Current Status and Challenges in CFD at the 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
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

Courtesy: Airbus D&S
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
Current Prediction Capabilities
High-Lift Aerodynamics

NASA TRAP Wing

- $M = 0.2$, $Re = 4.3 \times 10^6$, $\alpha = 6 - 36^\circ$
- SA turbulence model
- Transition prediction, $e^N$-method
  NTS = 8.5, NCF = 8.5
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
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)
Current Optimization Capabilities
Aerodynamic/Multidisciplinary Design & Optimization

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

A. Ronzheimer, 2012
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
Towards the Virtual Aircraft
Challenges & Capability Needs

Simulation of Flight Envelope
  - Separated flows
  - Transition laminar/turbulent
  - Unsteady effects
  - Multidisciplinary simulations

Grey gradient indicates level of confidence in CFD flow solutions
Towards the Virtual Aircraft
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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
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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
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 $g = 1/\sqrt{\omega}$

- $e^h$-JHh-V2 model
  (Jakirlic-Hanjalic model, extension by U. Braunschweig)

RSM yields experimental trend of junction separation

V. Togiti, 2013
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

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

A. Probst, 2014
CFD Solver

Goal: Secure Quality of CFD for Virtual Aircraft Requirements

Applicability and accuracy

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

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Applicability and accuracy

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

![Graph showing comparison of different grid types for turbulent flat plate, M=0.15, Re=5M]
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

High lift prediction workshop
Case 2a, No. of point, 10.2e6,
Re = 1.35e6, AoA = 7.0, Ma = 0.175

S. Langer, 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)
- Parallel efficiency

J. Jägersküpper, 2012
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)
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
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
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
Multidisciplinary Optimization

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Example

- Gust loads
  - Vertical gust
  - $M=0.836$, $Re=86\times10^6$, gust: 12m/s

L. Reimer, M. Ritter, 2014, Cooperation with Institute of Aeroelasticity
Multidisciplinary Optimization

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L. Reimer, M. Ritter, 2014

Cooperation with Institute of Aeroelasticity
Multidisciplinary Optimization
Loads Prediction

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 5 parameters
Real time prediction of distributed loads & forces

POD-ROM based on 1.960 CFD solutions

Trimmed polar + loads (surface distribution)
M=0.7, Re=1.0×10^6
250s for 700 trimmed polar points

N. Karcher, 2014
Multidisciplinary Optimization
Loads Prediction

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

Grid: 237,373 points, Euler computations

POD: all 25 snapshots
Isomap: 7 neighbors

T. Franz, 2014
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 $C_p$ used to correct unsteady DLM (Doublet Lattice Method), mapping between CFD and DLM grid
- POD for AIC
- Extension to maneuvers

Corrected $\Delta C_p$

Courtesy DLR Institute of Systems Dynamics and Control
M. Verveld, T. Kier, 2014
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

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