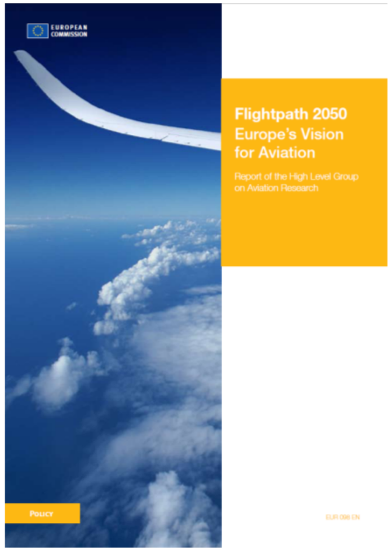
Digital-X

Towards Virtual Aircraft Design and Testing based on High-Fidelity Methods
- Recent Developments at DLR -

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

Prof. A. Jameson 80th
Symposium Mathematics, Computing & Design
– Where Analysis and Creativity Combine
20-21 Nov. 2014, Stanford, USA

Towards the Virtual Aircraft
Motivation & Strategic Objectives



Society: European Aviation Vision “Flightpath 2050” & Aeronautics Strategy Germany

- Environment: 75% CO_2, 90% NO_x, 65% noise
- Industrial Competiveness: innovation process from basic research to full-scale demonstrators

Industry:

- Robust & efficient design process with all disciplines
- More knowledge into processes

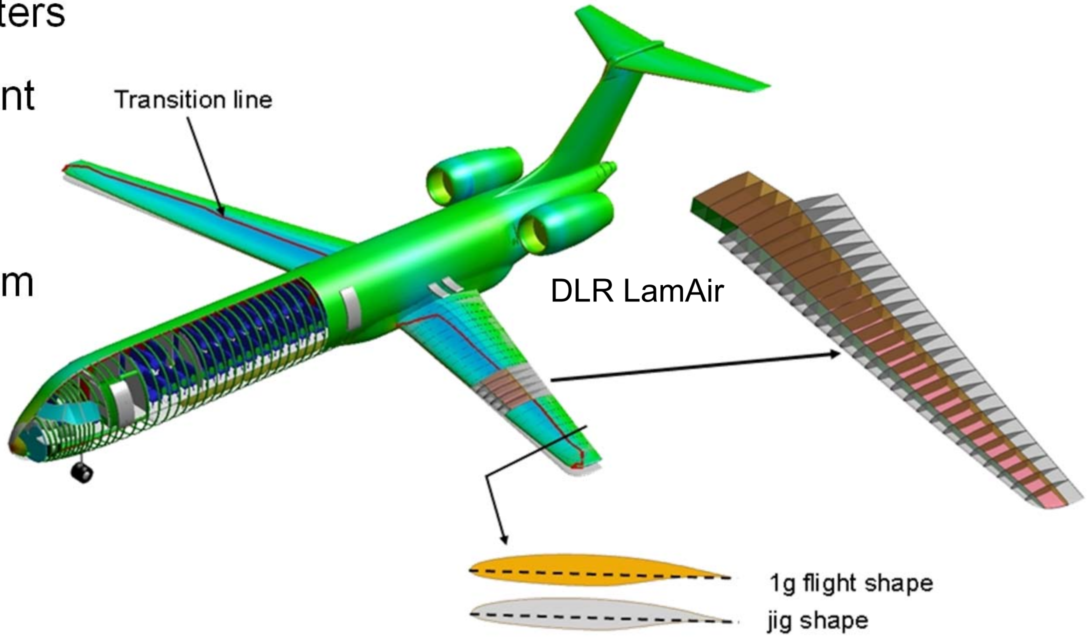
Need for DLR Virtual Aircraft Software Platform

- Support industrial and research activities in Germany
- Identify future options for HPC based aircraft design
- Simulate all Flight Physics aircraft properties relevant for design & certification
- Trade studies for technology evaluation
- Enhance and maintain aircraft design capabilities in DLR

Towards the Virtual Aircraft
Challenges & Capability Needs

Multi-Disciplines

- Link of preliminary overall aircraft and “detailed” MDA / MDO
- 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)

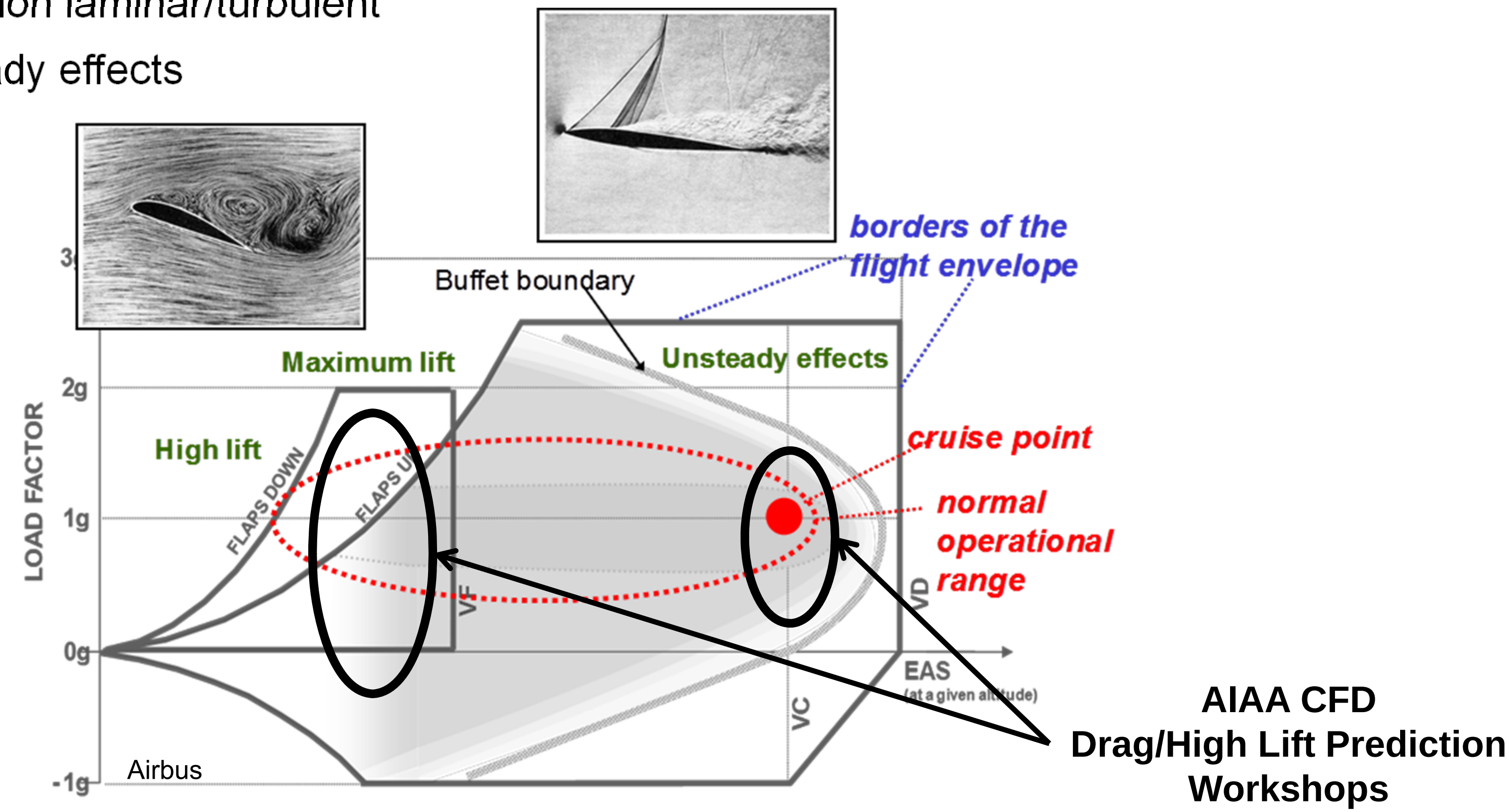


Towards the Virtual Aircraft
Challenges & Capability Needs

DIGITAL X

Aerodynamics

- Separated flows
- Transition laminar/turbulent
- Unsteady effects

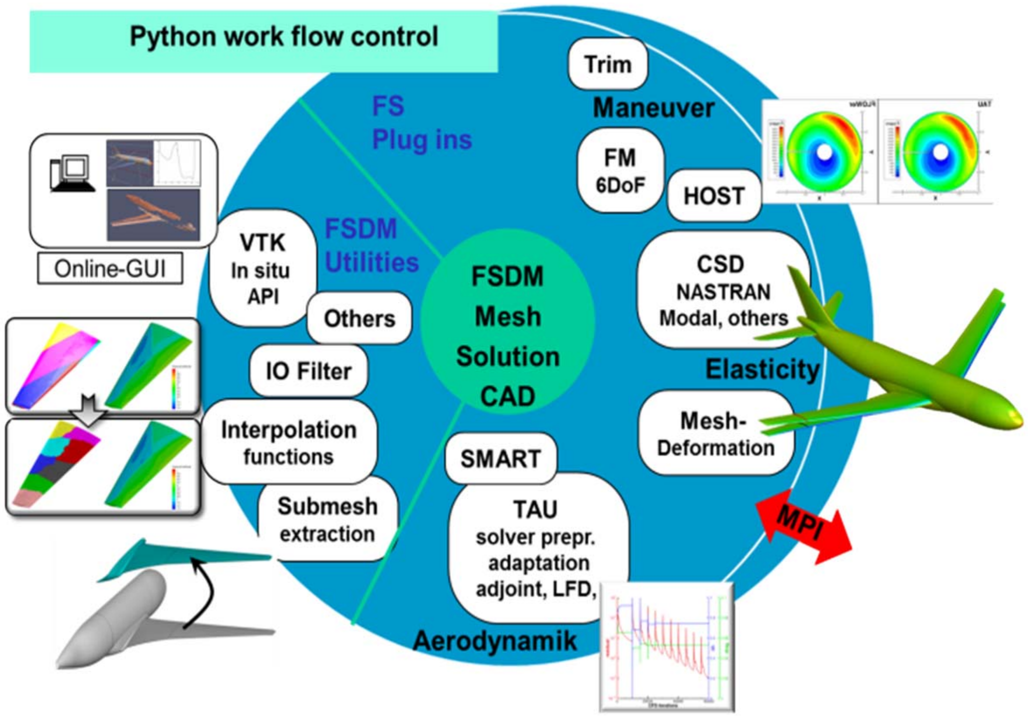


Grey gradient indicates level of confidence in CFD flow solutions

Towards the Virtual Aircraft
Challenges & Capability Needs

Software & Hardware

- Massively parallel computer hardware
- Workflow-management environment with “automatic” processes
- Consistent and comprehensive data formats



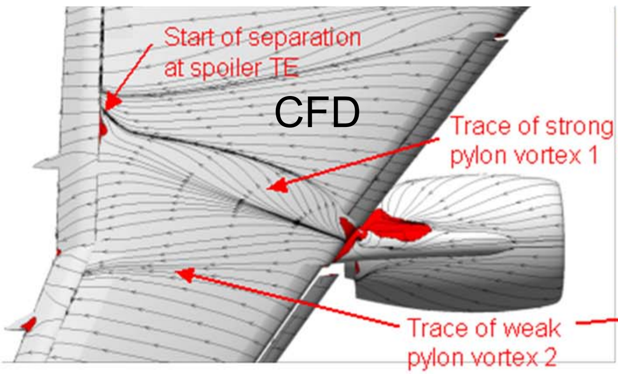
Towards the Virtual Aircraft
Verification & Validation Needs

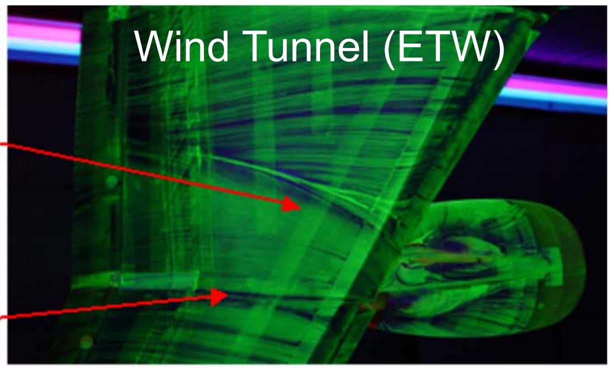
Reliable Multi-Disciplinary Simulation and Optimization require:

- Comprehensive verification & validation efforts

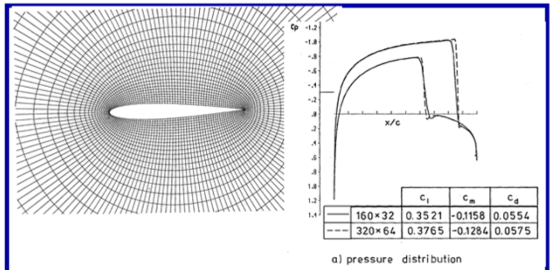
HINVA (High Lift Inflight Validation)

- German Aeronautics Research Program (LuFo) project
- 1st flight tests performed in August 2012 in Toulouse
- 2nd flight tests planned of end of 2014 in Braunschweig

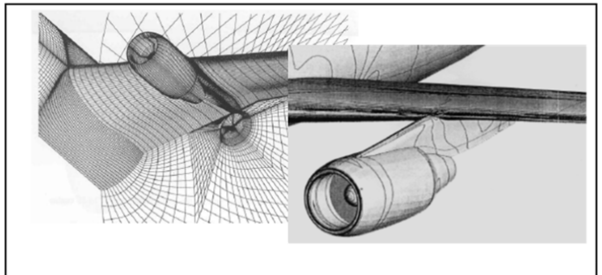




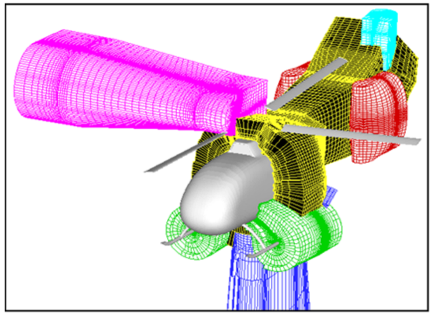
Previous Work
History



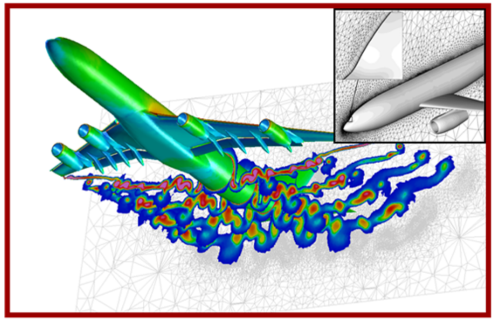
2D Euler Code (Jameson/Schmidt, 1982)



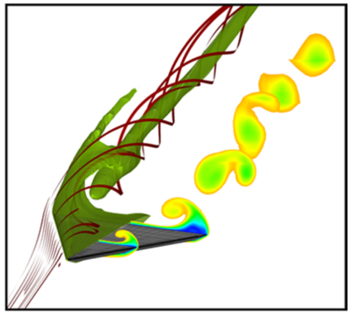
CEVCATS - block-structured RANS-Code, 1988



FLOWer - Code, since 1995



Hybrid TAU-Code, since 1998



PADGE – DG-Code, 2007

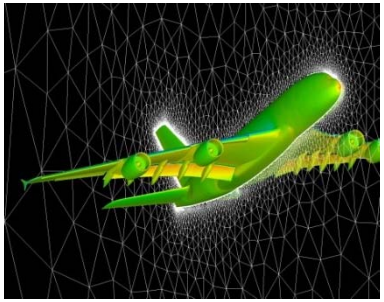
Next Generation Code

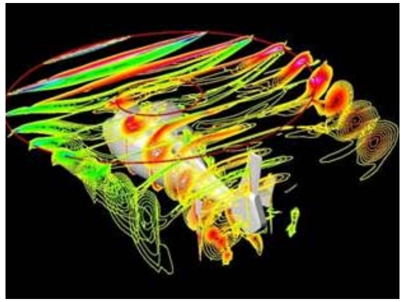
1982-1992	1993-1996	1996-1998	2000 - 2002	2003-2007	2007-2010	2009-2012	2012-2015
Cevcats Code	POPINDA Consolidation, parallelization of CFD codes	MEGAFLOW I Structured solve FLOWer	MEGAFLOW II Hybrid solver TAU	MEGADESIGN TAU, shape optimization	MUNA I CFD uncertainties	MUNA II CFD uncertainties	AeroStruct Integrate Flexibility in Design
				CHANCE II Complete helicopter	SHANEL I Advanced helicopter simulation	ComFliTe Computational Flight Testing	Digital-X

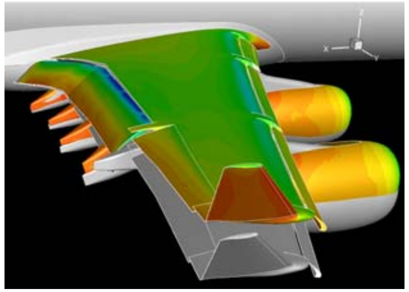
Previous Work
TAU CFD Solver

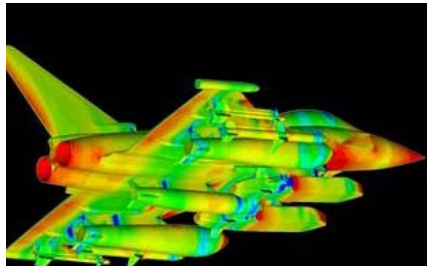
Reynolds-averaged Navier Stokes Code

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



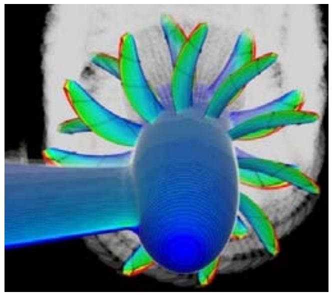


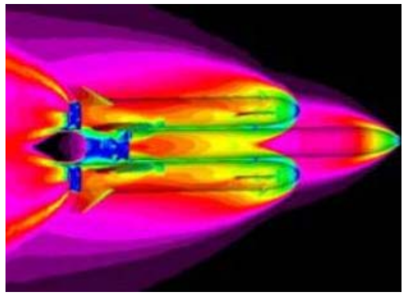




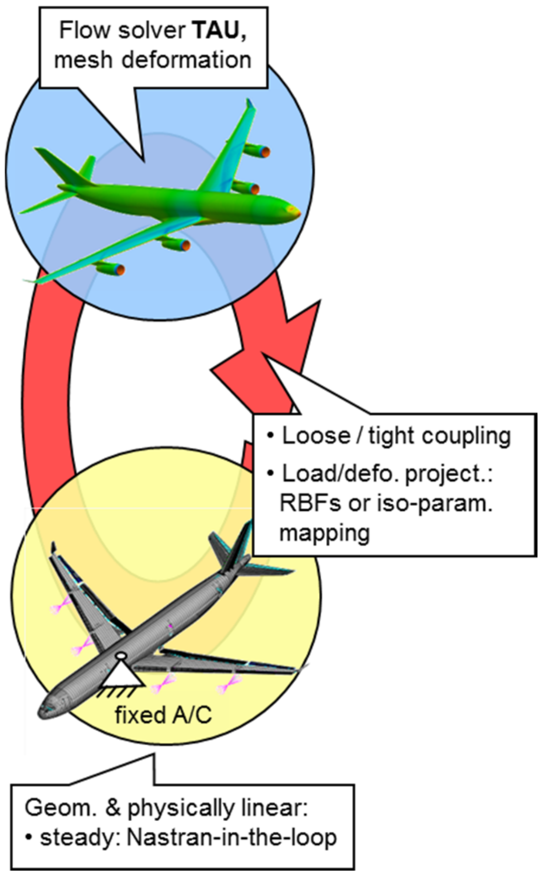
Courtesy: Airbus D&S

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





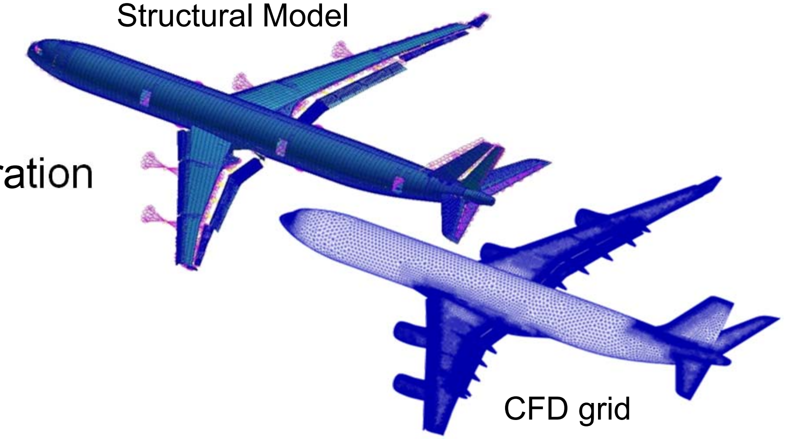
Previous Work
CFD-CSM Coupling

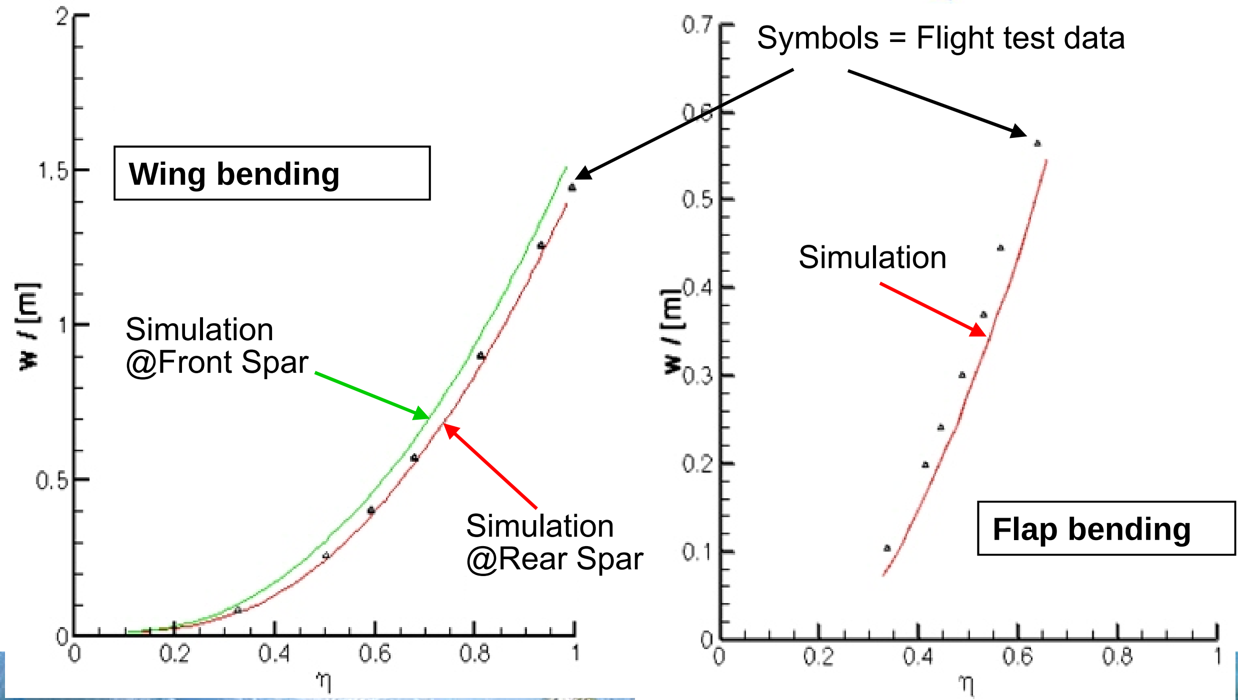


Flight test of high lift configuration

Ma=0.204, Re=~25M, α = 10°

- Trimmed aircraft
- Nastran-in-the-loop

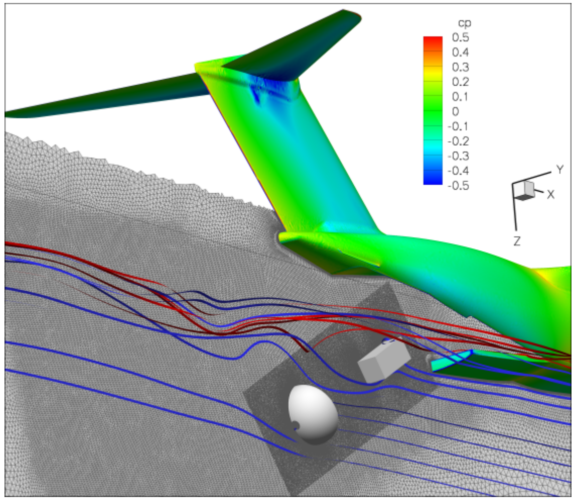


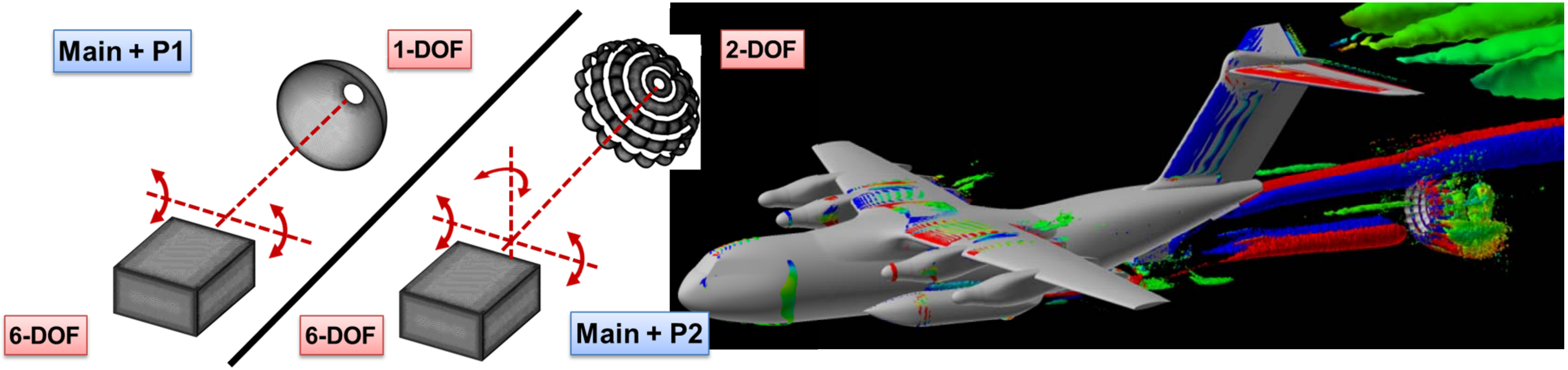


Previous Work
CFD-FM Coupling

Air Drop

- Time-consuming certification process of new airdrop systems or loads (costs/risks)
- Generic, blunt cargo bodies and parachutes
- Aircraft wake characterized by strong vortices
- Relative motion of cargo and parachute
  → coupling with multi-body simulation
- Experimental validation in wind tunnel

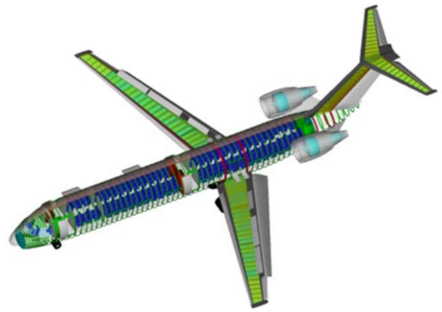


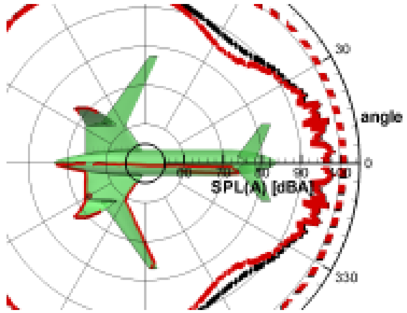


Previous Work
Aerodynamic/Multidisciplinary Design & Optimization

Preliminary Aircraft Design

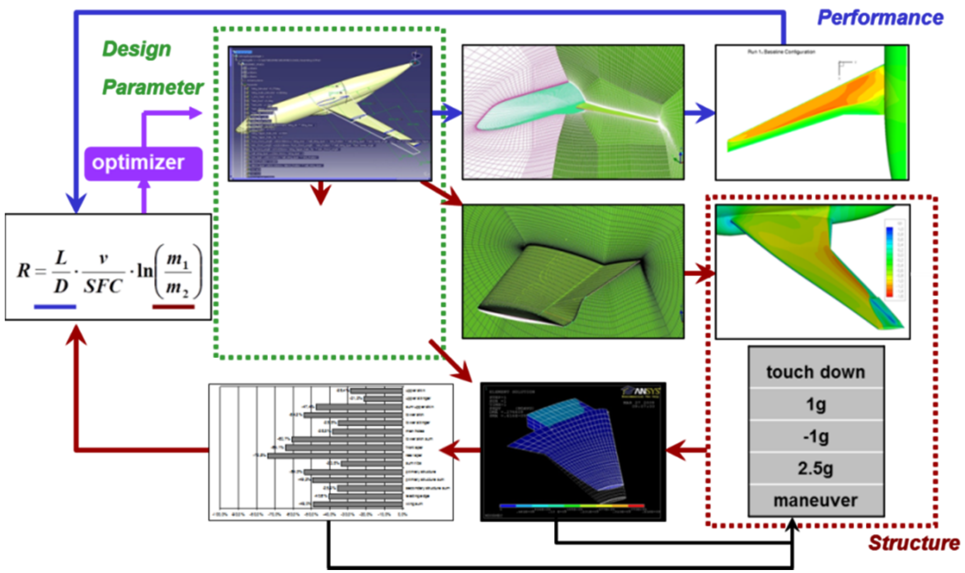
- Development of a system for preliminary aircraft design, CPACS





RANS-based Design & Optimization

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



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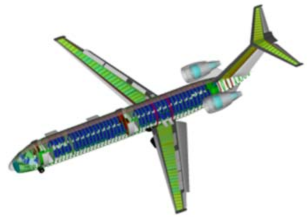

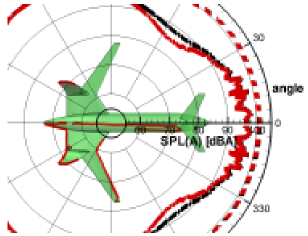

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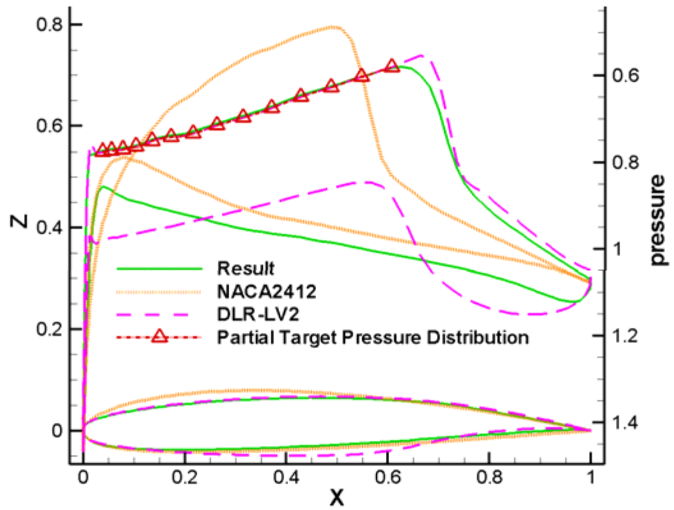
- Gradient-based:
  - 1st adjoint code bought from Prof. Jameson ca. 2000
  - Flower adjoint developments (discr.)
  - Development of adjoint in TAU (discr.) ca. 2004
  - Laminar airfoils:
    C_p on upper side & C_D min. @ C_L=const



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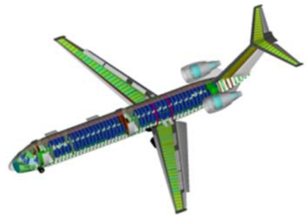

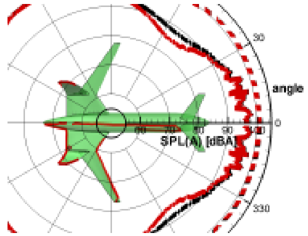

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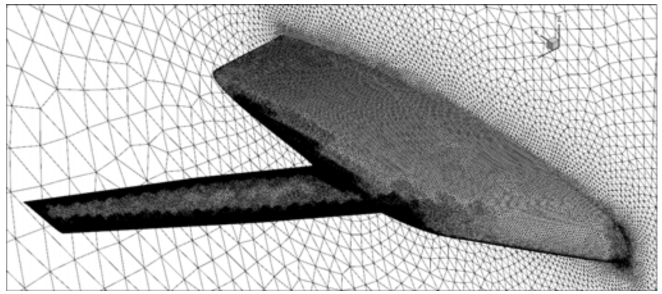
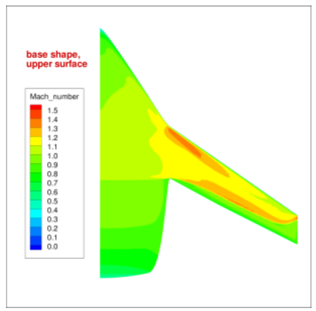
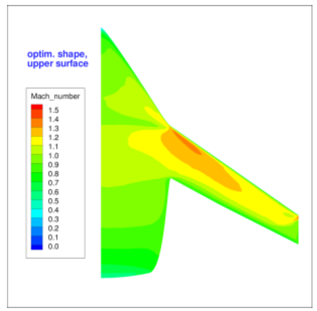
  - BWB optimization, 110k param., Euler, 2011







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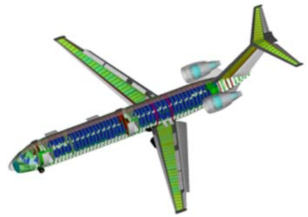

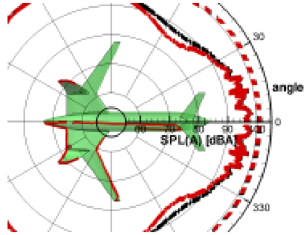

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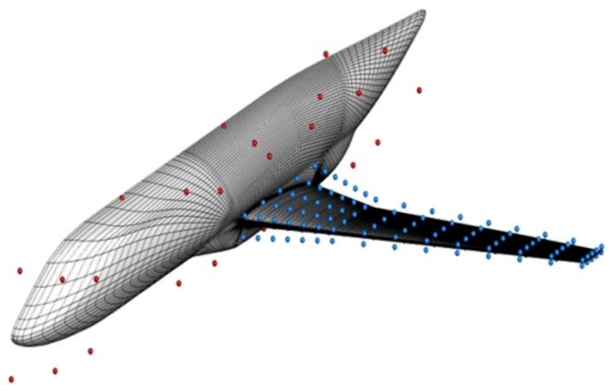
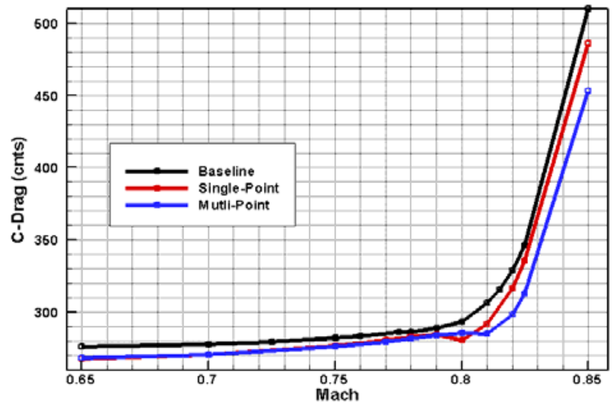
    C_p on upper side & C_D min. @ C_L=const
  - BWB optimization, 110k param., Euler, 2011
  - Multipoint shape optimization, 75 param., 2011
  - Aero-elastic adjoint (RANS), deformation included
  - Structural thickness constant





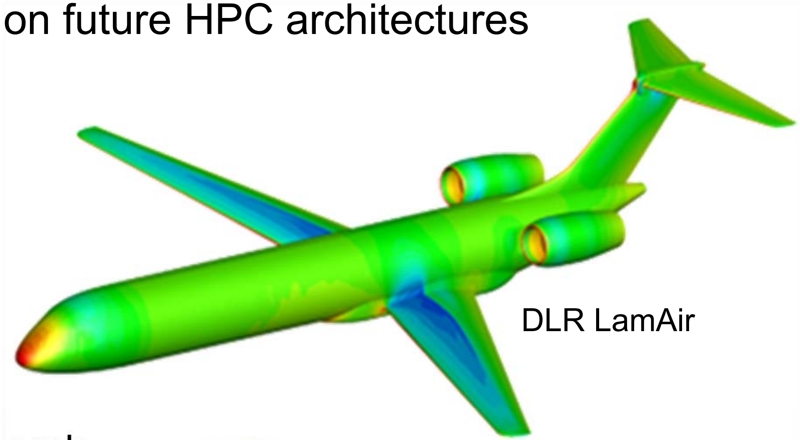
DLR Project Digital-X
Towards Virtual Aircraft Design and Flight Testing

Long Term

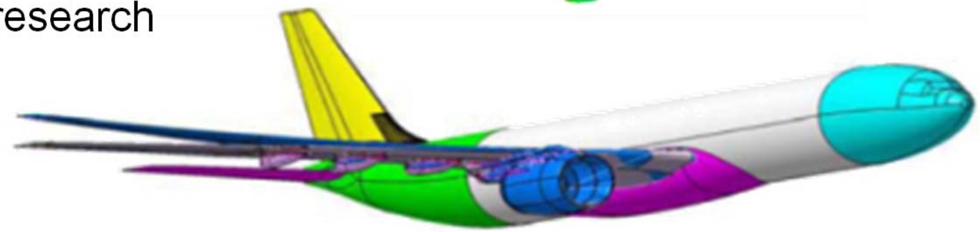
- Development of an integrated software platform for multidisciplinary analysis and optimization based on high-fidelity methods
  - Disciplines: aerodynamics, structures, flight mechanics & control
- Development of a next generation CFD solver with innovative solution algorithms and high parallel performance on future HPC architectures

Short Term (2015)

- Realistic maneuver simulations
- Integrated aero/structural design
- Demonstration of new capabilities using configurations relevant for industry & research
- First release of next generation solver

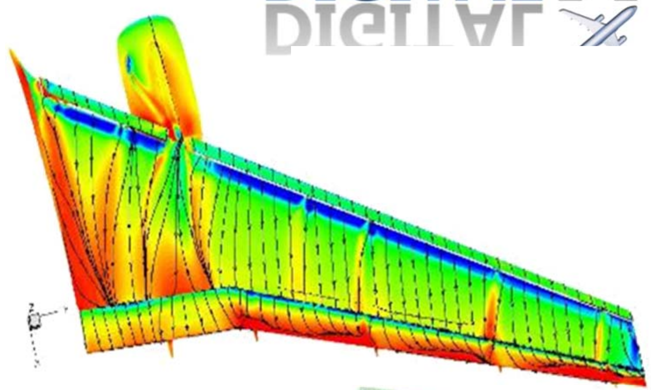


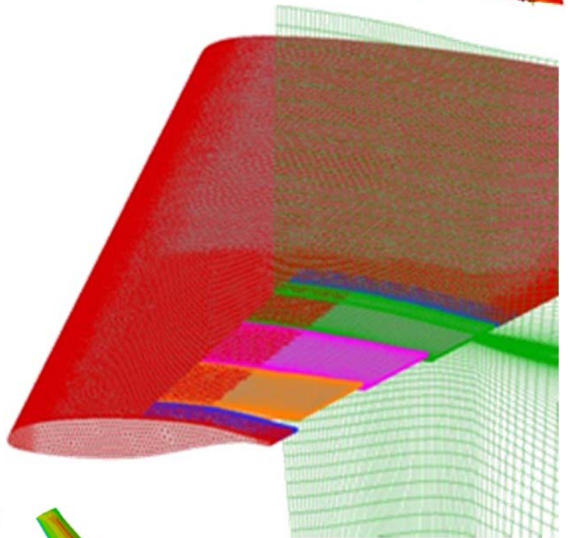
DLR LamAir

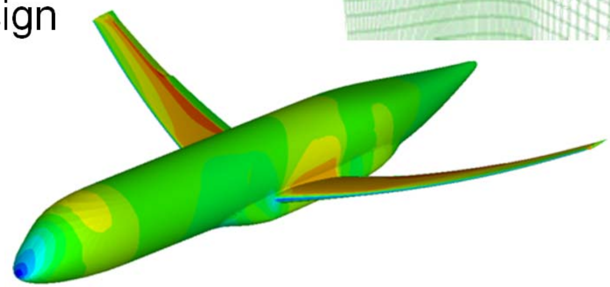


Airbus XRF-1

DLR Project Digital-X
Objectives 2015







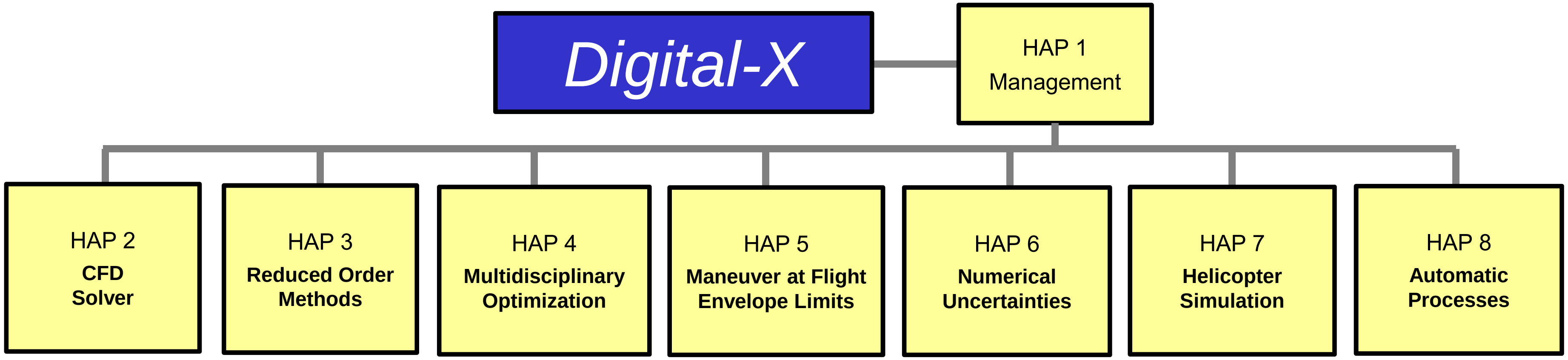
Simulations of the Flight Envelope
- Coupling of relevant disciplines
- Moving control surfaces
- Efficient prediction of static and dynamic loads

CFD Solver
- Improved modelling of physics
- Robust and efficient algorithms
- Software design of next generation solver (HPC)

Multi-Disciplinary Optimization
- Parametric representation of structure
- Identification of critical loads for structural sizing
- Planform and airfoil shape optimization
- Integrated process of preliminary and “detailed” design

Simulation Environment
- Integration of tools/methods into a single platform
- Efficient usage of HPC resources

DLR Project Digital-X
Content and Partner



DLR Institutes

- Aerodynamics and Flow Technology
- Aeroelasticity
- Propulsion Technology
- Structures and Design
- Composite Structures and Adaptive Systems
- Flight Systems
- Air Transportation Systems
- System Dynamics and Control
- Simulation and Software Technology

Partner / Links

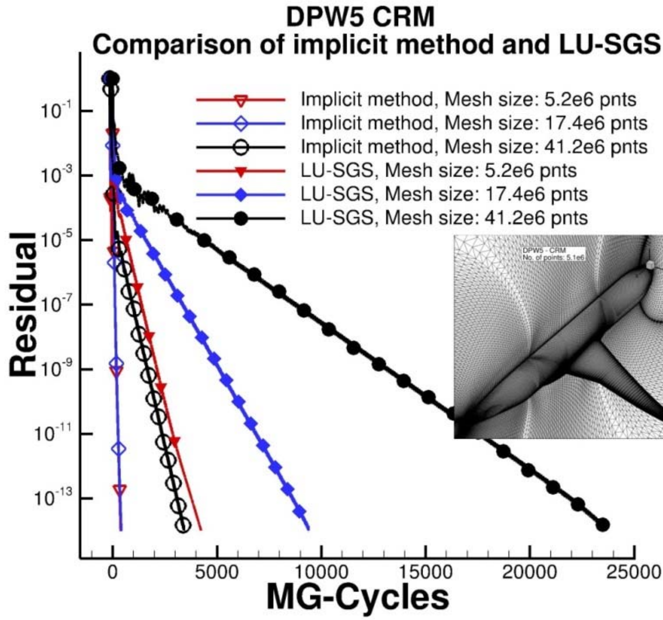
- Airbus
  - Industrial boundary conditions
  - Airbus research configuration XRF-1
  - Test of methods/processes
- Research Center Jülich
  - High Performance Computing
- Project AeroStrukt (universities)

Duration: 2/2012 – 12/2015
Efforts: 120 PY

DLR Project Digital-X
CFD Solver TAU

Improved Modelling of Physics

- Reynolds stress models (RSM)
  - As standard RANS method for all configurations
- Scale resolving simulations (SRS)
  - Targeted application for specific components of aircraft
- Transition prediction and modeling
  - Necessary for accurate results of turbulence models
- Turbulence modeling improvements
  - Targeted experimental investigations



Improved Robustness and Efficiency

- Agglomerated multigrid for complex applications
- Implicit algorithms (hierarchy of pre-cond.)
  - Integration of advanced turbulence models
- Adaptive local grid refinement
  - Best practice guide
- Adjoint solver for efficient sensitivity analysis

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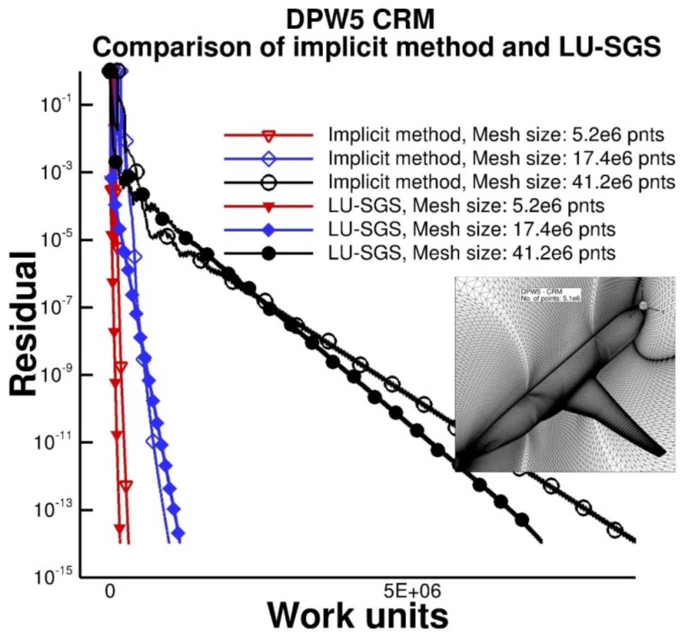

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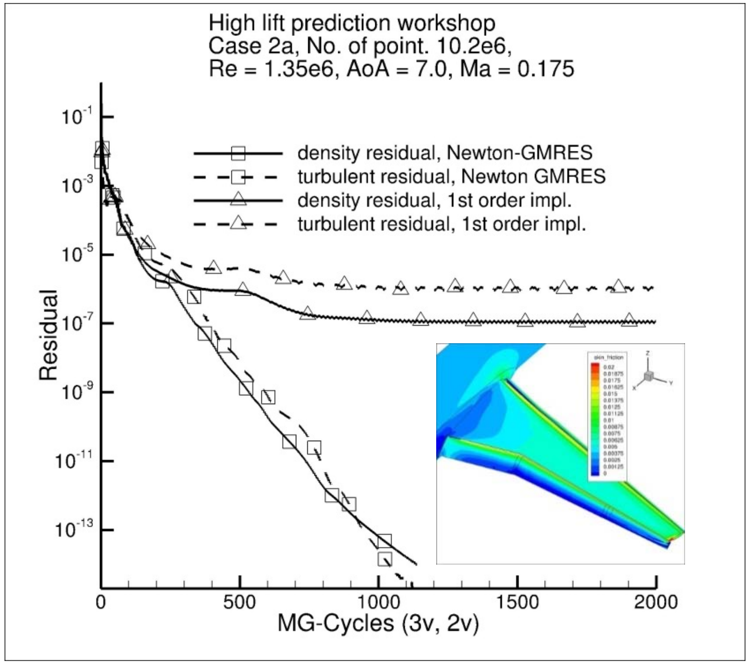

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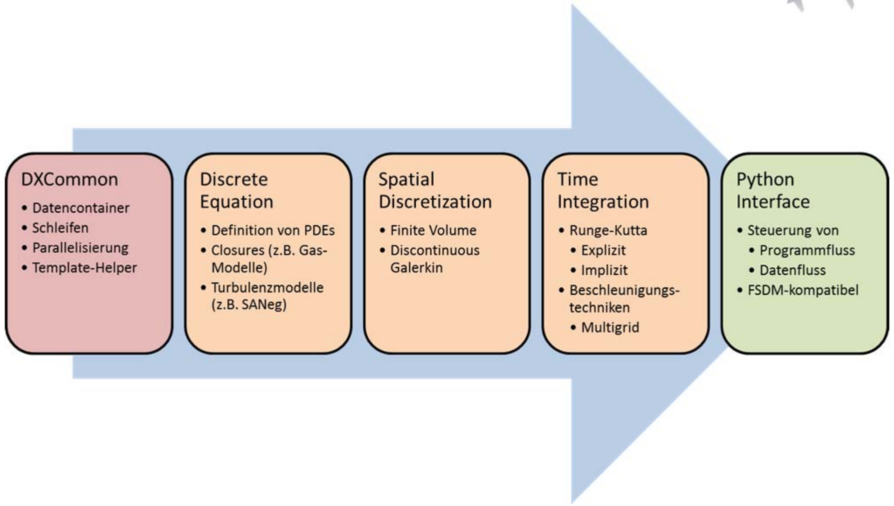
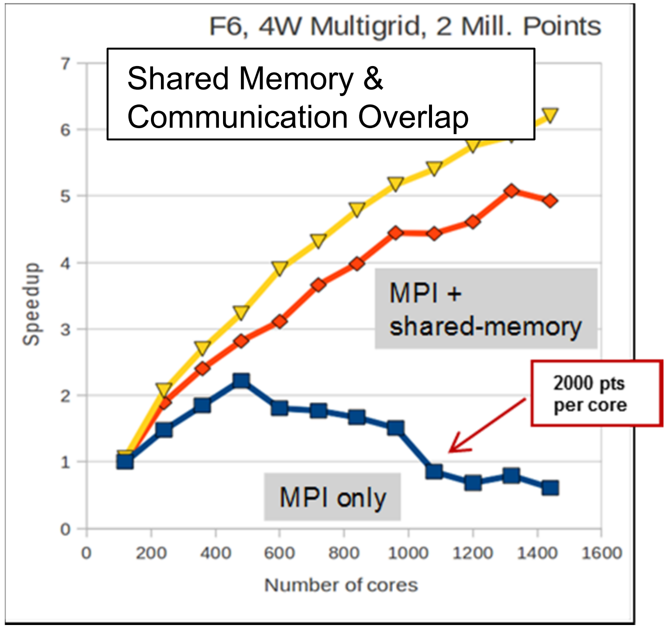
DLR Project Digital-X
Next Generation Solver

Future CFD

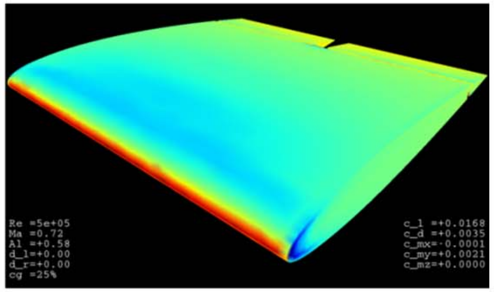
- Current TAU not sufficiently suited for strong scaling on future HPC
- Full exploitation of future HPC
- Consolidation of current DLR CFD solvers
- Basis for innovative algorithms & concepts, e.g. higher order finite element
- Integration into multidisciplinary simulation
- State-of-the-art software engineering methods, C++11, templates, multi-level parallelization





DLR Project Digital-X
Reduced Order Models

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

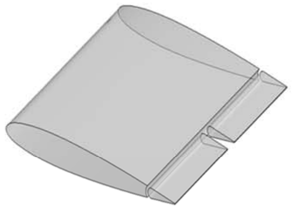


Motivation & Activities

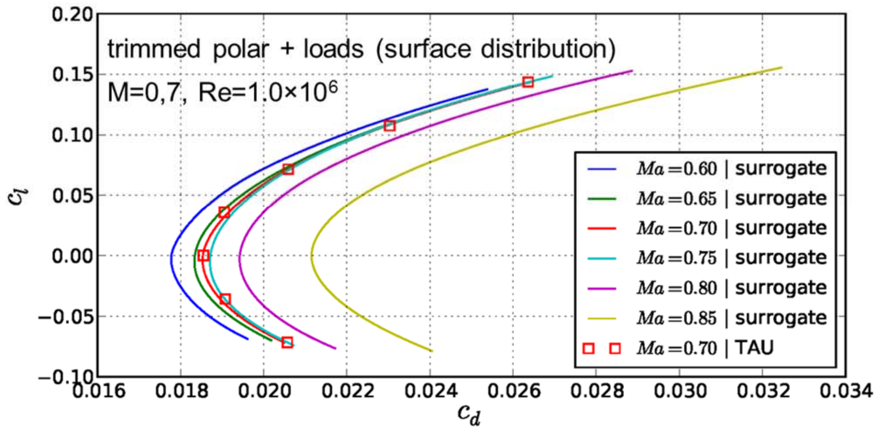
- Huge aero & aeroelasticity data required for aircraft loads analysis
- RANS computations for all cases of the flight envelope is still not feasible
- Development of parametric models for static & dynamic aero-loads prediction
- Development of correction methods for aeroelastic applications

ROM based on
1.960 CFD solutions
- 32 min per solution on a single compute core (Airbus)

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°



ROM for variation of:
- Mach number
- Center of gravity (cg)



Cost for	CFD - TAU	ROM
Model generation	-	74 h (**80 untrimmed** TAU simulations)
1 trimmed polar	47 h (7 points)	25 s (71 polar points.)
6 polar curves (cg=0.25)	≈282 h (42 points)	150 s (420 polar points)
+ 4 polar curves (M=0.7)	≈470 h (70 points)	250 s (710 polar points)

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MDA – Gust Loads

Objective

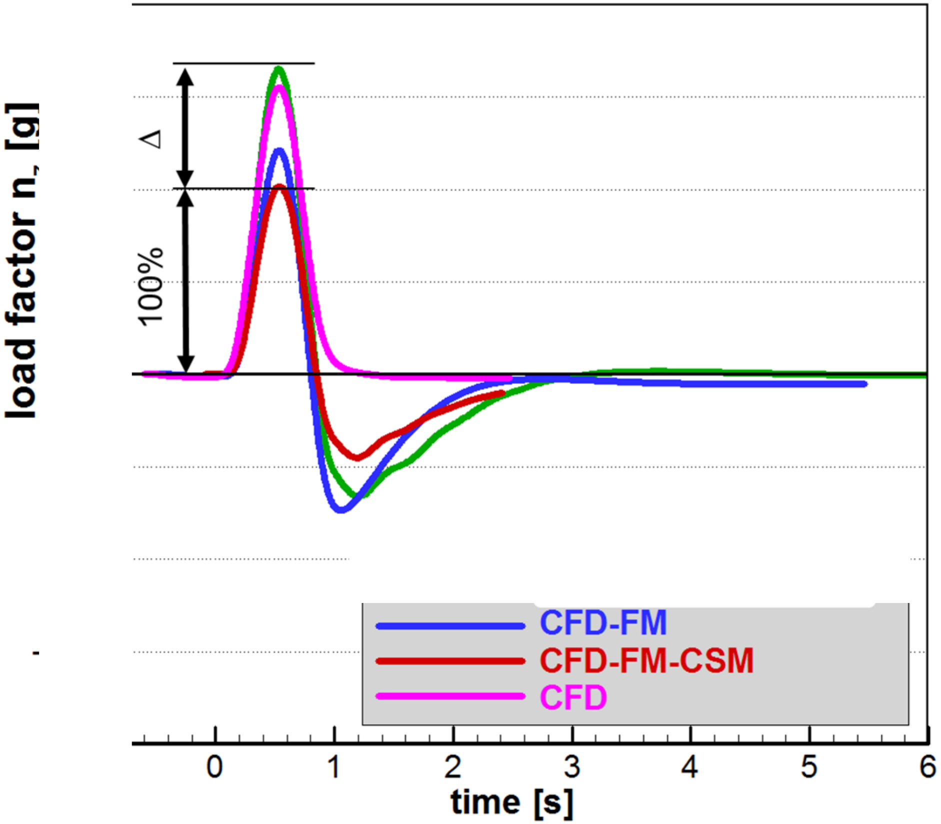
- Analysis of gust load based on different methods and coupled disciplines

Tasks

- Coupling of disciplines (CFD, CSM, FM)
- Integration of flight control
- Modelling / meshing of control surfaces
- Integration into parallel simulation backbone FlowSimulator

Need for High-Fidelity Simulations

- Potential for weight reduction?



- Ma = 0.8
- m = , Re = x 10^6 , H =
- λ_{gust} = 213.36 m, v_{gust} = 10.52 m/s

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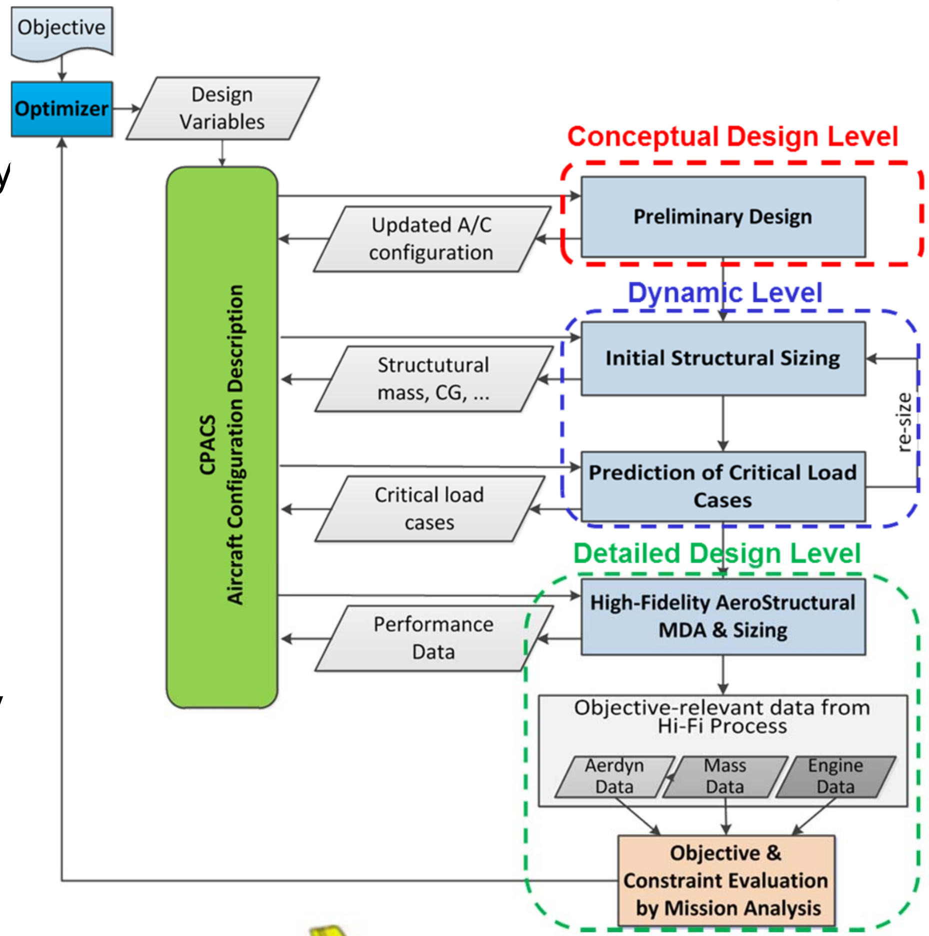
MDO

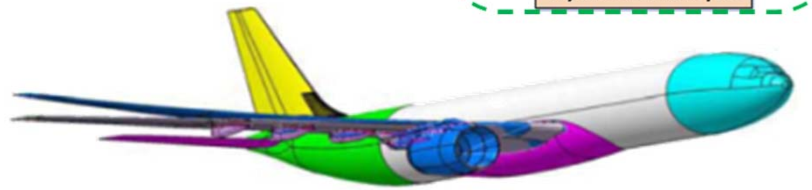
Objective

- MDO of full aircraft based on multi-fidelity

Method

- Low fidelity methods for preliminary design
- Fast methods for identification of critical load cases
- RANS methods for aerodynamics and structures for selected load cases
- Parallel software platform for high-fidelity
- Interactive workflow management
- Demonstration case: Airbus XRF-1





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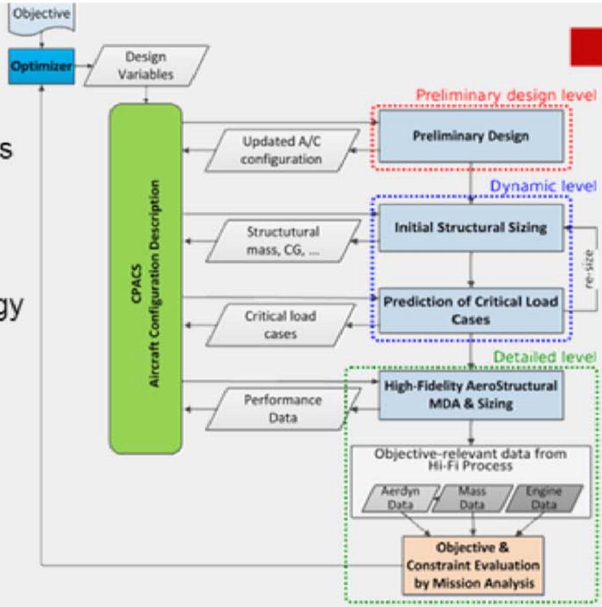
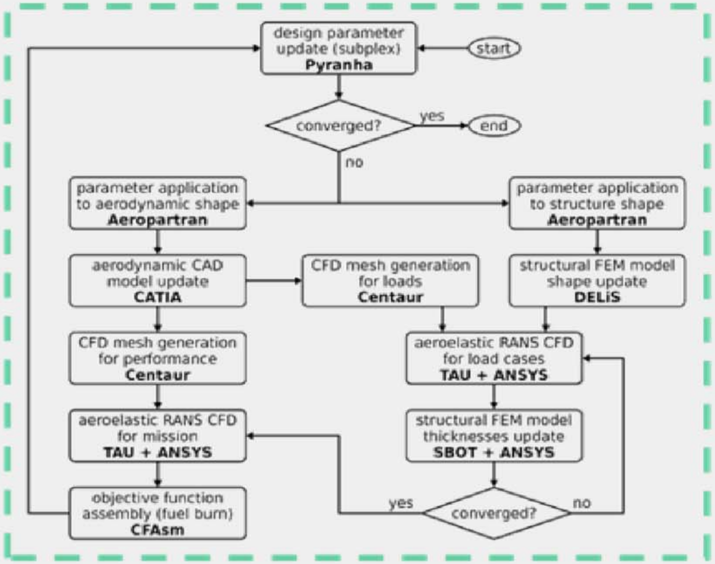
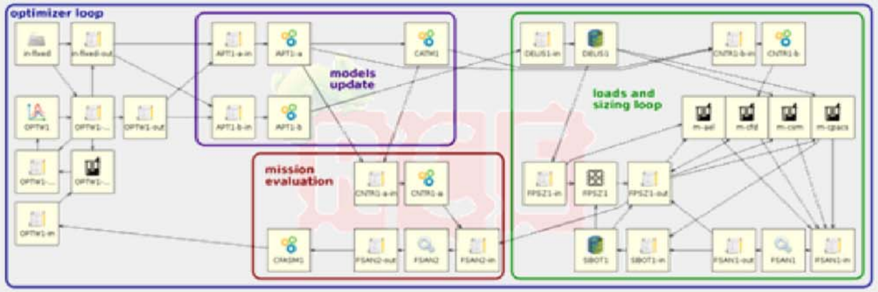
MDO – Implementation

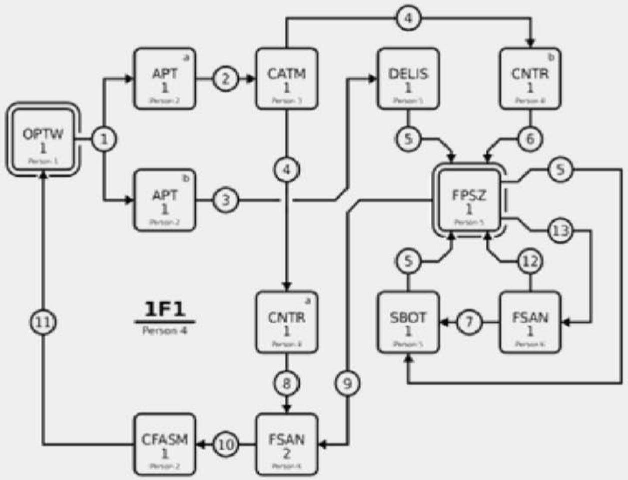
Informal flowchart
- Discussions among discipline aspects
- Methodology decided





Algorithmic flowchart
- Specific disciplinary tools decided





Blueprint
- Data flow & interfaces decided
- Allocation of component maintainer

Remote Component Environment (RCE)
- Graphical process assembly
- Distributed execution of components
- Automatic job issuing to HPC clusters

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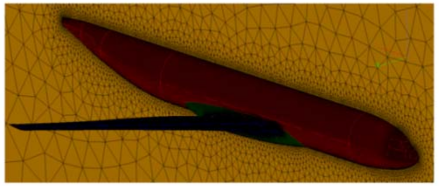
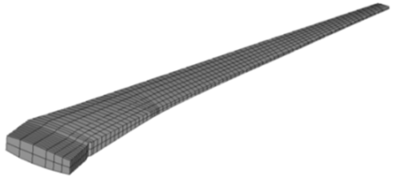
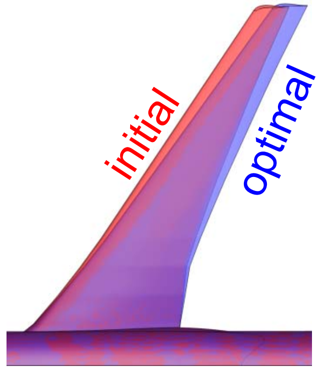
MDO – Implementation

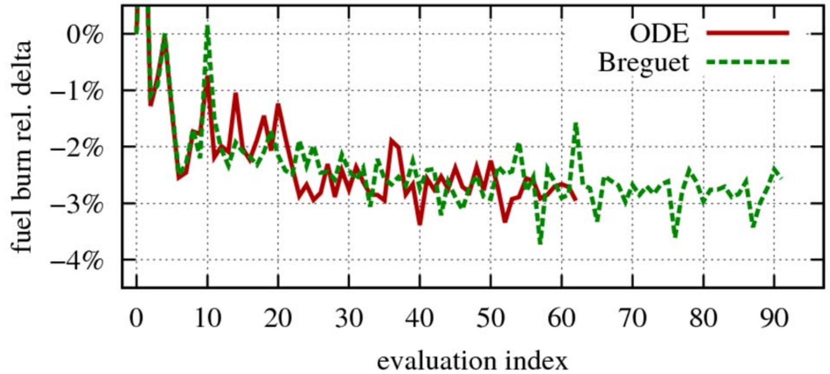
1st Test of Implemented Process

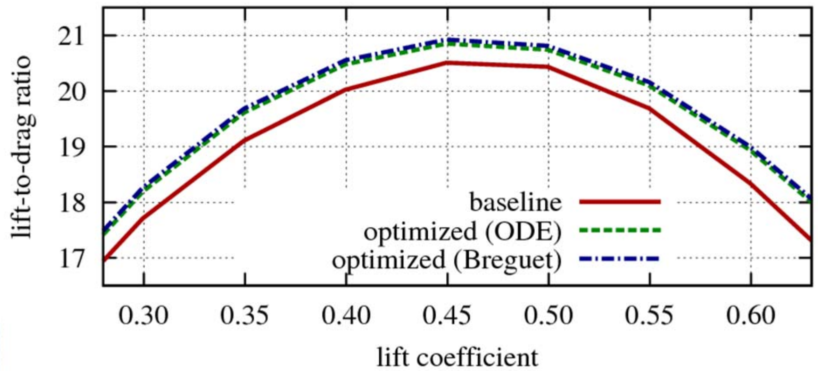
- Optimize wing with min. fuel burn (cruise)
- Wing-body geometry, XRF-1 as baseline
- RANS for aerodynamics, FEM for structure
- Fully-stressed design for structural thickness, 2.5g, -1g loads
- 5 parameters: AR, sweep, twist
- Target lift, wing area=const. (parameterization)
- No explicit constraints
- Cruise-climb: 3 altitude segments
- Comparison based on ODE integration & Breguet range eq.











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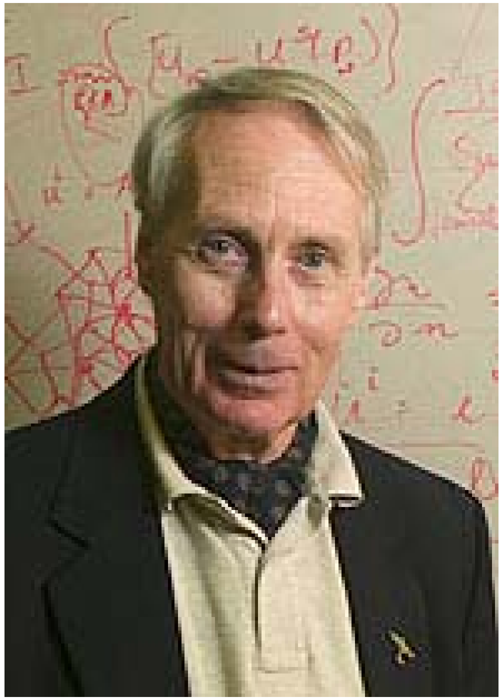
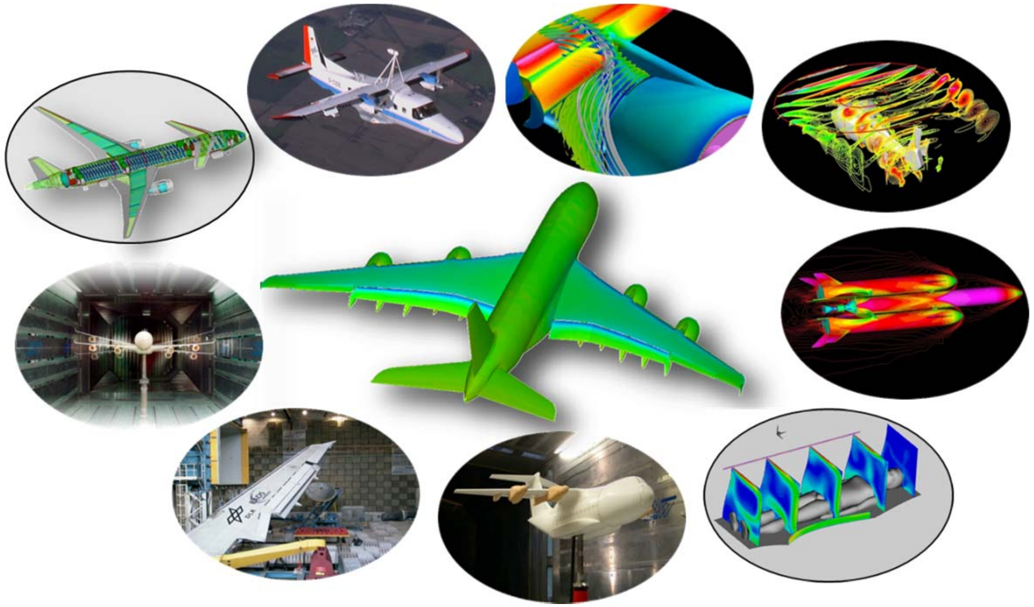
Future

- Project continues until end of 2015
- Progress achieved on disciplinary level as well as in linking all aeronautical institutes of DLR
- “Virtual Product” is one of DLR “Leading/Key Concepts”
- Follow-on project/s planning process started

Professor Jameson has significantly influenced our research!

Thank you very much!





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