Digital-X

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

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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

Aerodynamics

- Separated flows
- Transition laminar/turbulent
- Unsteady effects

Grey gradient indicates level of confidence in CFD flow solutions

AIAA CFD
Drag/High Lift Prediction Workshops

Airbus
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

1982-1992
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Cevcats

Code

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

1993-1996

1996-1998

2000 - 2002

2003-2007

2007-2010

2009-2012

2012-2015

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

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Previous Work

TAU CFD Solver

Reynolds-averaged Navier Stokes Code
- Unstructured grids, overlapping, adaptation
- Finite Volume method 2\textsuperscript{nd} order
- Advanced turbulence models, e.g. RSM
- Hybrid RANS/LES
- 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
Previous Work
CFD-CSM Coupling

Flight test of high lift configuration
Ma=0.204, Re=\~25M, \( \alpha = 10^\circ \)

- Trimmed aircraft
- Nastran-in-the-loop

Flow solver TAU, mesh deformation

Structural Model
CFD grid

Symbols = Flight test data

Wing bending
Simulation @Front Spar
Simulation @Rear Spar

Geom. & physically linear:
- steady: Nastran-in-the-loop

Loose / tight coupling
Load/defo. project.: RBFs or iso-param. mapping

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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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RANS-based Design & Optimization
- 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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  - Laminar airfoils:
    - $C_p$ 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
**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
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
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Content and Partner

HAP 1
Management

HAP 2
CFD Solver

HAP 3
Reduced Order Methods

HAP 4
Multidisciplinary Optimization

HAP 5
Maneuver at Flight Envelope Limits

HAP 6
Numerical Uncertainties

HAP 7
Helicopter Simulation

HAP 8
Automatic Processes

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

<table>
<thead>
<tr>
<th>Cost for</th>
<th>CFD - TAU</th>
<th>ROM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model generation</td>
<td>-</td>
<td>74 h (80 untrimmed TAU simulations)</td>
</tr>
<tr>
<td>1 trimmed polar</td>
<td>47 h (7 points)</td>
<td>25 s (71 polar points)</td>
</tr>
<tr>
<td>6 polar curves (cg=0.25)</td>
<td>~282 h (42 points)</td>
<td>150 s (420 polar points)</td>
</tr>
<tr>
<td>+ 4 polar curves (M=0.7)</td>
<td>~470 h (70 points)</td>
<td>250 s (710 polar points)</td>
</tr>
</tbody>
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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?

- $Ma = 0.8$
- $m = \ldots$, $Re = 7.7 \times 10^6$, $H = \ldots$
- $\lambda_{\text{gust}} = 213.36 \text{ m}$, $v_{\text{gust}} = 10.52 \text{ m/s}$
**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

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

**Blueprint**
- Data flow & Interfaces decided
- Allocation of component maintainer
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.
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!