Role of HPC in Aircraft Design

Norbert Kroll, German Aerospace Center (DLR)
DLR TAU-Code

Parallel data management
Data extraction
Adaptation
(Re-) Partitioning
Deformation
Primary grid
Solution
Preprocessor
Dual grid
Solver

Strong Scaling of DLR’s TAU Code on Juropa (Nehalem QC 2S, IB QDR NB FT), JST, SA, RK

Used in European aircraft industry, research organization and academia
Europe’s Vision for Aviation

- Maintaining Global Leadership & Serving Society’s Needs

**Goals** *(relative to typical aircraft in 2000)*

- CO₂ 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
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 indispensable 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
Numerical Simulation for Aircraft Design

Current Status

- Computational Fluid Dynamics (CFD) has significantly evolved over the last 25 years
- Mature tool for configurations at their design point in flight envelope
- Complementary to wind tunnel testing and flight tests
- Key tool for aeronautical research and aircraft technology development
- **Total potential not yet exploited:** full flight envelope, all relevant disciplines, multidisciplinary optimization
Numerical Simulation of Aircraft Aerodynamics
Status Cruise

A380 Performance

Pre-Flight prediction

1% L/Dmax

Source: Airbus

CFD & wind tunnel based performance prediction are comparable

CFD-based scaling

W/T-based scaling

flight test

Mach

Source: Airbus
Numerical Simulation of Aircraft Aerodynamics
Status High-Lift Configurations

- Simulation of complete Aircraft including structural deformations
- Effect of nacelle strakes

\[ \Delta C_L (\alpha = 12^\circ) \text{ EXP } = 0.03 \]
\[ \Delta C_L (\alpha = 12^\circ) \text{ CFD } = 0.018 \]
Numerical Simulation for Aircraft Design
Vision: Digital Aircraft

Full flight envelope coverage:  
*CFD mostly done near cruise point*

 configurations:
- *clean*
- *airbrakes deployed*
- *high lift*

- 50 flight points
- 100 mass cases
- 10 a/c configurations
- 5 maneuvers
- 20 gusts (gradient lengths)
- 4 control laws

~ 20,000,000 simulations

Engineering experience for current configurations and technologies

~ 100,000 simulations
Numerical Simulation for Aircraft Design
Vision: Digital Aircraft

- Time-accurate multi-disciplinary manoeuvring aircraft simulation
  “Fly the equations”

- Generation of surrogate model of sampled static & dynamic aerodynamic data relying on high-fidelity tools
  “Fly through the database”
Large range of scales (vortices/eddies of different sizes) in turbulent flows

- Largest vortices: characteristic size $l_0$ of the geometry, of the order of 10m
- Smallest vortices: very small due to the large flight Reynolds number, in particular in the near-wall region of the boundary layers adjacent to solid surfaces

$$\frac{\eta}{l_0} \sim Re^{-3/4}$$

- Large-scale vortices: vortex size given by macroscopic length scale of the airplane
- Vortices of separated boundary layer flow: Size of separation given by e.g. flap dimension
- Vortices in outer part of the turbulent boundary layer: weak Re-dependence
- Smallest structures: Harpin vortices in near-wall region: large Re-dependence
Physical Modeling
Increase Modeling Level

- DNS (Direct numerical simulation)
  - resolve irregular vortical motion down to the smallest persistent eddies

- LES (Large eddy simulation)
  - resolve irregular vortical motion of the large-scale vortices
  - model effects of the smallest eddies

- RANS (Reynolds-averaged Navier-Stokes eq.)
  - model the effects of the irregular vortices on the mean flow

Givi et al., Univ., Pittsburgh, PSC annual report 2009
**Physical Modeling**

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Multidisciplinary Aircraft Simulation

Motivation

⇒ For aircraft design & assessment loads prediction due to control surface movement essential for
  ⇒ Structure design
  ⇒ Design of control surfaces & flight control system

⇒ **Aim:** Simulate aircraft maneuvers prior to the first flight *(virtual flight testing)*
Multidisciplinary Aircraft Simulation

Challenges

- Tight coupling of all relevant aircraft disciplines (high-fidelity methods)
- Efficient modeling of moving control surfaces
- Huge unsteady computations

strong scaling
Multidisciplinary Aircraft Simulation Challenges

- Tight coupling of all relevant aircraft disciplines (high-fidelity methods)
- Efficient modeling of moving control surfaces
- Huge unsteady computations
- Software environment for massively parallel computations

Diagram showing the integration of various components such as CFD, Spatial coupling, CSM, Trimming, FM 6 DoF, and Flight control, all interfaced through Python interfaces.
**Multidisciplinary Aircraft Simulation**

**Vertical gust encounter of Aircraft in Cruise Condition**

**Unsteady example:** Gust encounter of flexible A/C

- M=0.82, Re=35.3M, m=195 t, λ\text{gust}=60m, v\text{gust}=15m/s

- Gust modeled via disturbance velocity approach
- Coupling to flight mechanics (6DoF)
- Coupling to structure
Multidisciplinary Aircraft Simulation
Vertical gust encounter of Aircraft in Cruise Condition

Realistic simulation
- 50 million grid points
- $\Delta t = 0.005s$
- 4s real time

Estimation
- 12 days on 250 cores per case
- 12h on 10,000 cores (50% scalability) per case
- Load cases > 10

Strong scaling
- Reduction in turnaround time requires improved scaling

Unsteady example: Gust encounter of flexible A/C
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Aerodynamic Loads Data

In aircraft design huge sets of aerodynamic data are required for the complete flight envelope as input for:
- Flight simulator data base
- Development of flight control system
- Layout of control surfaces
- Structural layout

Requirements
- high-fidelity simulations based surrogate models

Computational requirements
- current experience:
  - 1 case: 50 million grid points ~ 1h on 500 cores
- 5000 load cases
  - 2.5 million core hours ~ 5h on 500,000 cores
  - Additional factor of 5-10 due to grid resolution, improved physical modeling, flexible A/C

Adaptive strategies
Multi-Disciplinary Optimization (MDO)
High-Fidelity MDO Key Enabler for Future Aircraft Design

- Solely way to
  - Consider complex multi-disciplinary interactions
  - Deliver valuable compromises between disciplines
  - Give confidence on design of innovative configurations

- Requires
  - Massively simultaneous computations
  - Flexible use of high performance computers

Optimal engine position for rear fuselage mounted engine aircraft
Multi-Disciplinary Optimization
Detailed Design

Status: Aero-Structural Wing Planform Optimization

\[ R = \frac{L}{D} \cdot \frac{v}{SFC} \cdot \ln \left( \frac{m_1}{m_2} \right) \]
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

A. Ronzheimer
Multi-Disciplinary Optimization
Detailed Design

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- Time for optimization:
  - 213 optimization cycles ~36 days.
- Resources used:
  - 24x12=288 cores and 213x20=4260 jobs
Aero-acoustic Simulation
Airframe Noise

Sound generation
- Tonal, broadband

Sound propagation
- Large spectral bandwidth
- Long propagation distances

Flow noise of high lift wing using scale resolving flow simulation (DES)
- $10^{10}$ degrees of freedom at model Re-number (1:10 scale)
- Not appropriate for design tasks
- Important for clarifying source mechanisms

Scattering of engine sound in boundary layer
- $10^{11}$ degrees of freedom required to resolve aero-acoustics around A/C
- Excessive computational cost

Source: Thiele/Knacke TU Berlin

Weak scaling
Multiple levels of explicit parallelism in cluster hardware

1. nodes
2. sockets (multiple CPUs)
3. multi-core CPUs
4. symmetric multi-threading
5. SIMD (vector) units

Parallel software must reflect all levels of hardware parallelism

→ Multi-level (“hybrid”) parallelization matching hardware’s characteristics
→ Asynchronous computation/communication to overlap/hide latencies and/or load imbalances

Parallelization of most legacy CFD codes used in aircraft industry will hardly fit with future HPC hardware
Current HPC architectures require **data-parallel computations** to make optimal use of the compute power – in particular GPGPUs, but also CPUs!

Mathematically well-suited algorithms often feature **data dependencies**, making it hard to realize a scalable parallel implementation (e.g. ILU)

Collaboration of experts in application domain and parallel computing necessary to extract – or even generate – data parallelism in algorithms

Target: \#iterations $\times$ wall clock / iteration
HPC for Aircraft Design
Advanced Solution Strategies

Gridding techniques for complex configurations
- Flexible, high quality
- Automatic for complex geometries

Solution strategies
- Efficient, multilevel solvers
- Mesh refinement / de-refinement
- Higher-order methods
- Multi-physics

Challenge: Optimize total performance:
Trade-off parallel vs algorithmic performance
Conclusions

Numerical Simulation
- Key enabler for meeting the strategic goals of future air transportation (Digital Aircraft)
- Indispensable tool for aeronautical research
- Important driver for competitiveness of European aeronautical industry and research

Future HPC needs
- Access to dedicated supercomputers
  - Weak scaling (improved modeling, aero-acoustics, ..)
  - Strong scaling (maneuver, MDO)
  - Farming (aero loads data)
- Investment in numerical methods
  - Next generation CFD solver (multi-level parallelization)
  - Highly scalable algorithms with good convergence properties
  - Parallel simulation environment for multi-physics
- Medium term (5 years)
  - Multi-disciplinary optimization, > $10^2 - 10^3$ times today’s capability
- Long term (15 years)
  - Real time maneuver simulation, > $10^4 - 10^5$ times today’s capability
Acknowledgement

Contributions from DLR colleagues:
O. Brodersen, R. Ewert, R. Heinrich, R. Hartmann, J. Jägersküpper, T. Knopp, M. Mifsud, A. Ronzheimer

Selected papers:
- M. Mifsud, R. Zimmermann, S. Görtz, “A POD-based reduced order modeling approach for the efficient computation of high-lift aerodynamics”, Eurogen 2011, Capua, Italy, 2011