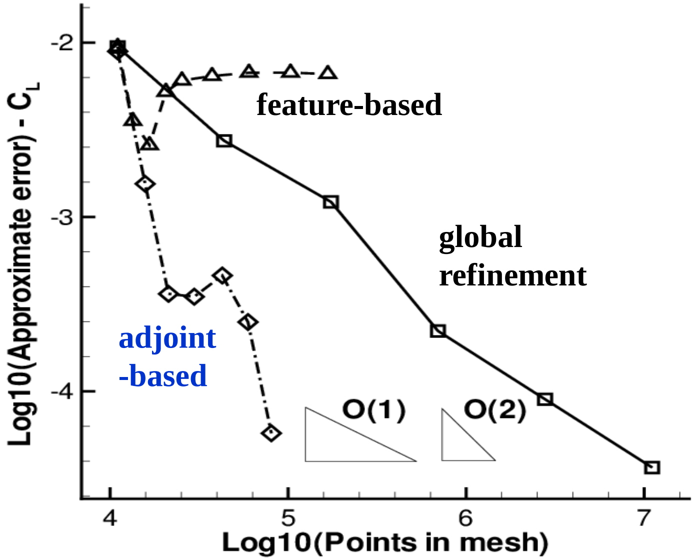
CFD Solver
Adaptive Mesh Refinement

Status TAU – Adjoint-based adaptation

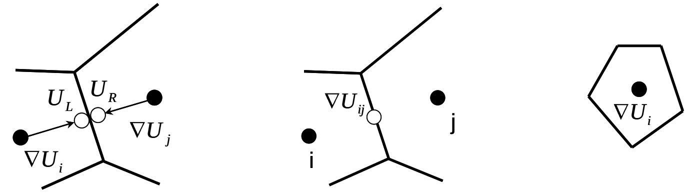
- Measure sensitivity of dissipation based error on aerodynamic coefficients using adjoint calculus
- Use sensitivity as indicator for local grid refinement
- Couple indicator to TAU adaptation tool or mesh generation software







CFD Solver
Discretization Issues

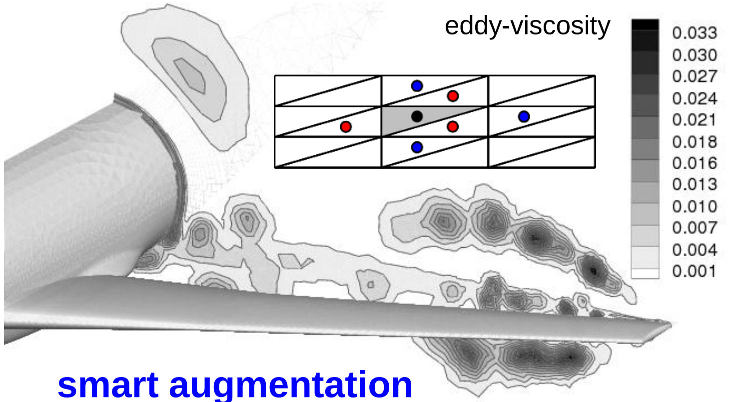


value reconstruction | viscous fluxes | turbulent sources

Computation of Gradients (FV)

Accurate gradients needed for

- Value reconstruction (upwind)
- Viscous fluxes
- Turbulent sources



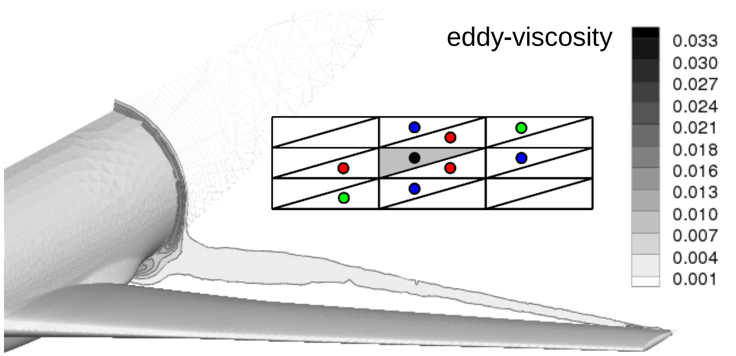
smart augmentation least-squares gradients

Standard gradient construction methods fail on arbitrary meshes

- Unweighted / weighted least-squares
- Green-Gauss
- Averaged & corrected cell gradients on faces

Improvement (e.g. least squares)

- Enhance weighted stencils to improve condition of linear system



conditioned smart augmentation least-squares gradients

Consequence

- Extend edge-based data structure to provide information that is needed

Collaboration with B. Diskin (NIA)

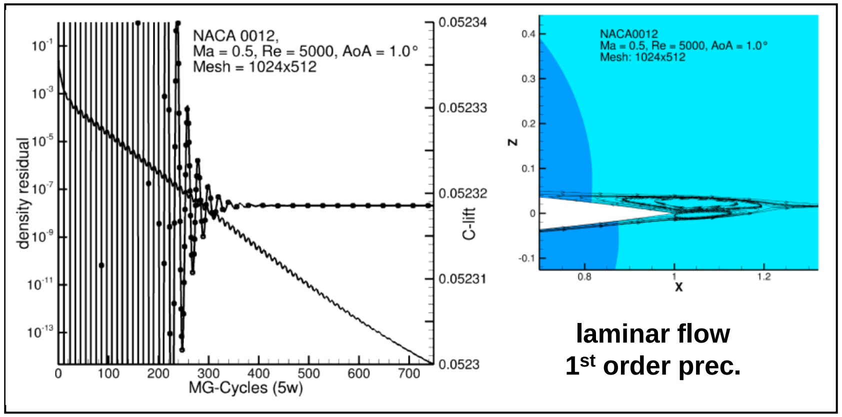
DLR

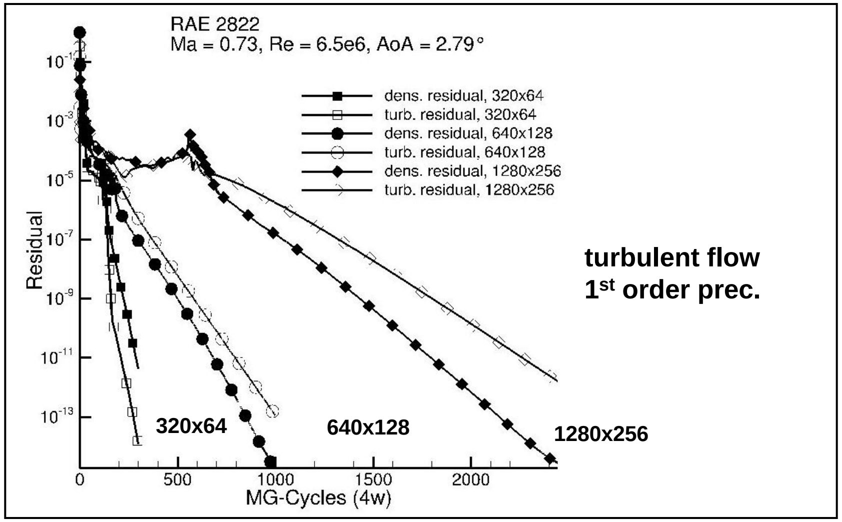
CFD Solver
Implicit Methods

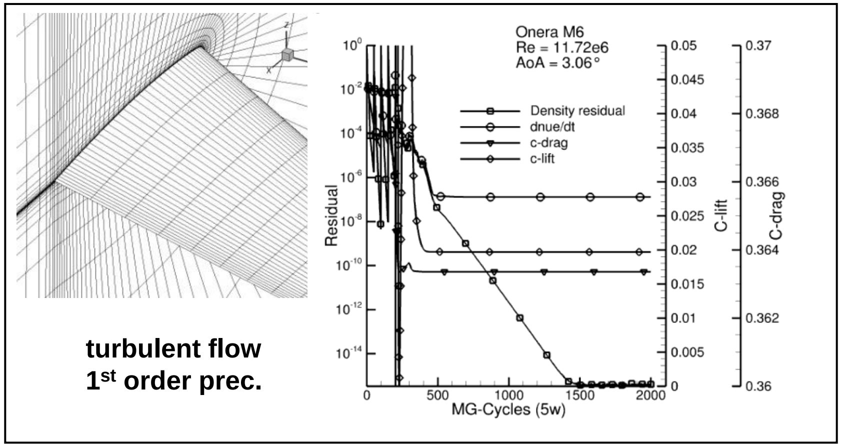
Goal
- Reduce stiffness (grid, turbulence)
- Improve robustness and reliability (**unstructured FV solver TAU**)

Approach (TAU prototype)
- Preconditioned implicit multistage Runge-Kutta (RK) method as multigrid smoother
- Hierarchy of preconditioners: (point implicit, line implicit, 1st-order Jacobian)
- Efficient solution of linear systems
- Directional coarsening strategy
- Coarse grid discretization / agglomeration

Open issues
- Treatment of turbulence equations
- Treatment of anisotropic areas in 3D (e.g. wing nose region)
- Parallelization
- Higher-order discretization







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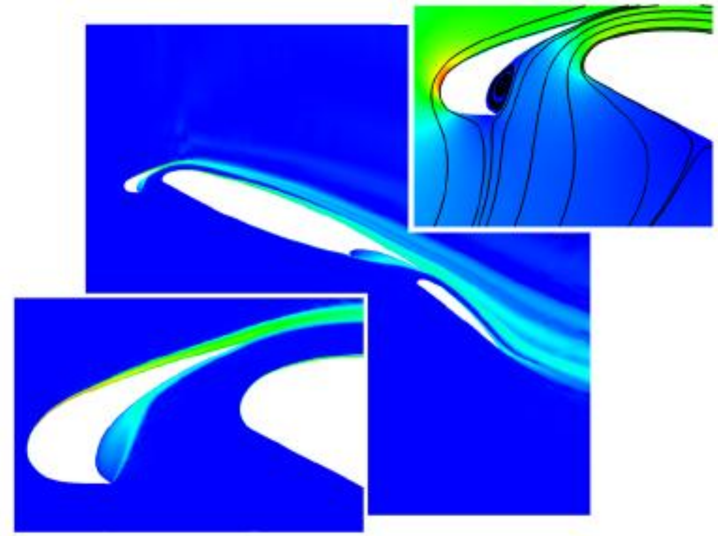
Collaboration with C. Swanson

CFD Solver
Adaptive Higher-Order DG Method



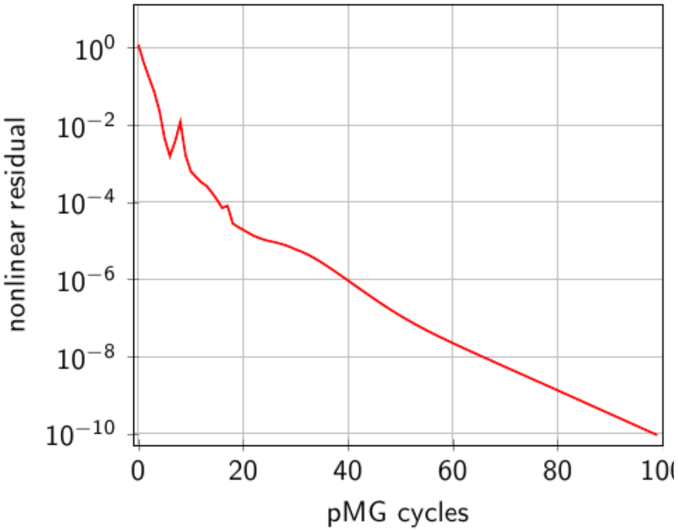
DLR PADGE Code

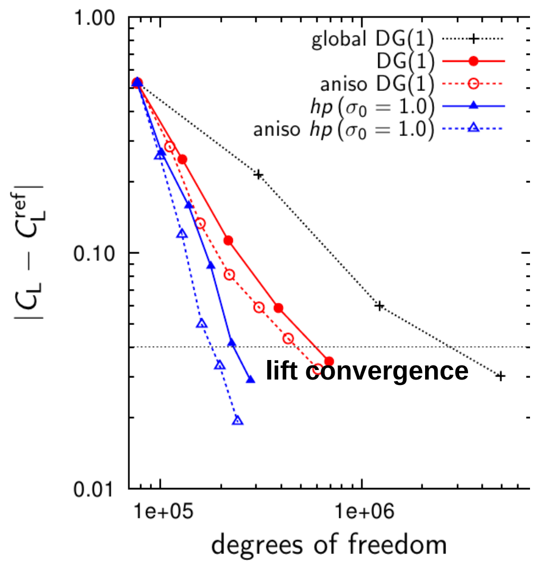
3-element airfoil, L1T2 test case

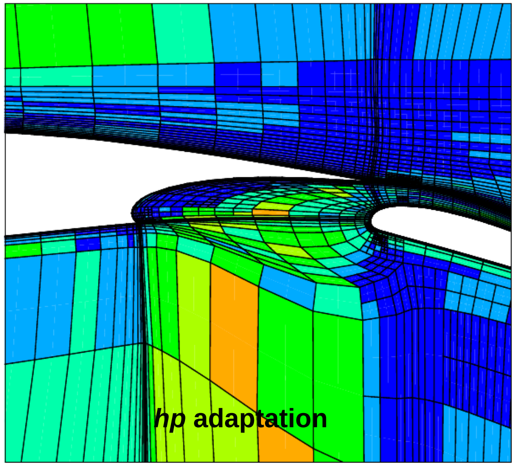
M=0.197   Re=3.52×10^{6} $\alpha=20.18^{\circ}$

RANS-kω, fully turbulent computation

p-multigrid, fourth order solution







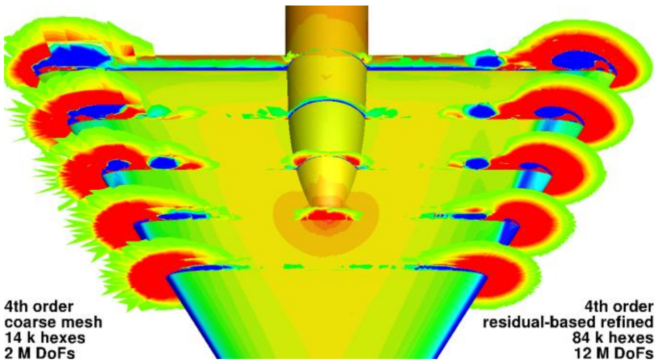
DLR

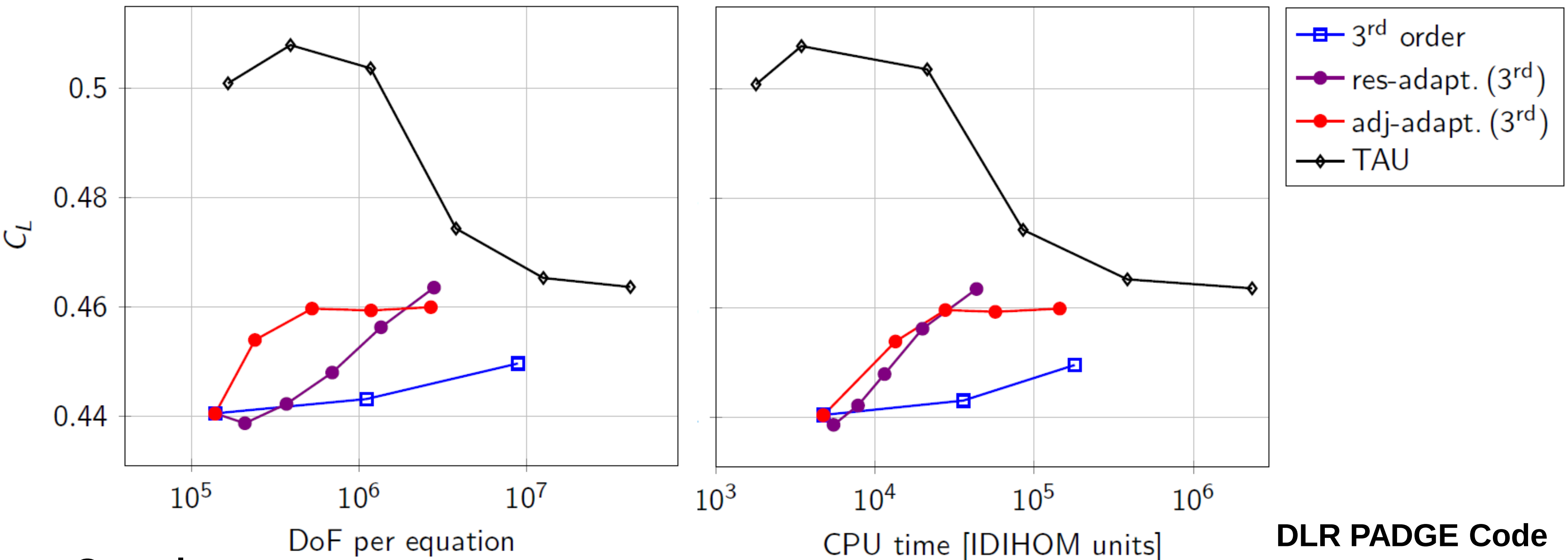
CFD Solver

Adaptive Higher-Order DG Method

- Subsonic turbulent flow around VFE-2 delta wing
- Adapation improves the overall time to solution, in particular if based on an adjoint problem

M=0.4, AoA=13.3^0, Re=3x10^6





DLR PADGE Code

Open issue:

- Applicability to complex configurations
  (computational complexity, higher-order boundary representation)

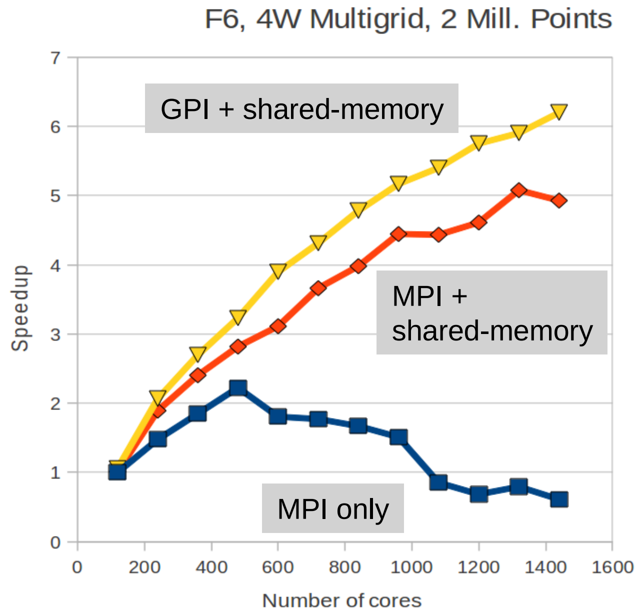
DLR

CFD Solver

The Manycore Shift – Facing Massively Parallel Systems

Challenges (in particular for RANS simulations)

- HPC clusters offers multiple levels of explicit parallelism *(task & data parallelism)*
- Number of mesh points per core drops due to rapid increase in core count
- Classical domain decomposition using one domain per core no longer appropriate because of load imbalances, e.g. due to algorithmic constraints (e.g. “lines”)
- Communication is becoming a bottle neck



Approaches

- Multi-level parallelization allowing for relaxed synchronization, e.g. one domain per chip plus shared-memory parallel processing of domains
- Overlap communication with computation
- Use 1-sided RDMA-based asynchronous communication (e.g. “GPI” instead of MPI)

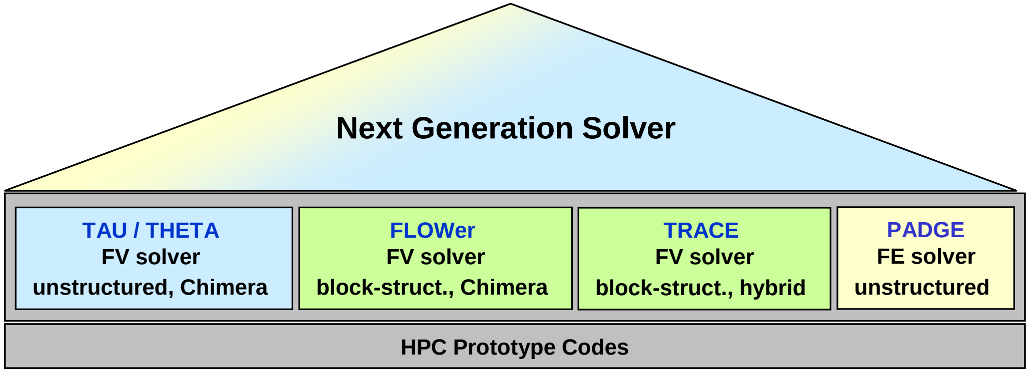
Goals

- Hide load imbalances and communication to improve (strong) scalability
- Compromise algorithmic vs. parallel efficiency to minimize turn-around time

DLR

CFD Solver

Activities / Perspective



DLR Next Generation Solver

Objectives

- Data layout driven by
  - Full exploitation of new HPC hardware (multi-level, task & data parallelism)
  - Flexible data structure for allowing enhanced discretization stencils
  - Integration of different discretization strategies (FV, FE, …)
  - Integration of various meshing strategies
    (e.g.: overlapping meshes, hanging nodes, grid adaptation, …)
  - Support of sophisticated solution algorithms
- Modular software design
  (Use of libraries: post processing, Chimera functionalities, linear solvers, …)
- **Selection of appropriate numerics on a case-by-case basis**
- Meet increasing user requirements
- Basis for internal and external flows
- **Seamless integration into multi-disciplinary simulation environment (FlowSimulator)**

DLR

Maneuver Simulation
Loads Prediction

Current situation

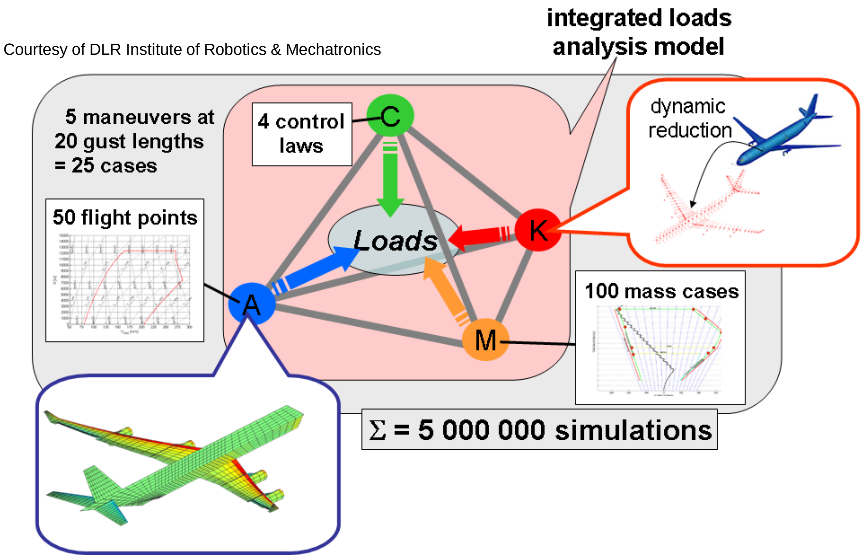
- Loads prediction mainly on low-fidelity methods

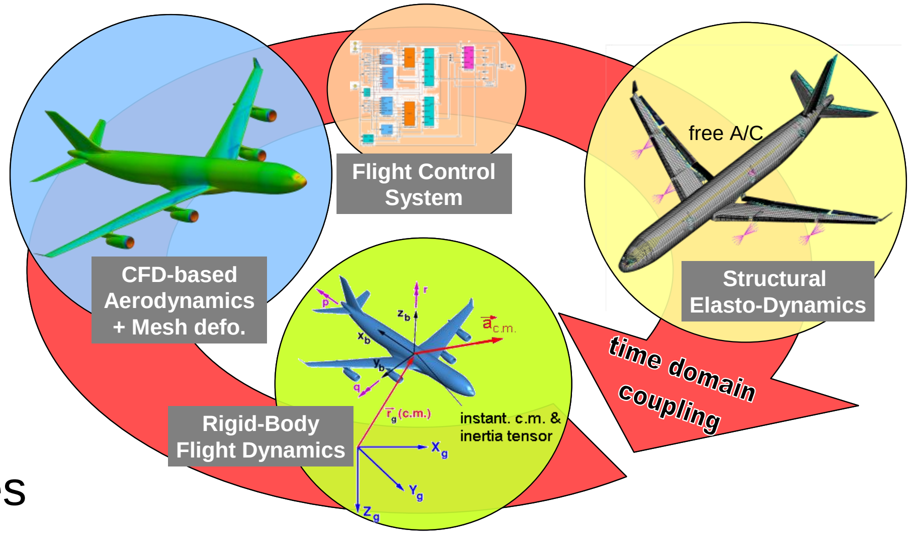
Objective

- Accurate maneuver and gust loads analysis for entire flight envelope

Challenges

- Coupling of relevant disciplines for free-flying flexible A/C in time domain based on high-fidelity methods
- Reduced order modeling
- Modeling of moving control surfaces
- Massively parallel simulation environment





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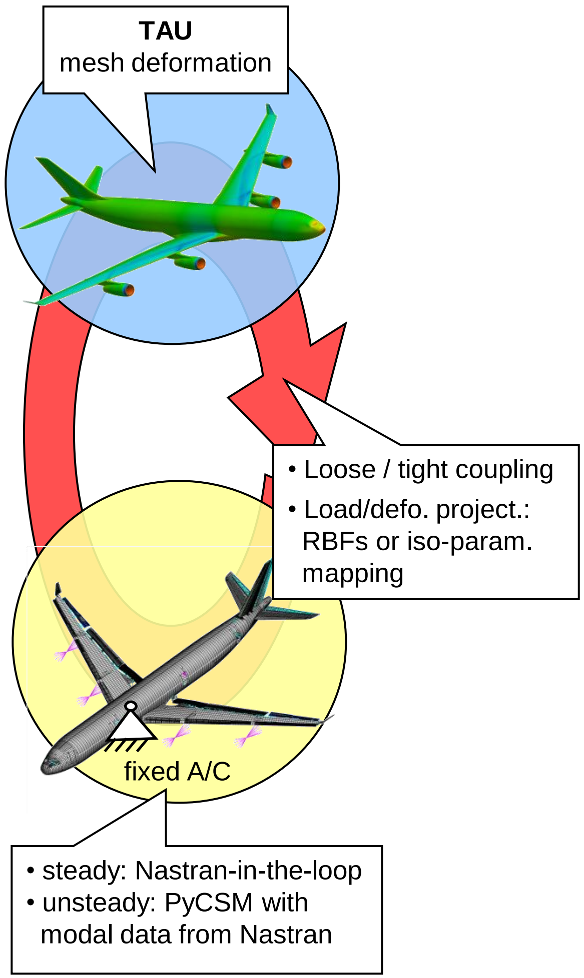
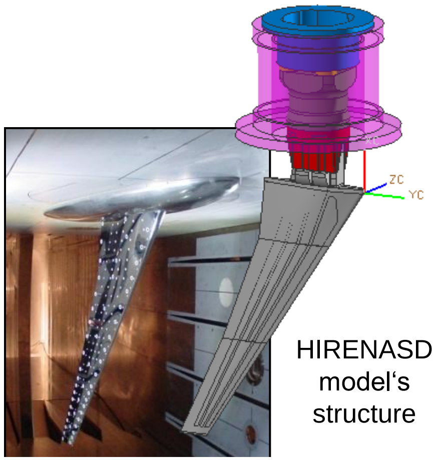
CFD /CSD Coupling – Unsteady Aeroelastics

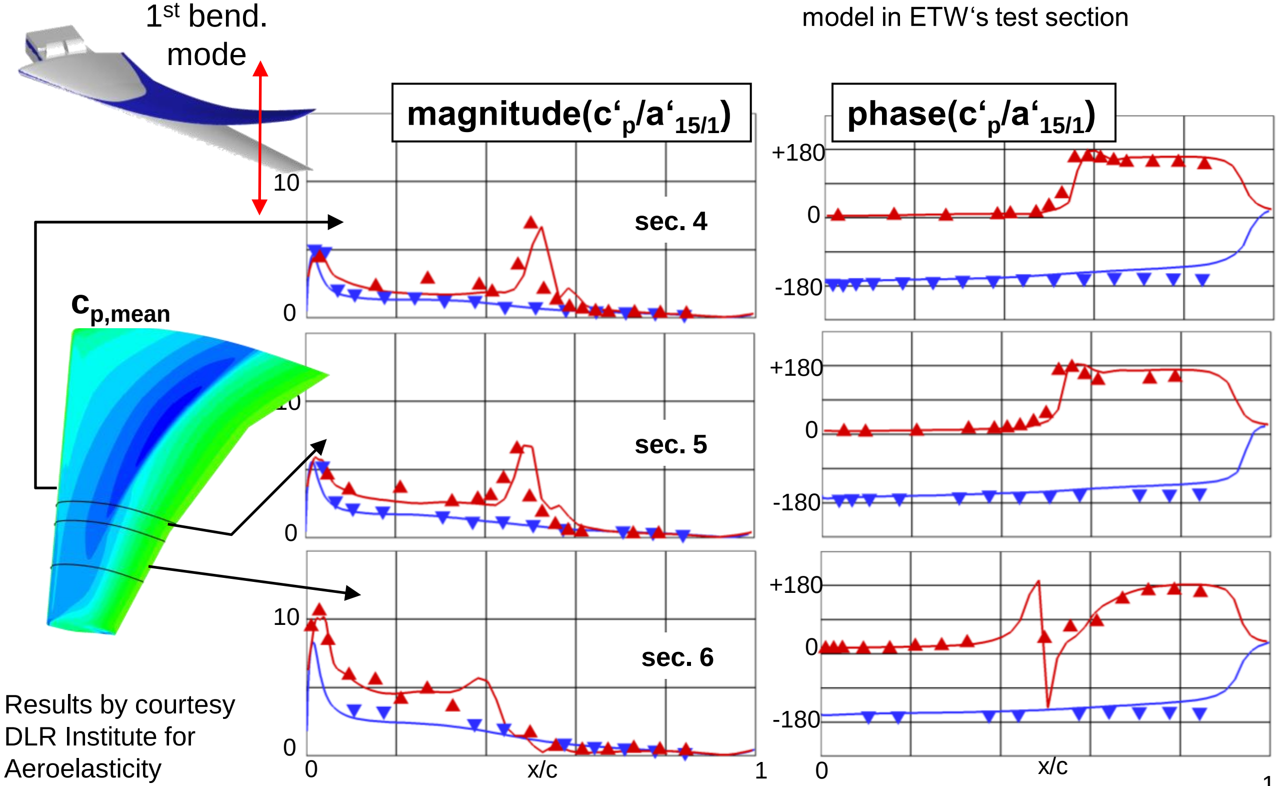


Example: HIRENASD configuration (AePW)

Test 143

- M=0.8, Re=7M, α=1.5°, f_{exc}=26.92Hz
- Excitation of 1st bending mode

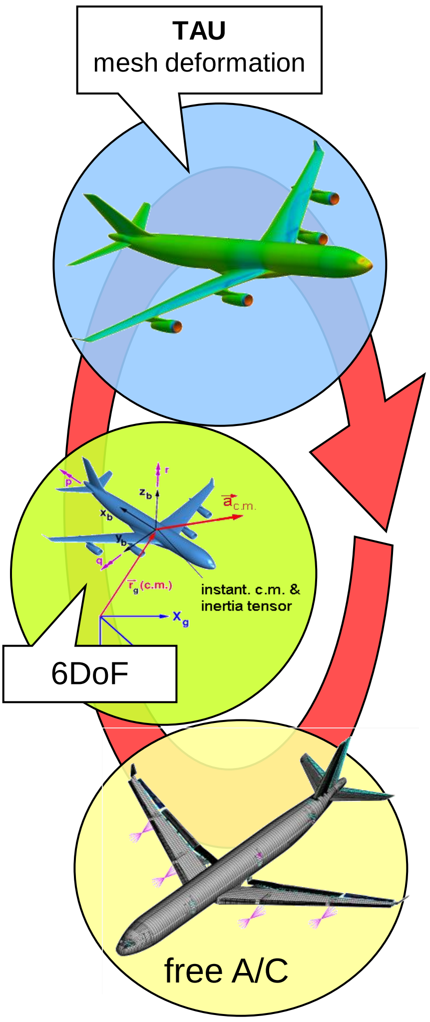




Results by courtesy DLR Institute for Aeroelasticity

DLR

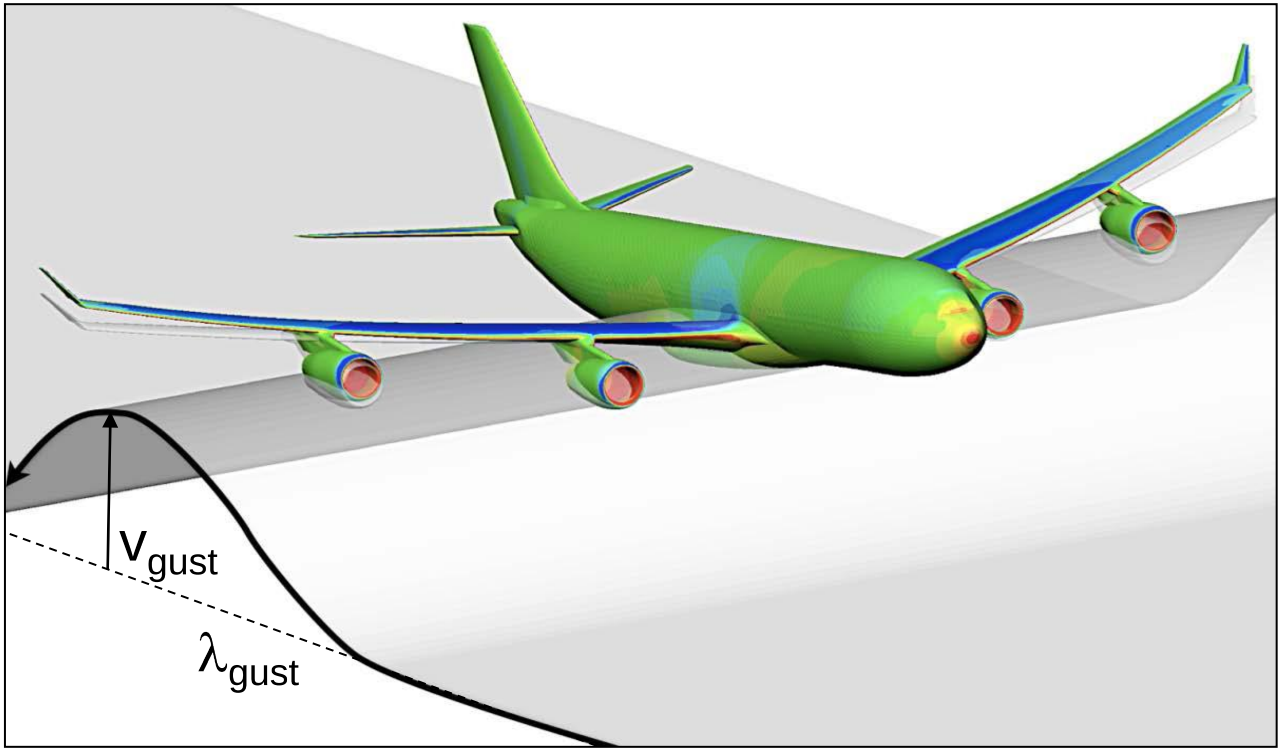
Steps Towards CFD-CSM-FM Coupling



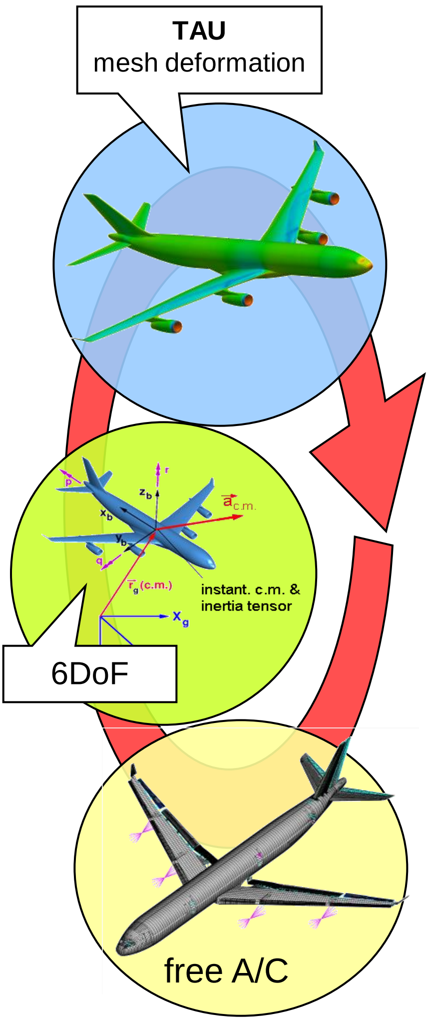
Unsteady example: Gust encounter of flexible A/C

M=0.82, Re=35.3M, m=195 t, λ_{gust}=60m, v_{gust}=15m/s

- Gust modeled via disturbance velocity approach
- Coupling to flight mechanics (6DoF)
- Coupling to structure

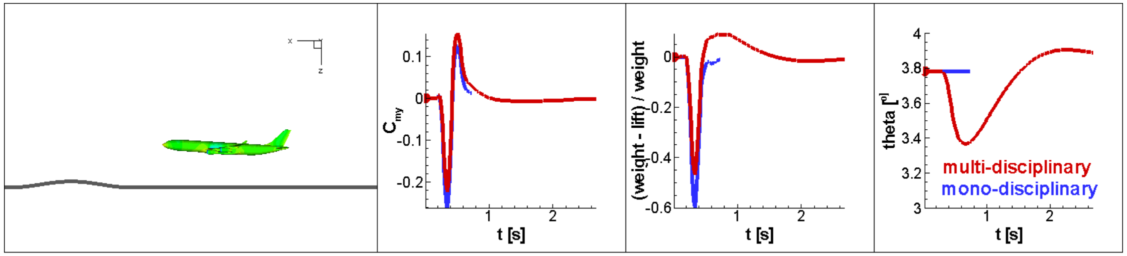


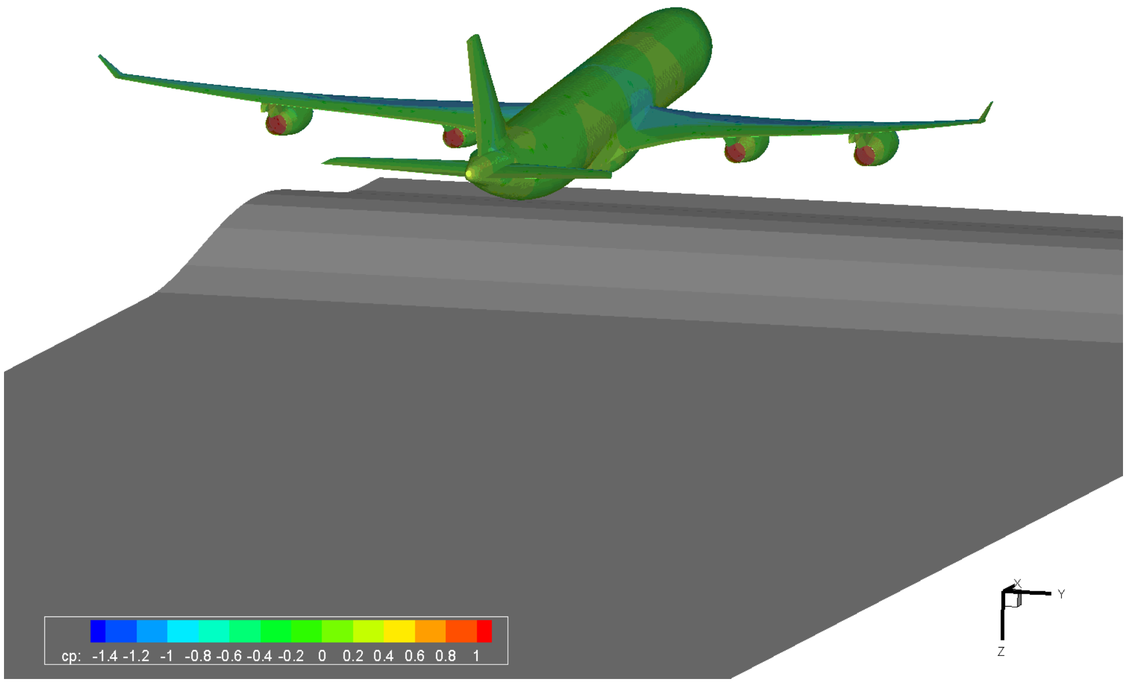
Steps Towards CFD-CSM-FM Coupling



Unsteady example: Gust encounter of flexible A/C (structure; quasi steady)

M=0.82, Re=35.3M, m=195 t, λ_{gust}=60m, v_{gust}=15m/s

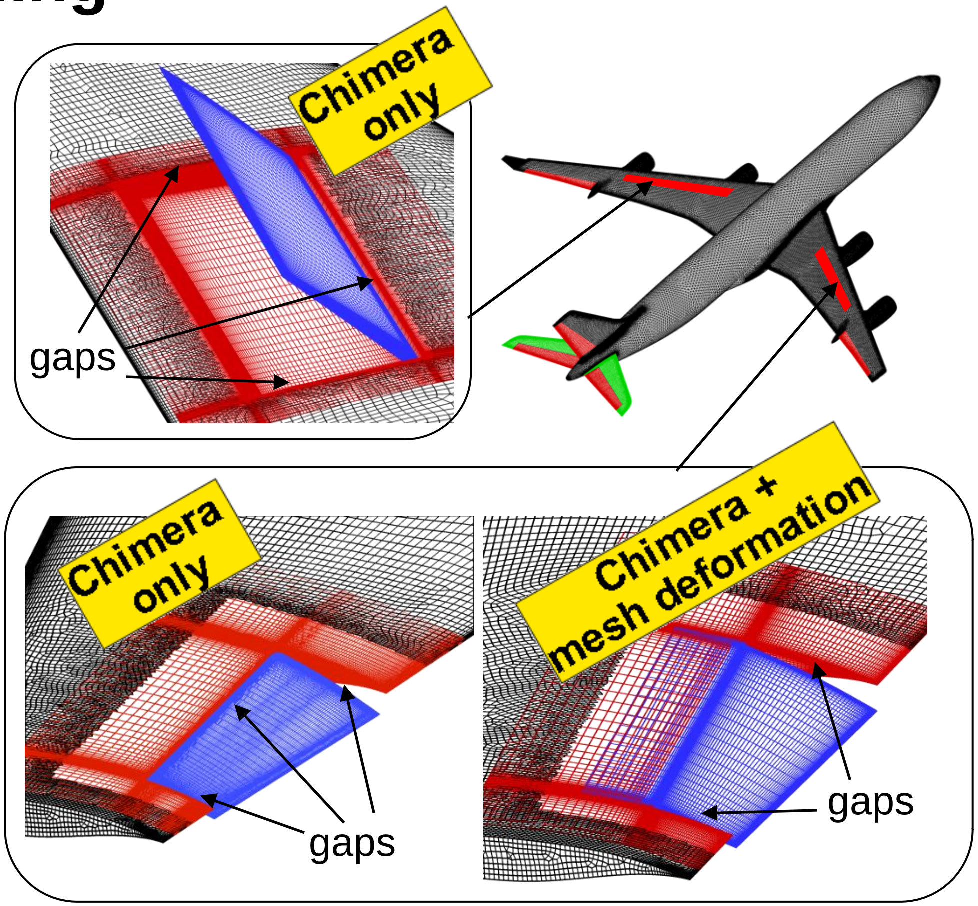




Control Surface (CS) Modeling

Challenge: Moving control surfaces

- Handling of gaps
  - Mesh deformation: small deflections
  - Chimera: waste of grid points for overlap
- Automatisms for CS set-up
- Solver robustness
- Flexible A/C configurations



Approach

- Combination of Chimera and mesh deformation
- Improvement of CFD solver with respect to Chimera applications (hole cutting, interpolation techniques, set-up)
- Investment in sliding interface technique

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Gust Modeling / Wake vortex Convection

Challenge

- Realistic gust modeling
- Accurate prediction of gust convection or wake vortices

Approach

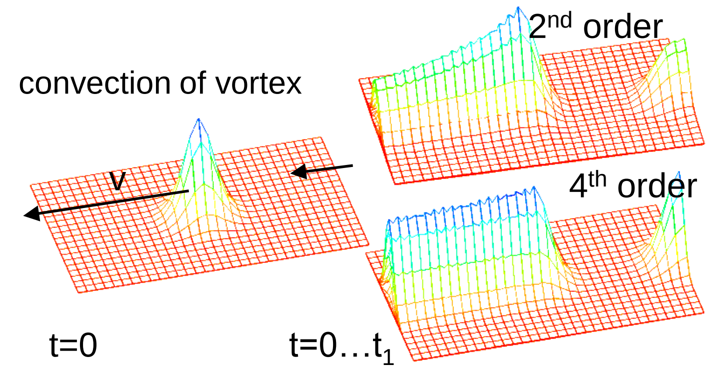
- Coupling of higher-order Cartesian solver (CTAU) to 2^{nd}-order baseline TAU solver

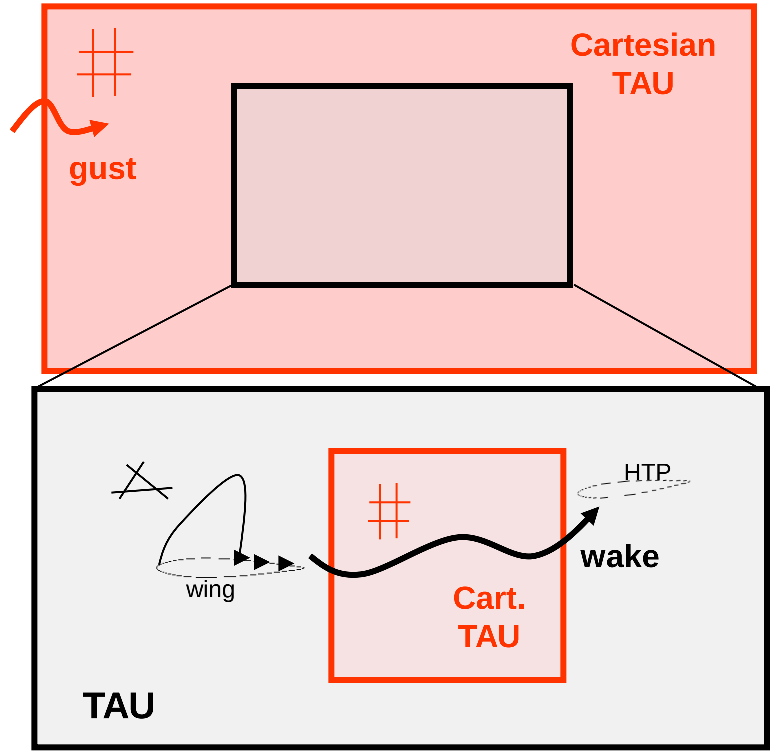
Cartesian TAU

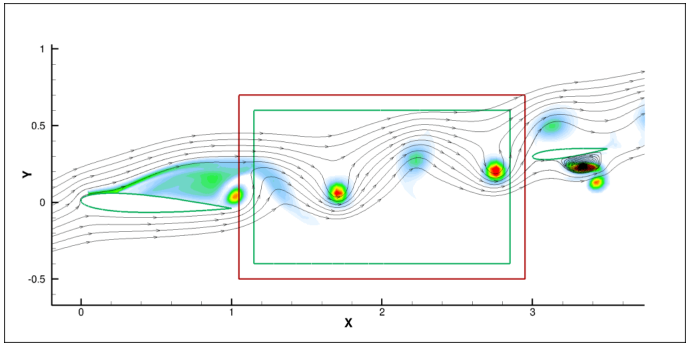
- Off-body solver based on TAU data structure
- Dedicated to Cartesian meshes
- $\geq 4^{th}$-order in space (PADE scheme)

Code-to-code coupling

- Chimera-like volume interpolation

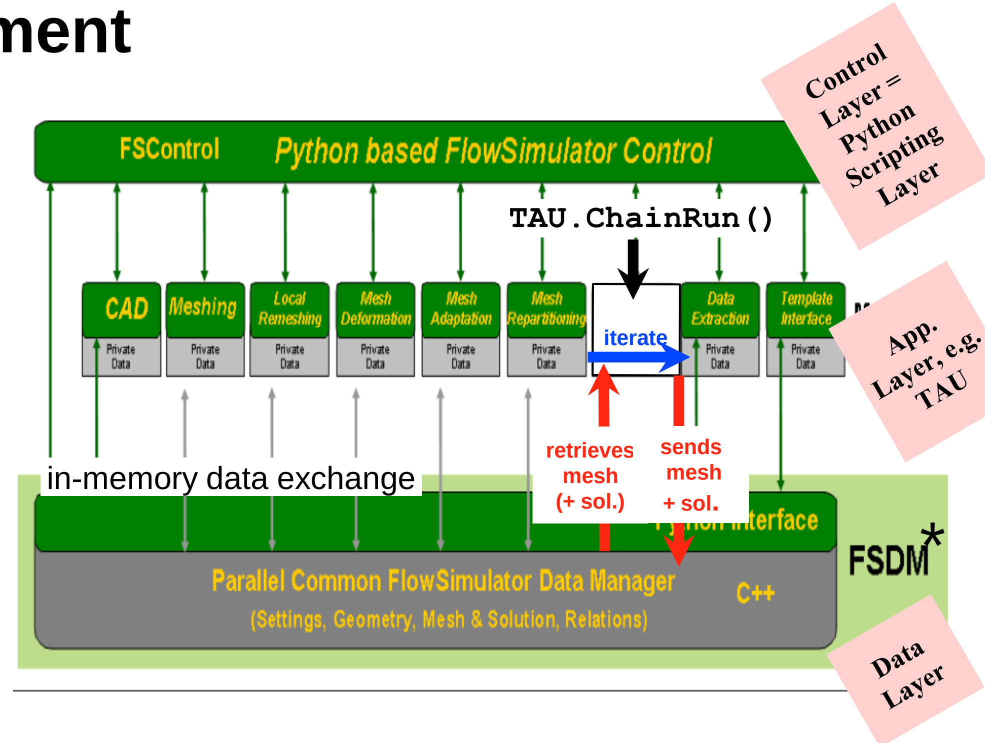






Parallel Simulation Environment

FlowSimulator

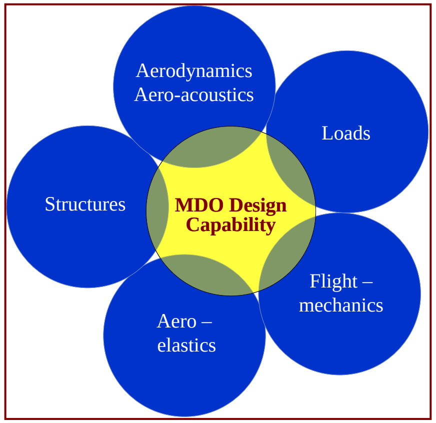


Objective: Working horse for multi-disciplinary simulations

- Kernel jointly developed by Airbus, Cassidian, **DLR**, ONERA, universities, …
- Designed for efficient massively-parallel in-memory data exchange
- Data exchange via common parallel data structure (FSDM)
  - Easy interchangeability of process chain components
- Python-based scripting layer enables rapid prototyping of tool chains

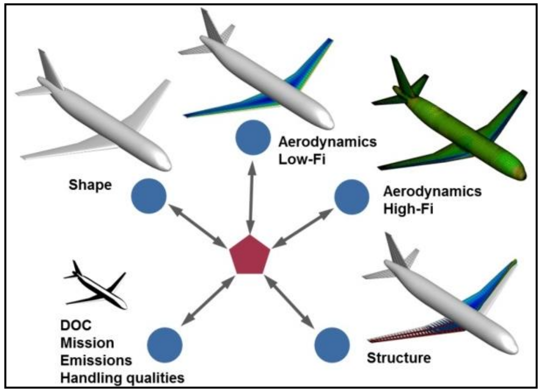
*open source: visit http://dev.as.dlr.de/gf

Multi-Disciplinary Optimization



Current status

- Overall aircraft design capability based on low fidelity models
  - Development of a data model common for all disciplines CPACS - *Common Parametric Aircraft Configuration Scheme*
- Prototype aero/structural optimization using CFD



CEPACS

Main objective

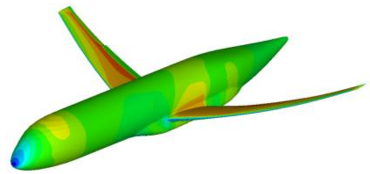
- Integrated high-fidelity aero/structural design platform

Challenges

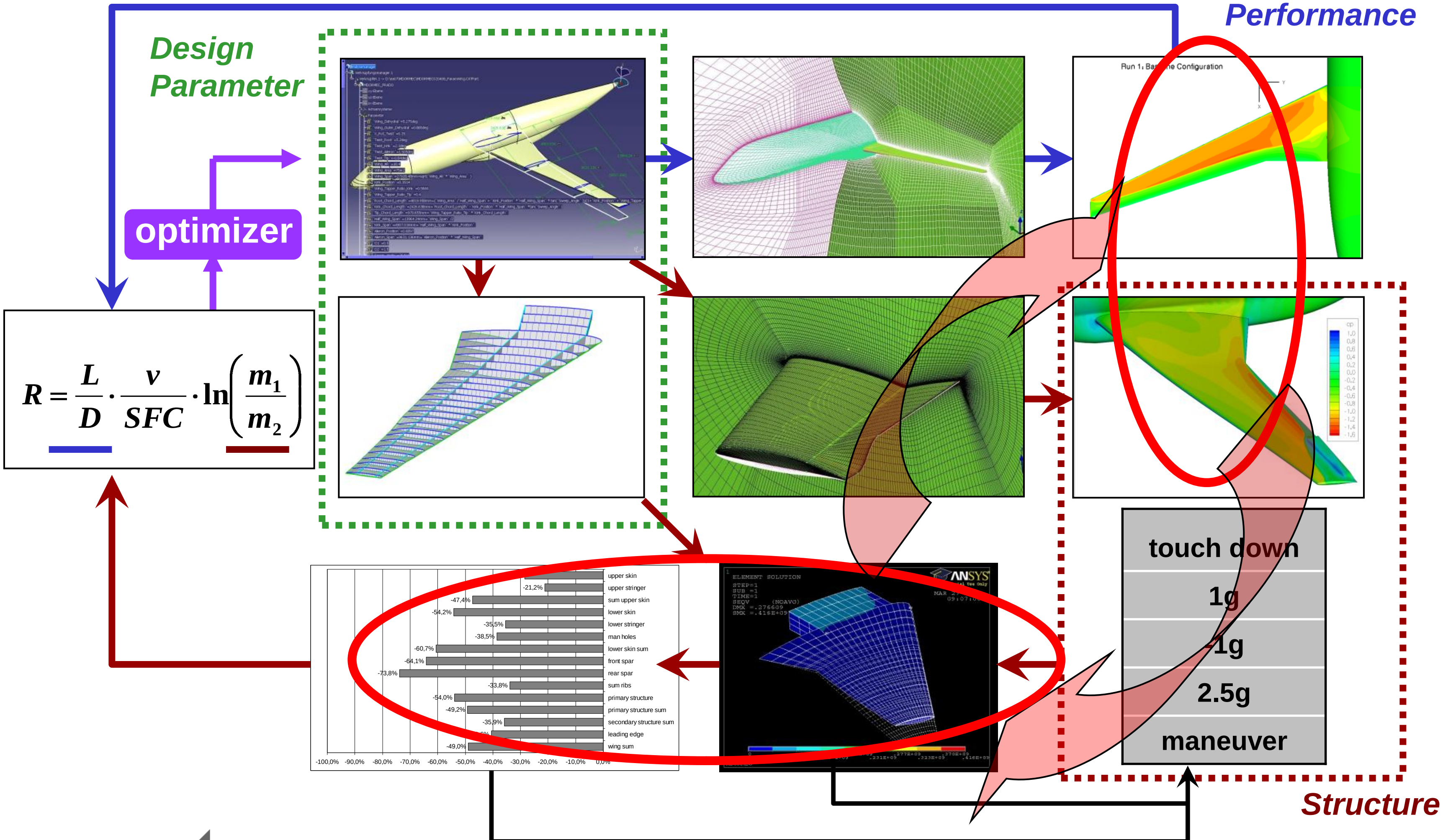
- Efficient multi-level fidelity MDO architecture, combining detailed & overall A/C design capabilities
- Consistent A/C description (CEPACS) for all fidelity levels
- Mix of global (wing planform) & local (airfoil shape) parametrization
- Realistic load cases at appropriate level of fidelity
- Consistent hierarchical structure generator, structural sizing & optimization methods for metallic and composite materials

Multi-Disciplinary Optimization

Detailed Design



Status: Aero-Structural Wing Planform Optimization



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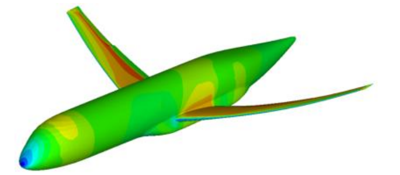
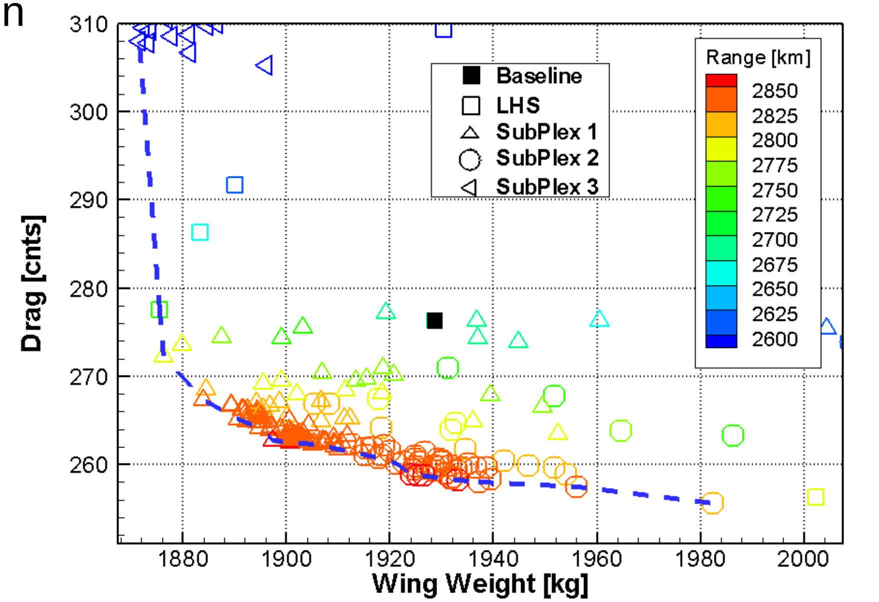
Multi-Disciplinary Optimization

Detailed Design



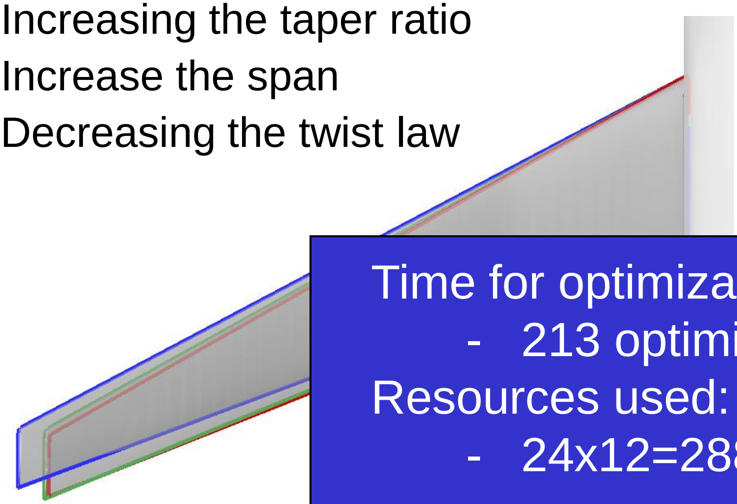
Status: Aero-Structural Wing Planform Optimization

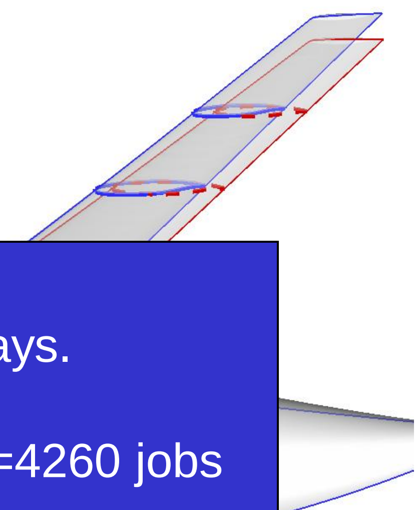
- 7 Design parameters
  - Aspect and taper ratios
  - Sweep angle
  - Twist at 4 sections
- Structure sizing
  - 27 Ribs, 2 Spars, Lower & Upper Shell
  - 4000 nodes



Result:

- Increase the range by 6%
  - Decreasing drag and weight
  - Increasing the taper ratio
  - Increase the span
  - Decreasing the twist law





Time for optimization:

- 213 optimization cycles ~36 days.

Resources used:

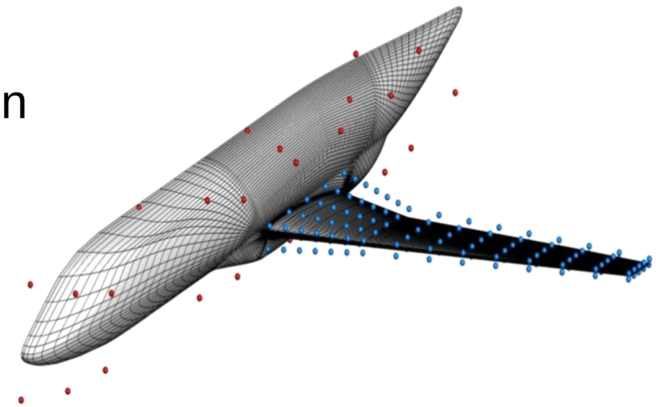
- 24x12=288 cores and 213x20=4260 jobs

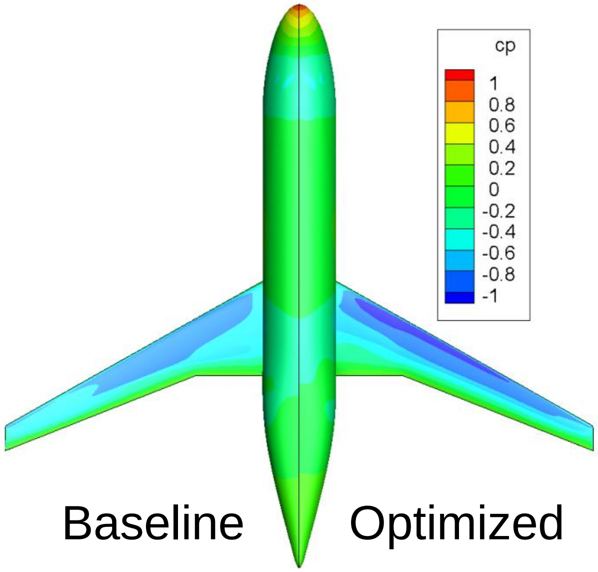
Multi-Disciplinary Optimization

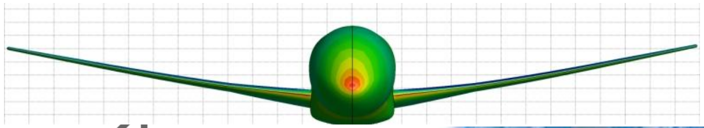
Fluid/Structure Coupled Adjoint for Detailed Design

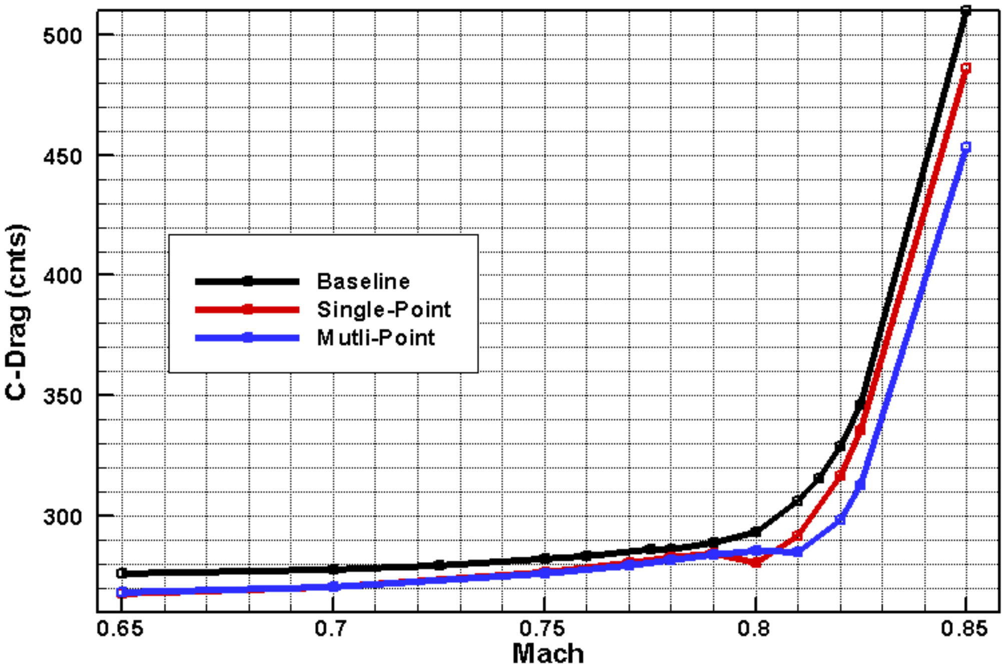
Discrete adjoint approach for efficient gradient evaluation

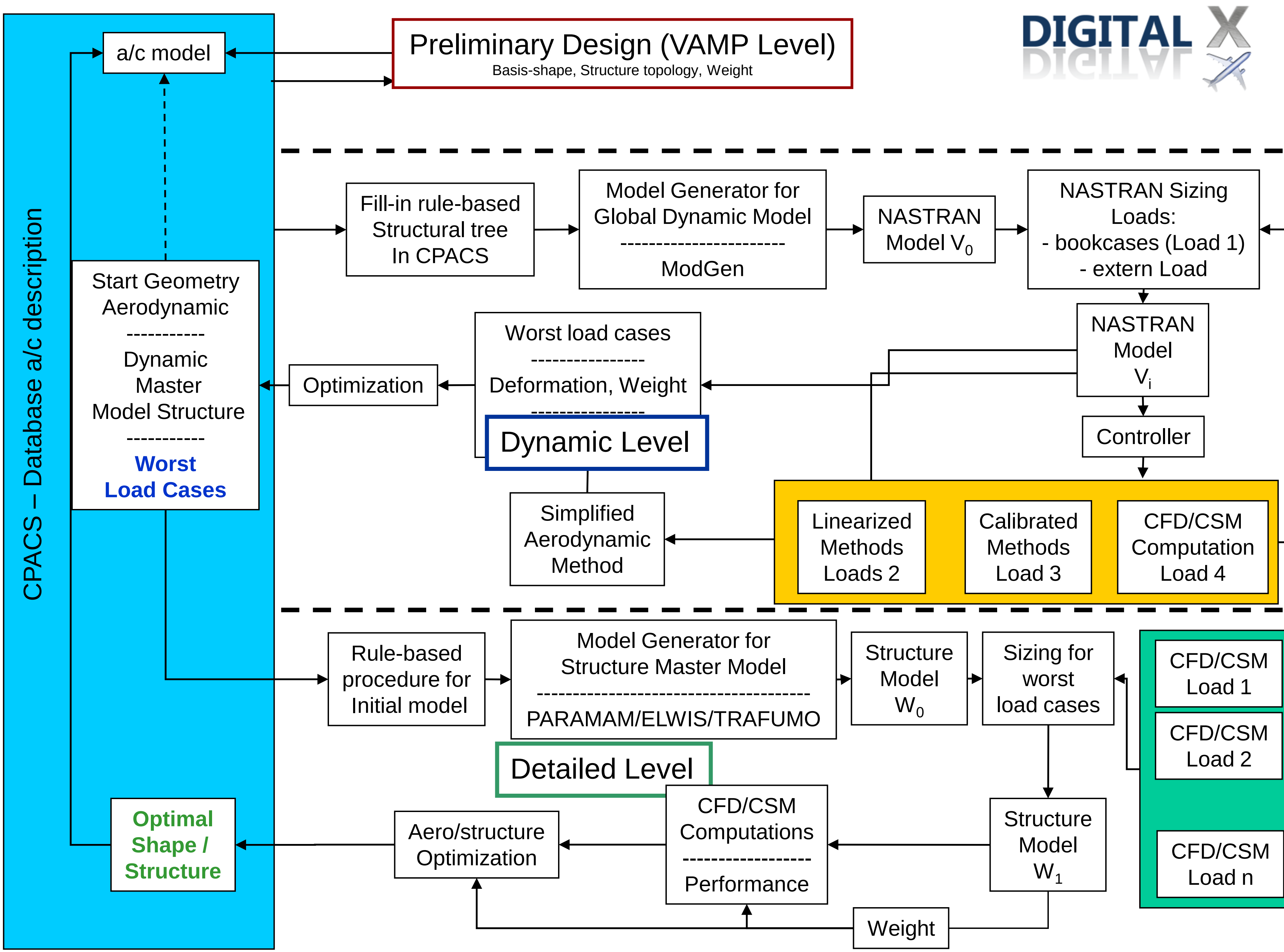
- Shape optimizations with 75 design variables
- Aero-elastic deformation considered
- Structure thickness considered as constant
- Single/Multi-point optimizations in viscous flows










DIGITAL X
CPACS – Database a/c description
a/c model
Preliminary Design (VAMP Level)
Basis-shape, Structure topology, Weight
Fill-in rule-based Structural tree In CPACS
Model Generator for Global Dynamic Model

ModGen
NASTRAN Model V_0
NASTRAN Sizing Loads:
- bookcases (Load 1)
- extern Load
Start Geometry Aerodynamic

Dynamic Master Model Structure

Worst Load Cases
Optimization
Worst load cases

Deformation, Weight

Dynamic Level
NASTRAN Model V_i
Controller
Simplified Aerodynamic Method
Linearized Methods Loads 2
Calibrated Methods Load 3
CFD/CSM Computation Load 4
Rule-based procedure for Initial model
Model Generator for Structure Master Model

PARAMAM/ELWIS/TRAFUMO
Structure Model W_0
Sizing for worst load cases
CFD/CSM Load 1
CFD/CSM Load 2
CFD/CSM Load n
Detailed Level
CFD/CSM Computations

Performance
Structure Model W_1
Aero/structure Optimization
Optimal Shape / Structure
Weight

Summary

- Digital Aircraft / Digital Product – DLR perspective for numerical simulation (long term vision)
  - Focus of numerical simulation activity at DLR
- DLR project set up: 1st phase 2012-2015
  - Multi-disciplinary project
  - Main goal: **Prototype of integrated MDA/MDO high-fidelity based simulation platform**
  - CFD key enabler, but not the only ingredient
- Dedicated CFD improvements/enhancements
  - Physical modeling (RSM approach)
  - Exploitation of heterogeneous manycore HPC clusters
  - Improvement of solver efficiency & reliability
    - **Layout and prototype implementation of DLR Next Generation Solver**
- Grid generation of high quality grids is still an issue ……

Summary

Strategic networking to gain full advantage

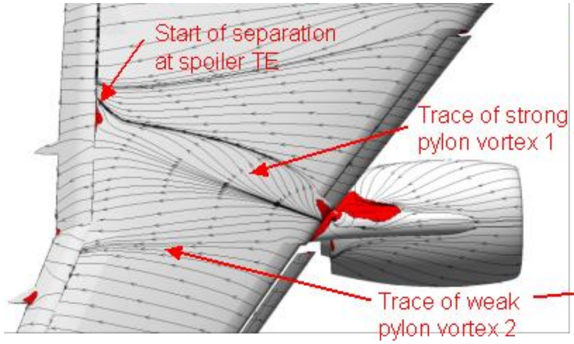
- Simulation — Supercomputing
- Validation — Dedicated Windtunnels
- Demonstration — Flight Test Capability

Example: HINVA (High Lift INflight Validation)

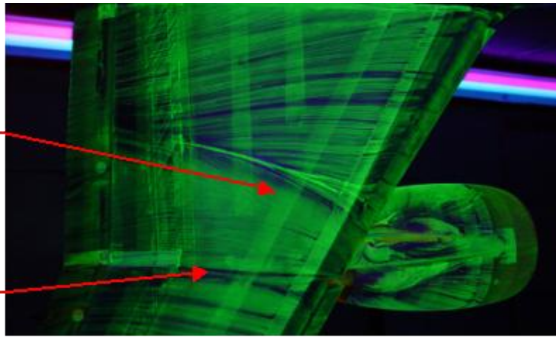
(Project within in the frame of the German Aeronautics Research Programme)

DLR A320-Flight Test A/C

CFD



ETW Windtunnel



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