PRACE Industrial Seminar, 15 -16 April, 2013, Bad Boll,

Role of HPC in Aircraft Design

Norbert Kroll, German Aerospace Center (DLR)

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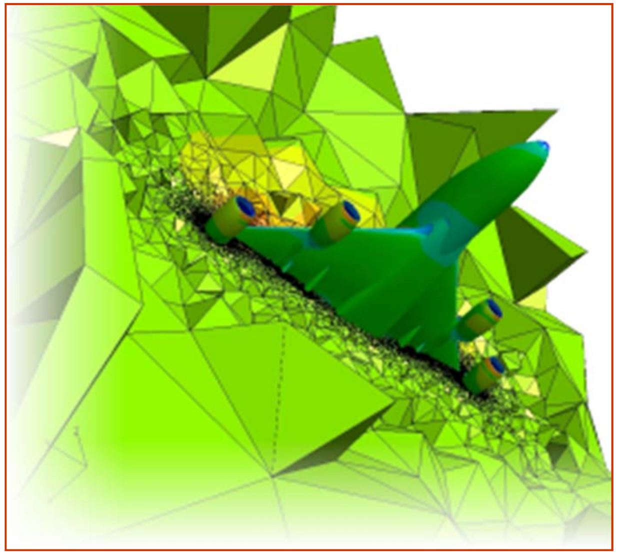
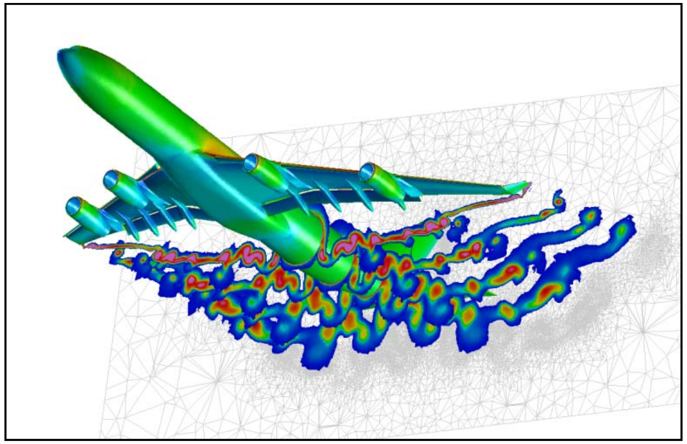
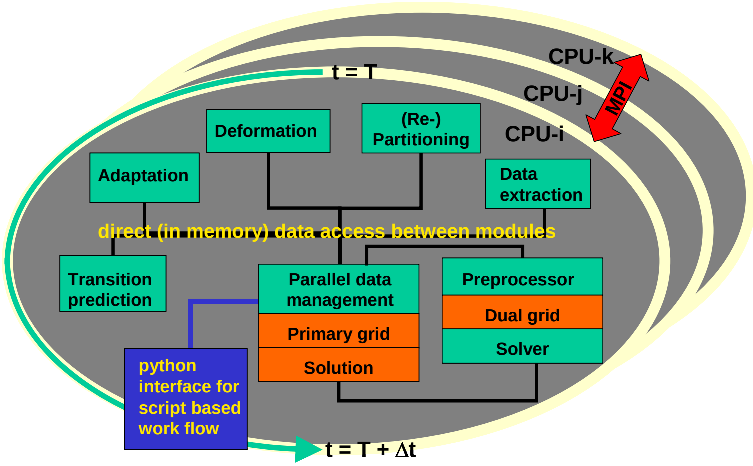
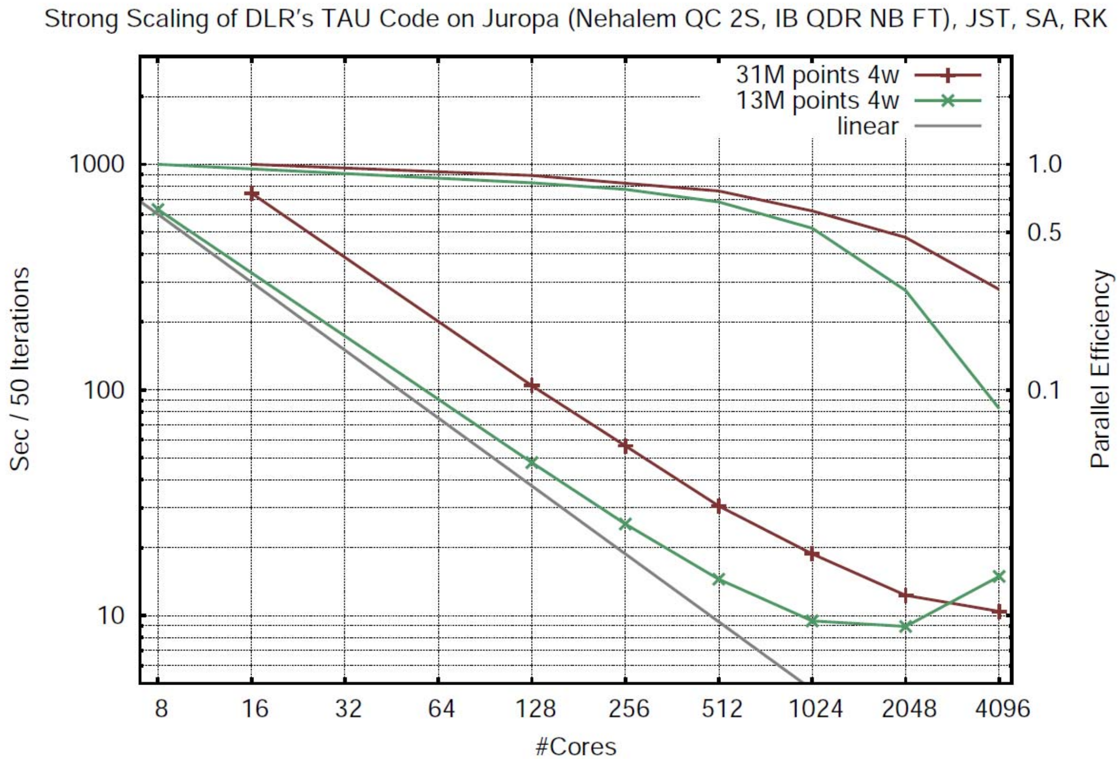
DLR TAU-Code





Used in European aircraft industry, research organization and academia





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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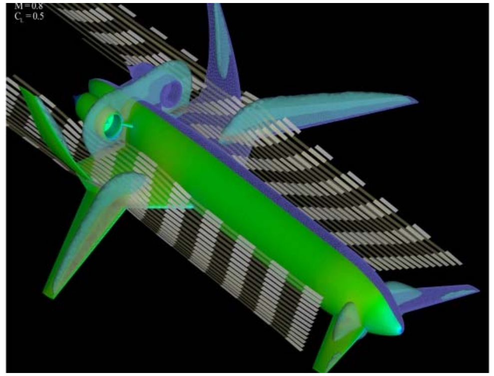
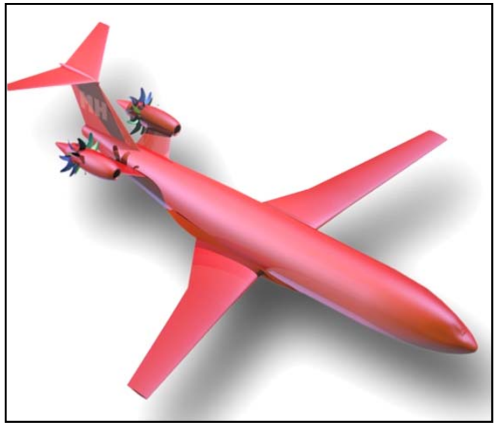
Numerical Simulation
Key Enabler for Future Aircraft Design



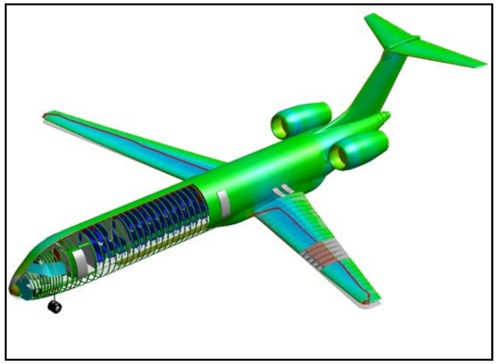
Future aircraft

- 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

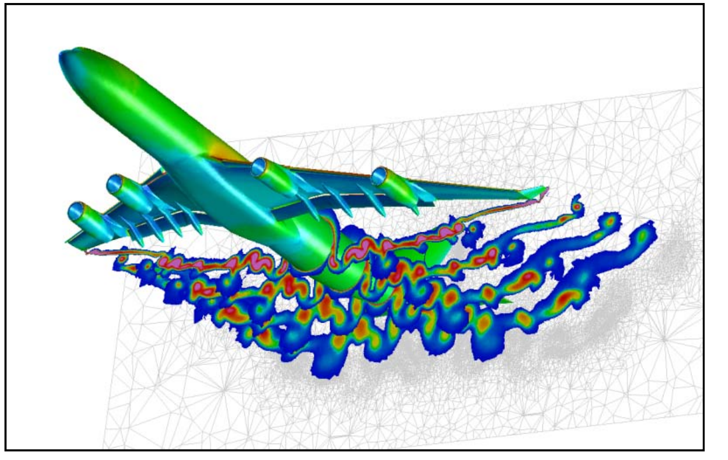


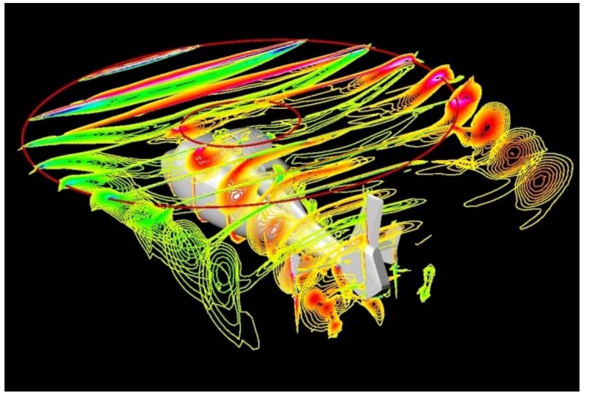
Further improvement of simulation capability necessary

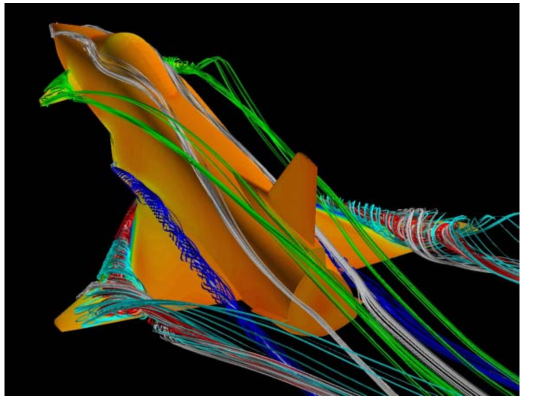
Numerical Simulation for Aircraft Design

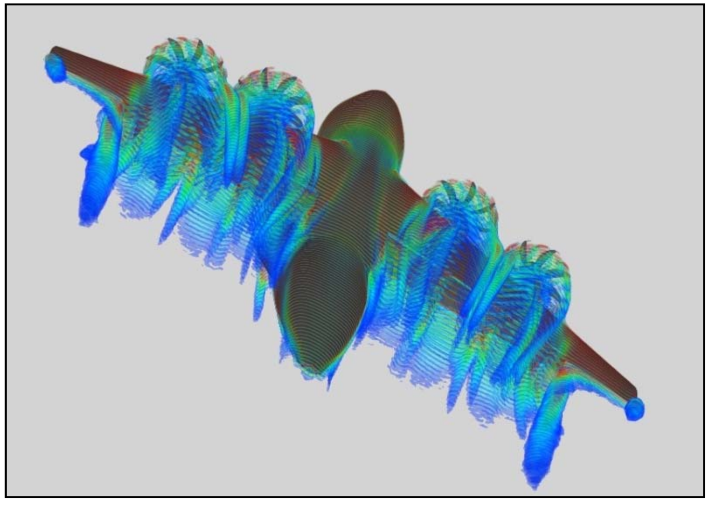
Current Status

- 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**









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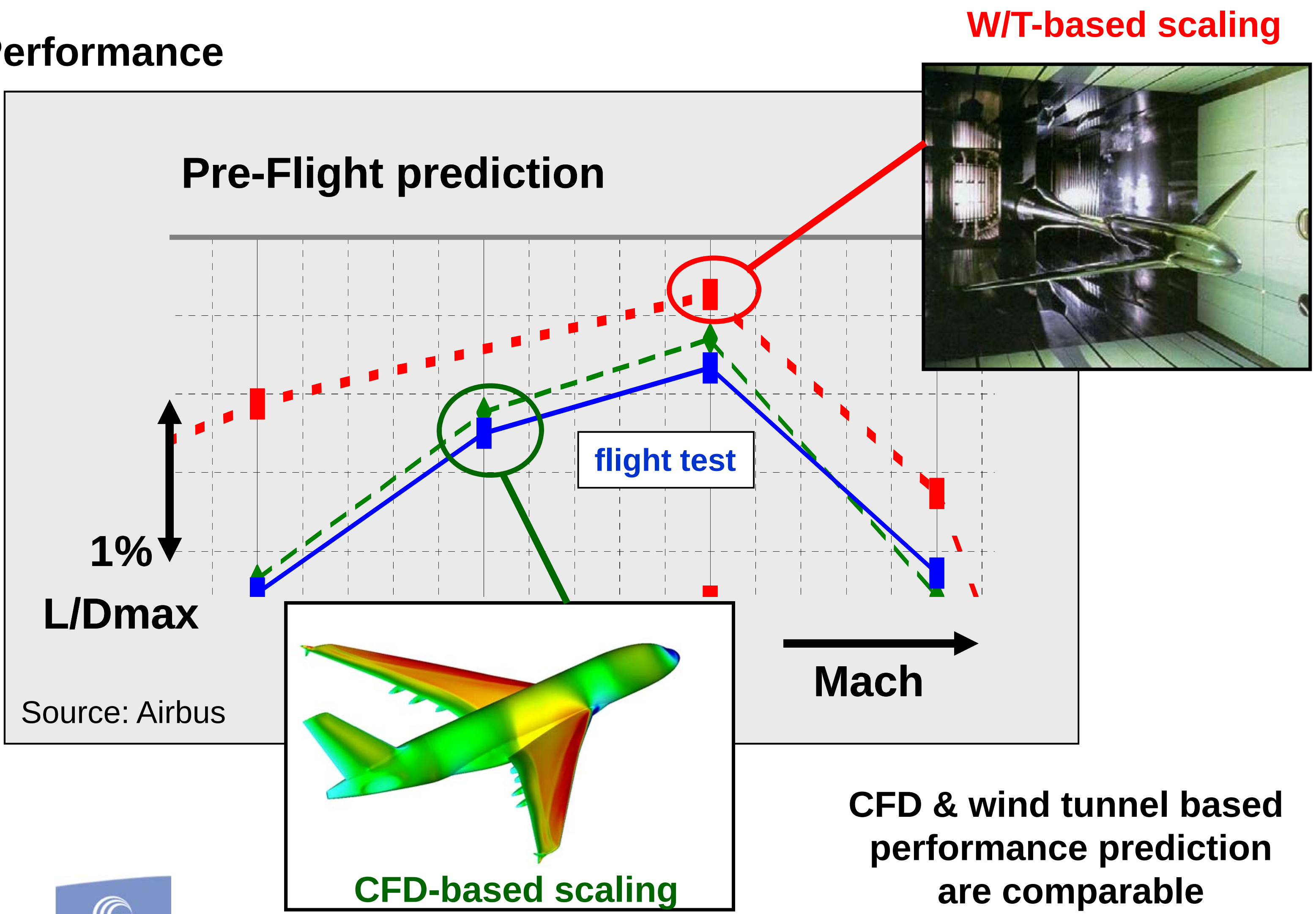
Numerical Simulation of Aircraft Aerodynamics

Status Cruise

A380 Performance

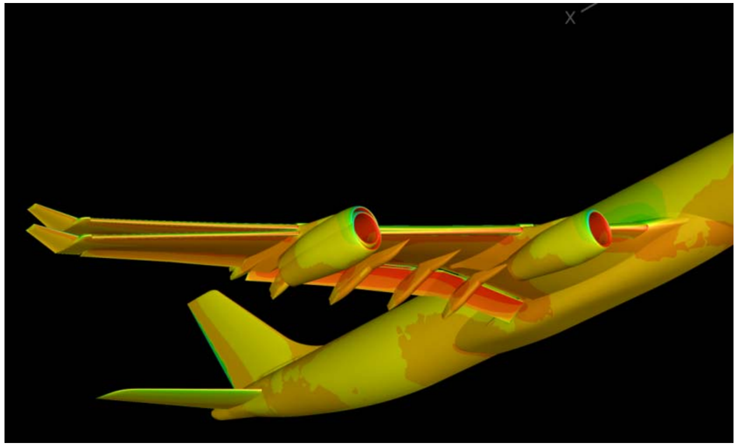


CFD & wind tunnel based performance prediction are comparable

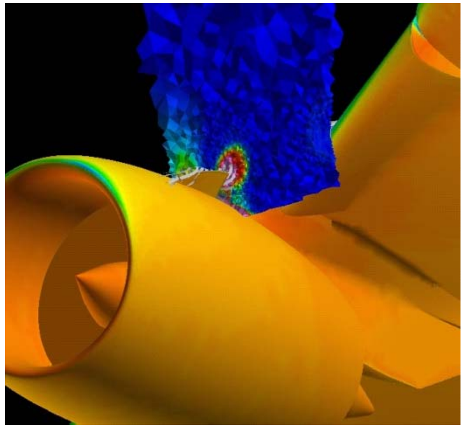
Numerical Simulation of Aircraft Aerodynamics
Status High-Lift Configurations

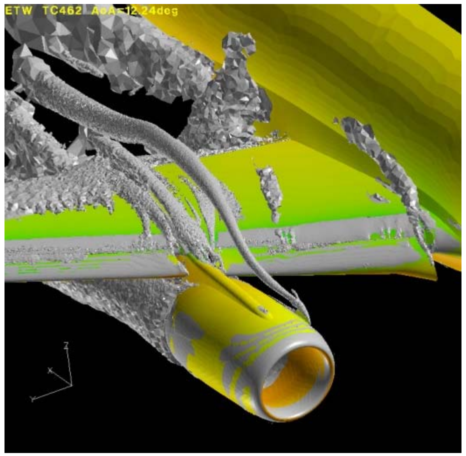
- Simulation of complete Aircraft including structural deformations
- Effect of nacelle strakes

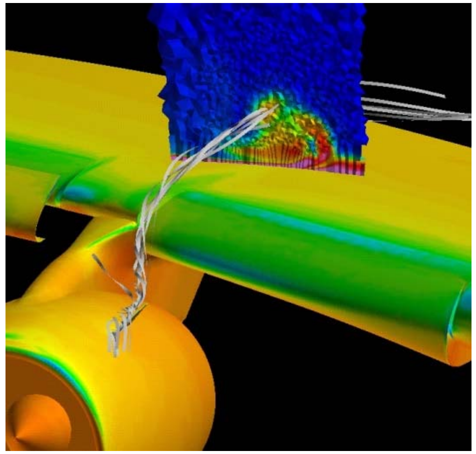
DLR TAU Code



Lift increase due to strake vortex
- $\Delta C_L\ (\alpha = 12^\circ)_{EXP} = 0.03$
- $\Delta C_L\ (\alpha = 12^\circ)_{CFD} = 0.018$







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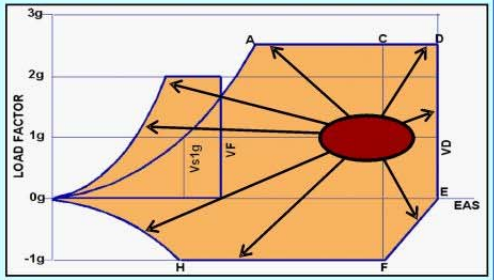
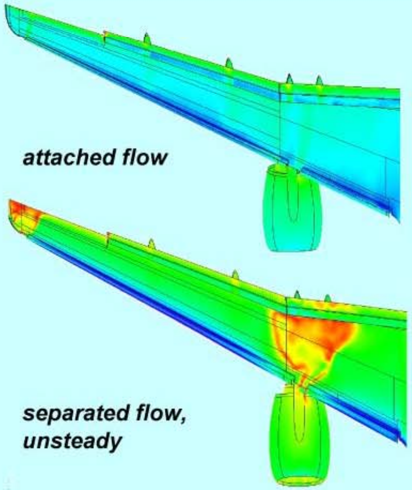
O. Brodersen

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

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Numerical Simulation for Aircraft Design

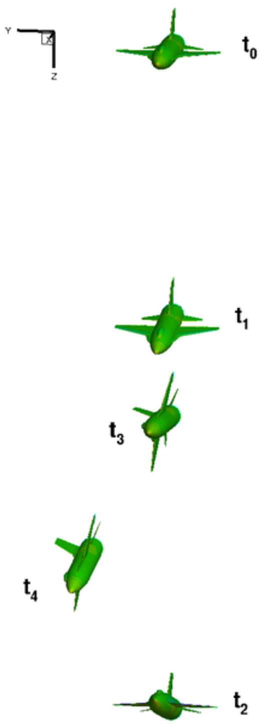
Vision: Digital Aircraft

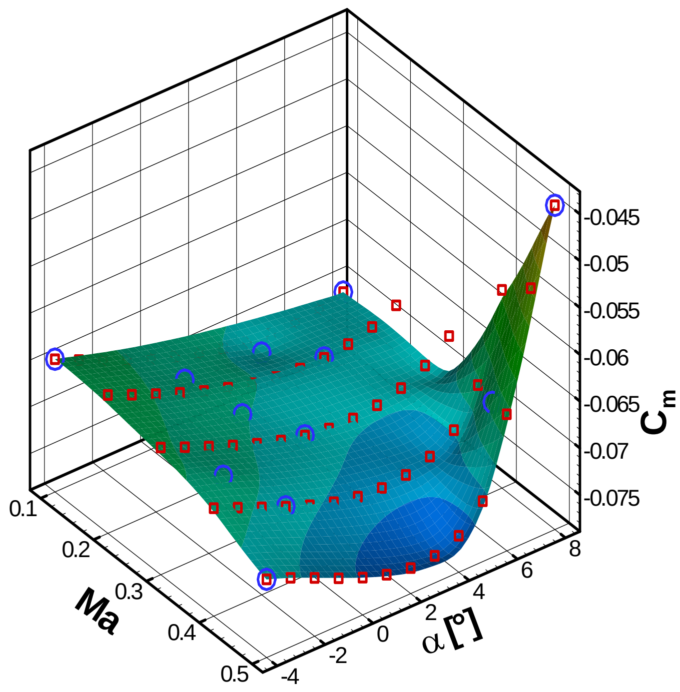
- Time-accurate multi-disciplinary manoeuvring aircraft simulation

“Fly the equations”

- Generation of surrogate model of sampled static & dynamic aerodynamic data relying on high-fidelity tools

“Fly through the database”





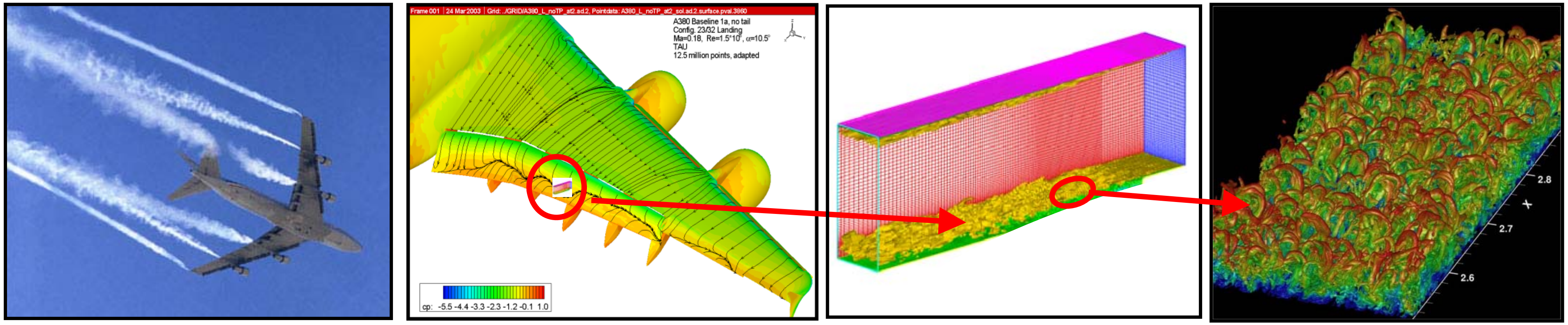
Physical Modeling

Scales of Turbulent Flows in Aerospace Aerodynamics

- 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

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

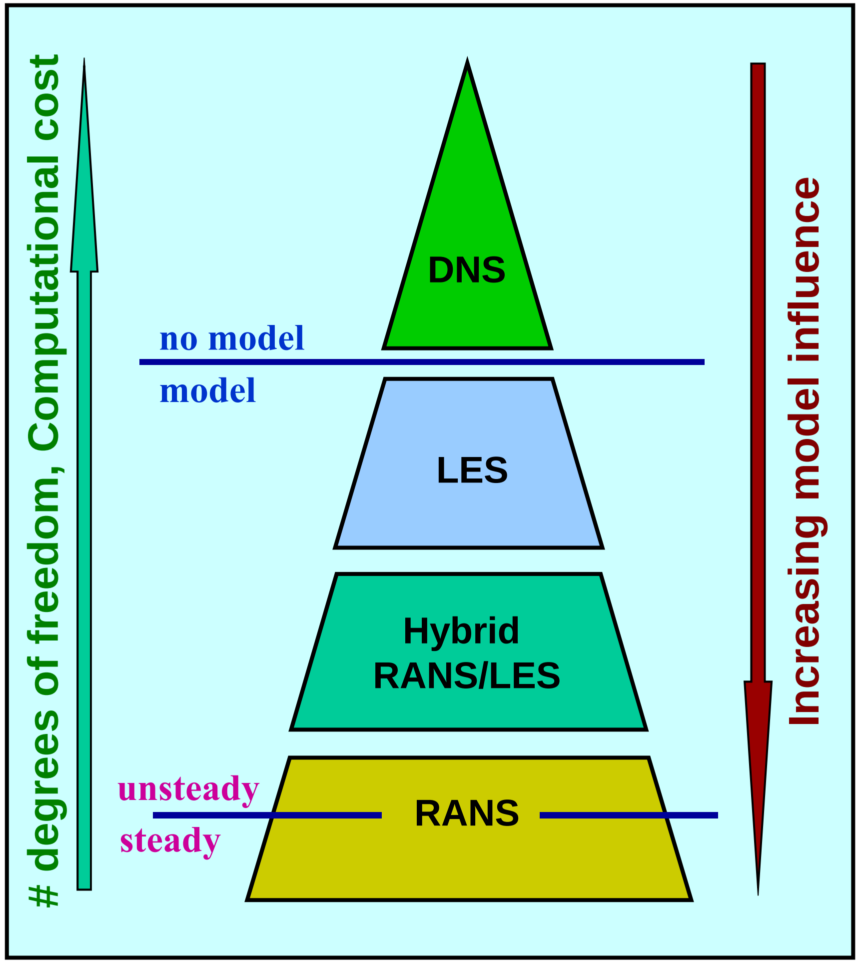
Large-scale vortices:	Vortices of separated boundary layer flow:	Vortices in outer part of the turbulent boundary layer:	Smallest structures:
vortex size given by macroscopic length scale of the airplane	Size of separation given by e.g. flap dimension	weak Re-dependence	Harpin vortices in near-wall region: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

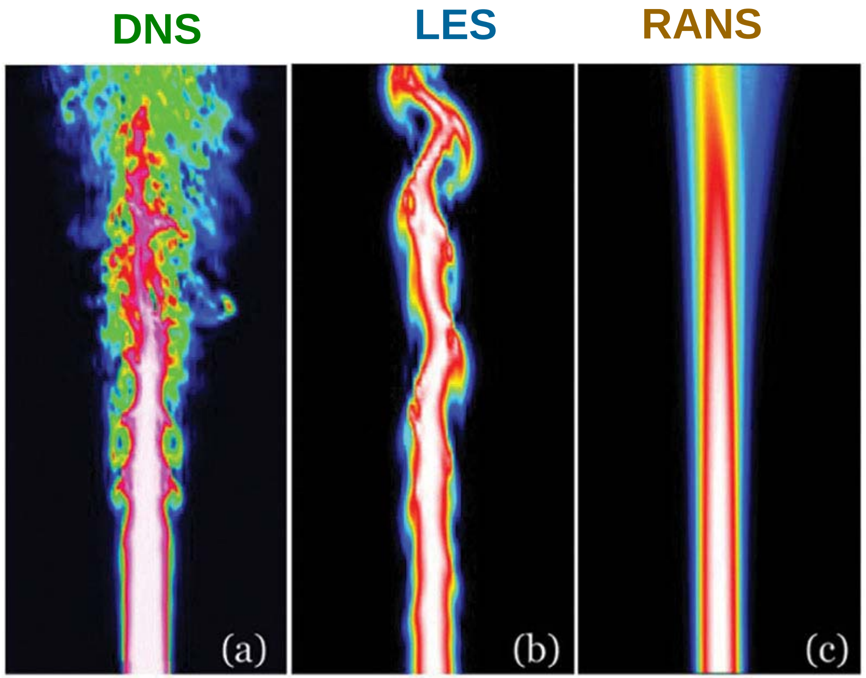


Wu & Moin, JFM **630**, 5-41, 2009

Physical Modeling

Increase Modeling Level





Givi et al, Univ., Pittsburgh,PSC annual report 2009

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

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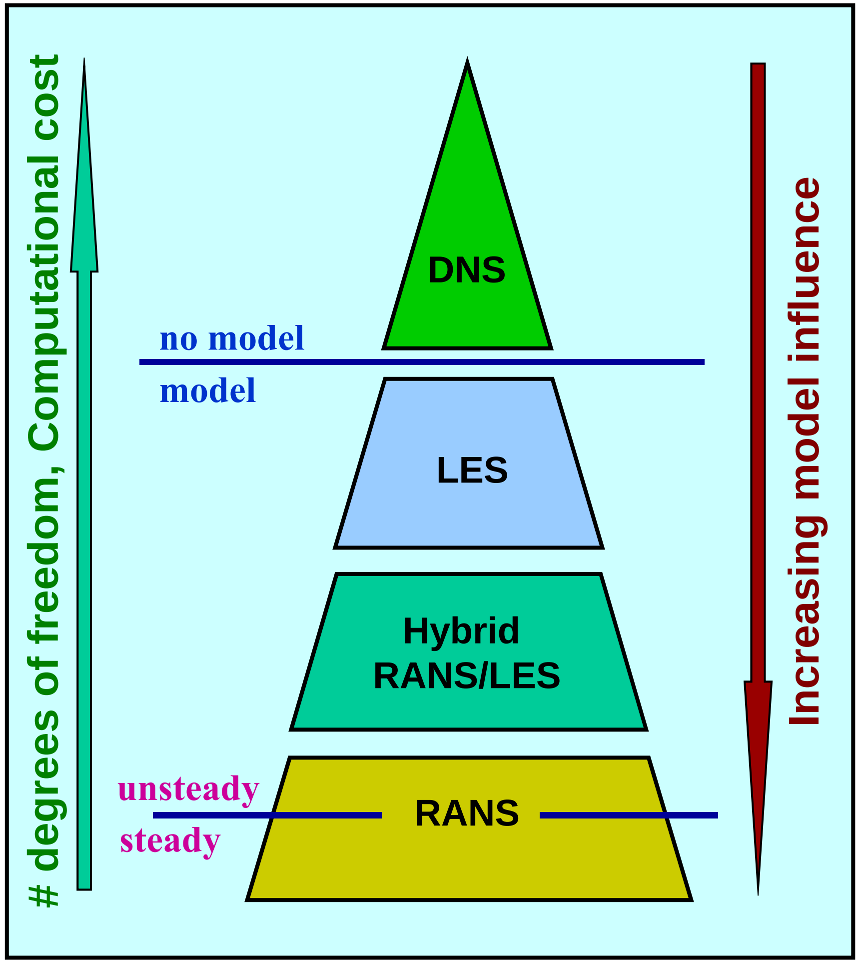
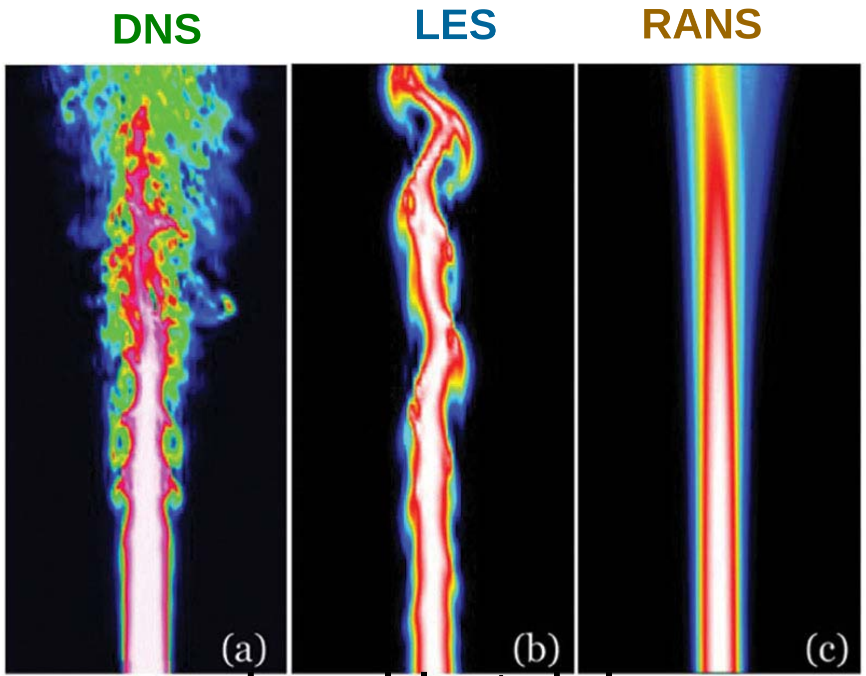
Physical Modeling
Increase Modeling Level





scale resolving turbulence
Givi et al, Univ., Pittsburgh,PSC annual report 2009

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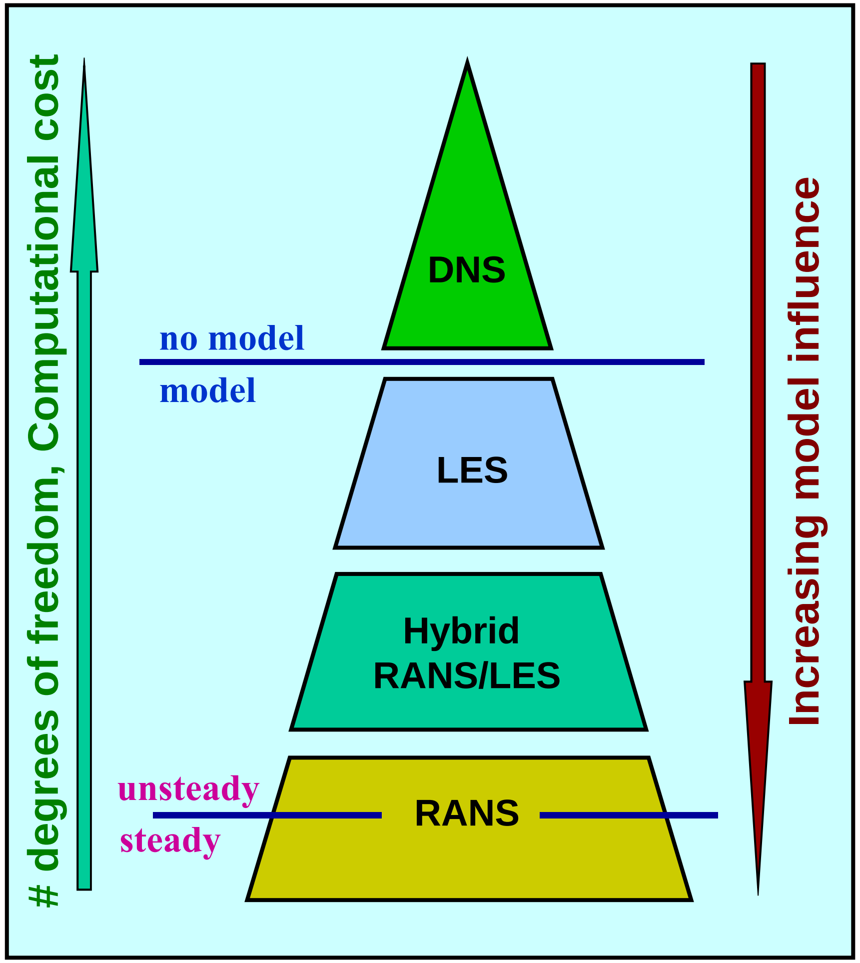
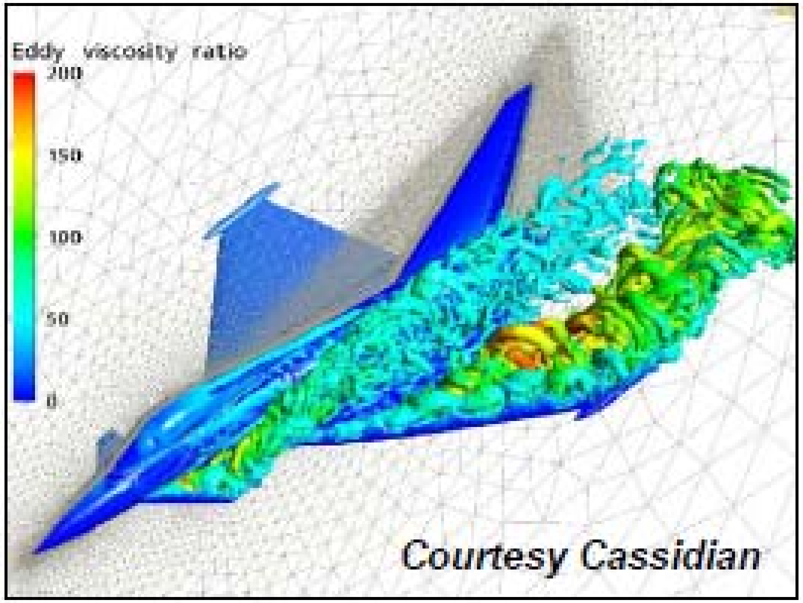


➡ **weak scaling**



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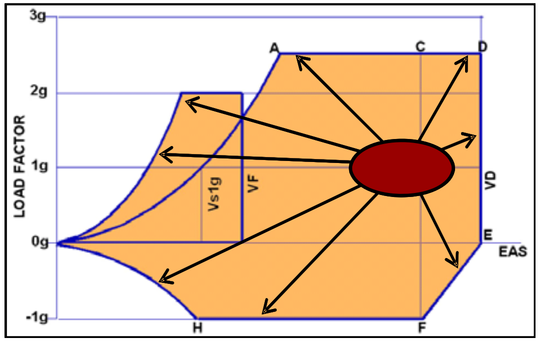
Multidisciplinary Aircraft Simulation

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)

gust

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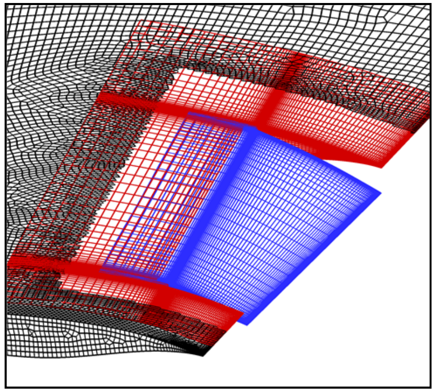
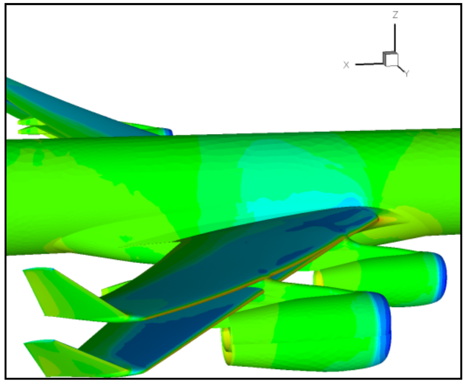
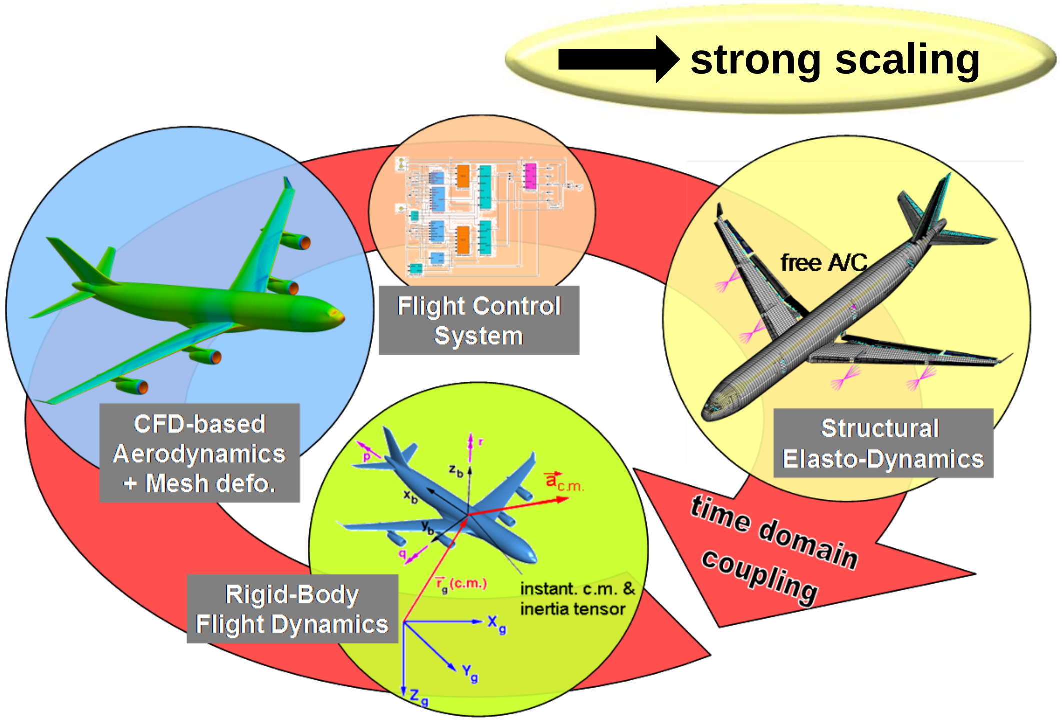
Multidisciplinary Aircraft Simulation

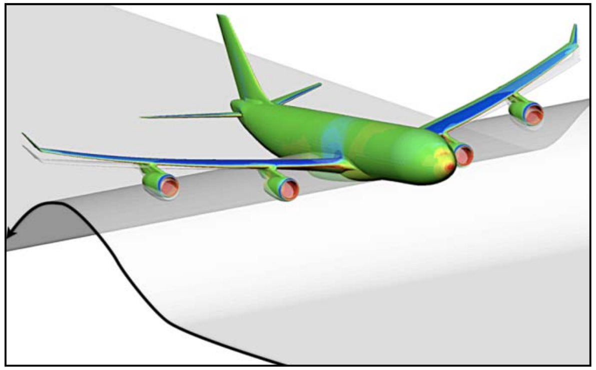
Challenges

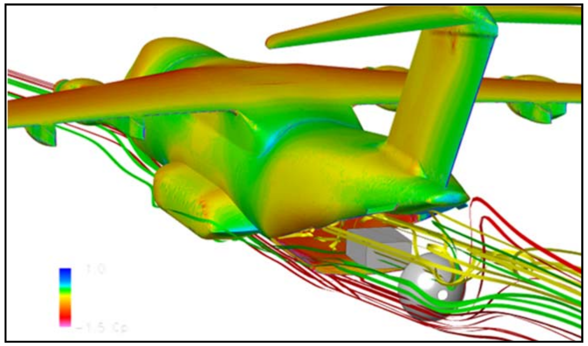
- Tight coupling of all relevant aircraft disciplines (high-fidelity methods)
- Efficient modeling of moving control surfaces
- Huge unsteady computations





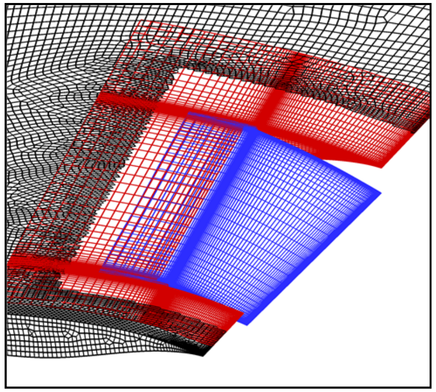


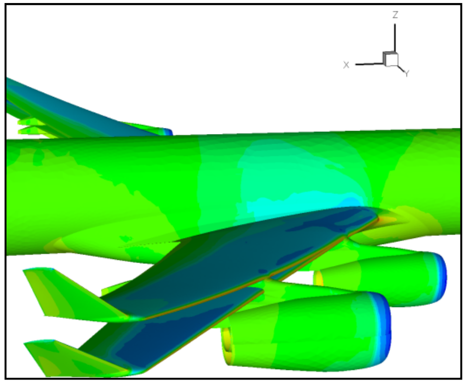


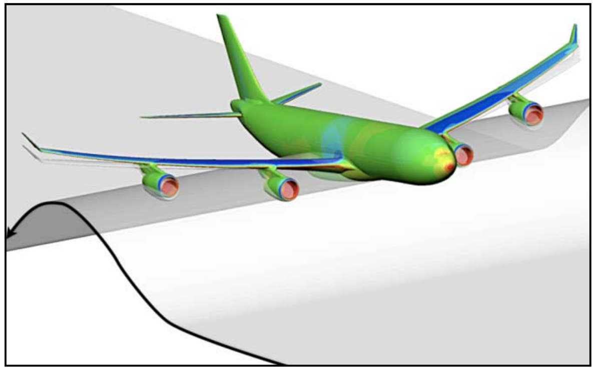


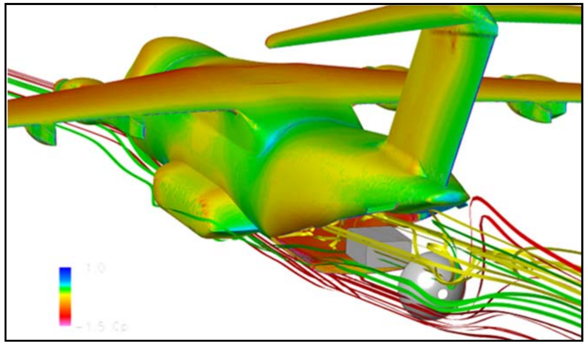
Multidisciplinary Aircraft Simulation
Challenges

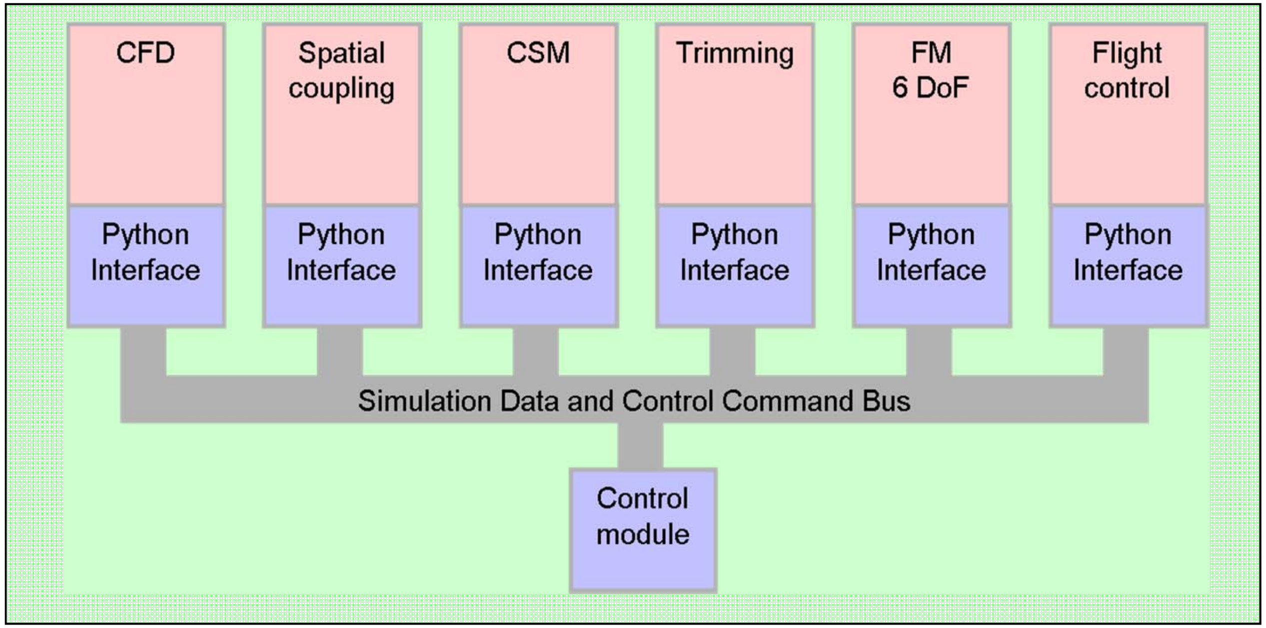
- Tight coupling of all relevant aircraft disciplines (high-fidelity methods)
- Efficient modeling of moving control surfaces
- Huge unsteady computations
- Software environment for massively parallel computations





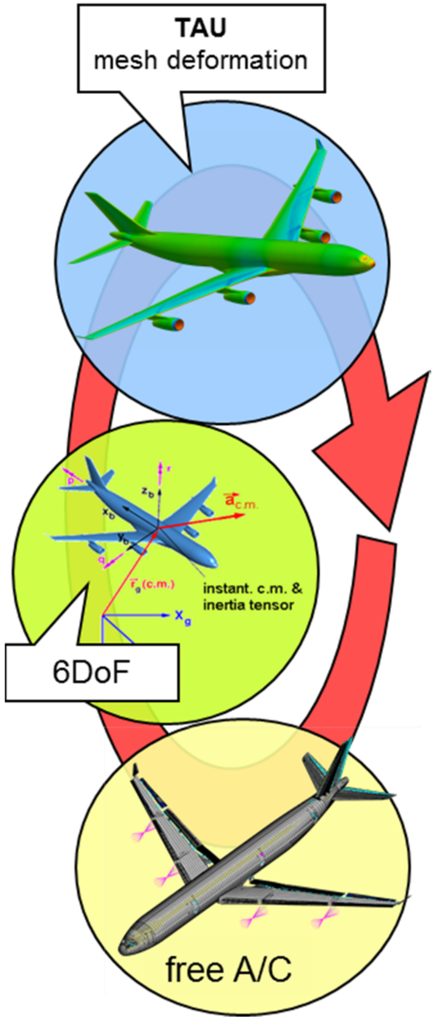






Multidisciplinary Aircraft Simulation

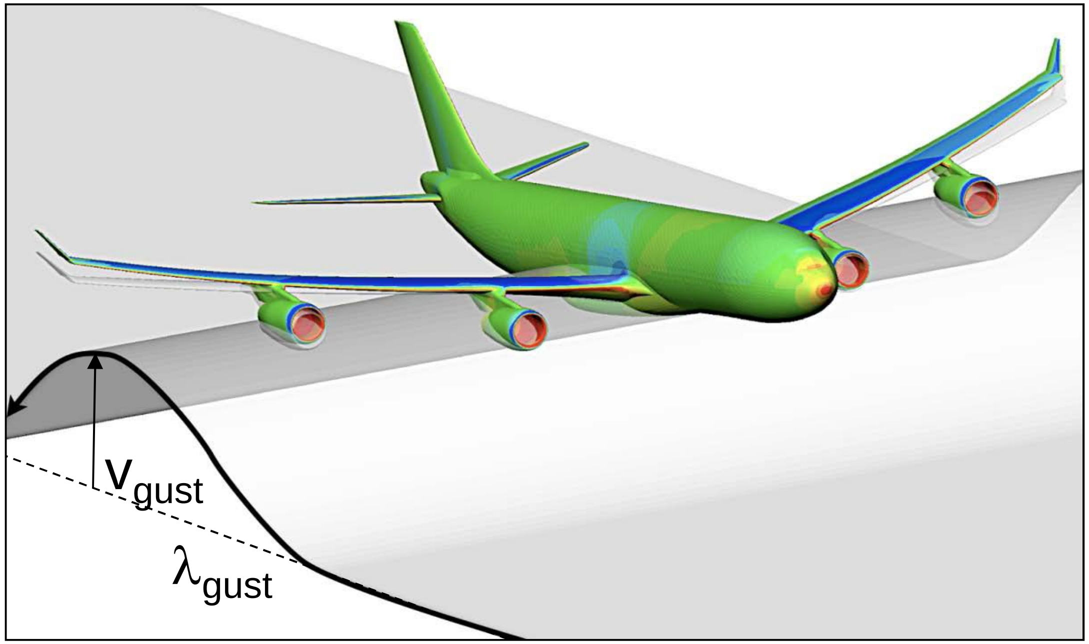
Vertical gust encounter of Aircraft in Cruise Condition



Unsteady example: Gust encounter of flexible A/C

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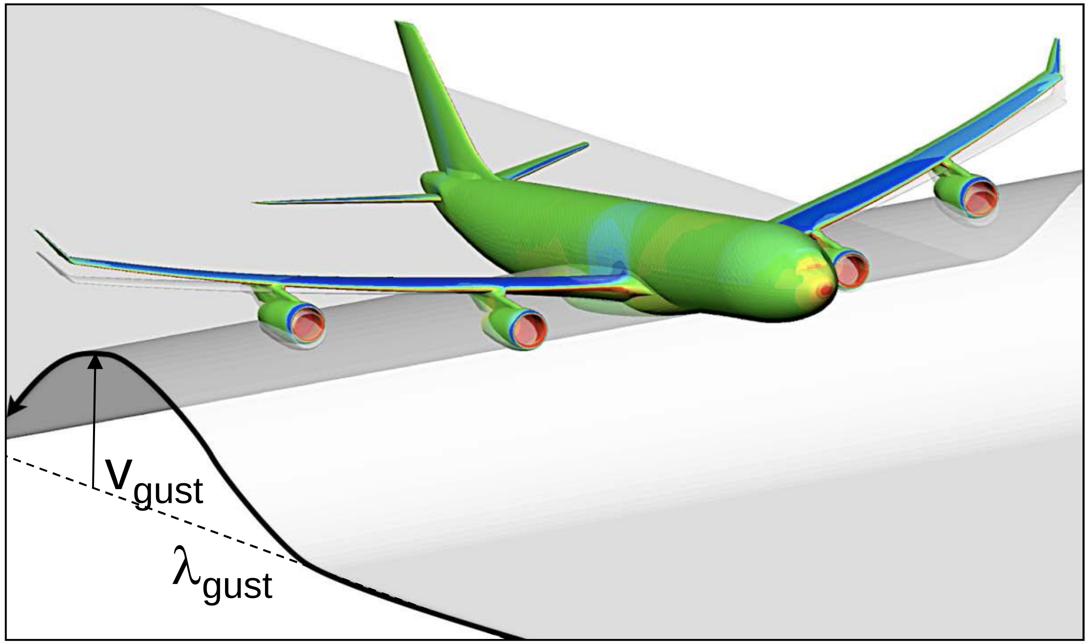
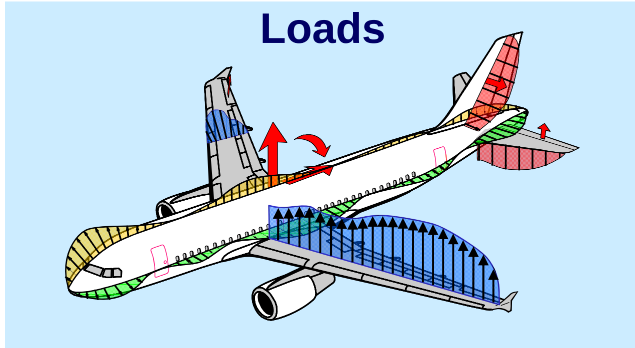


Aerodynamic Loads Data



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

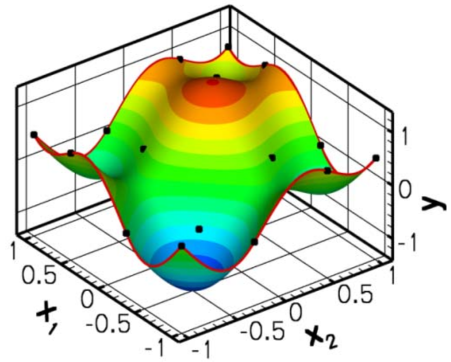
Requirements

- high-fidelity simulations based surrogate models

➡ farming on HPC

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

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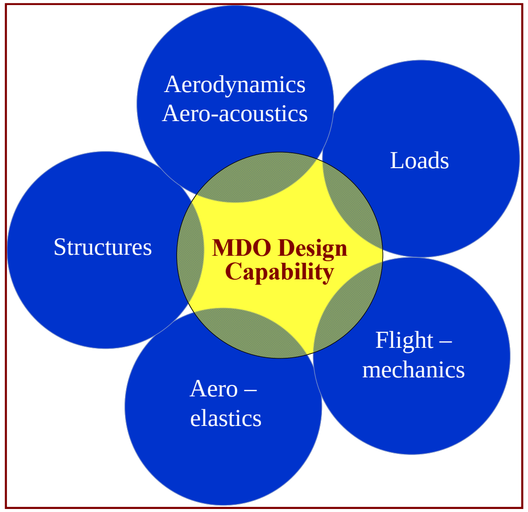
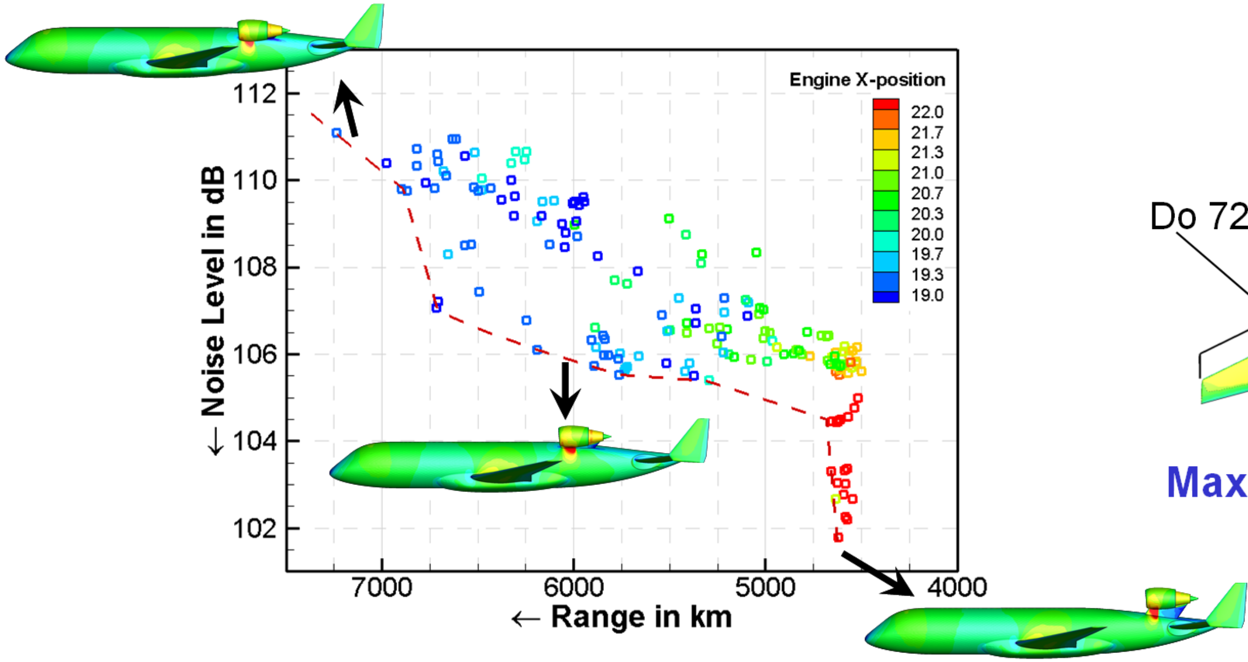
Multi-Disciplinary Optimization (MDO)

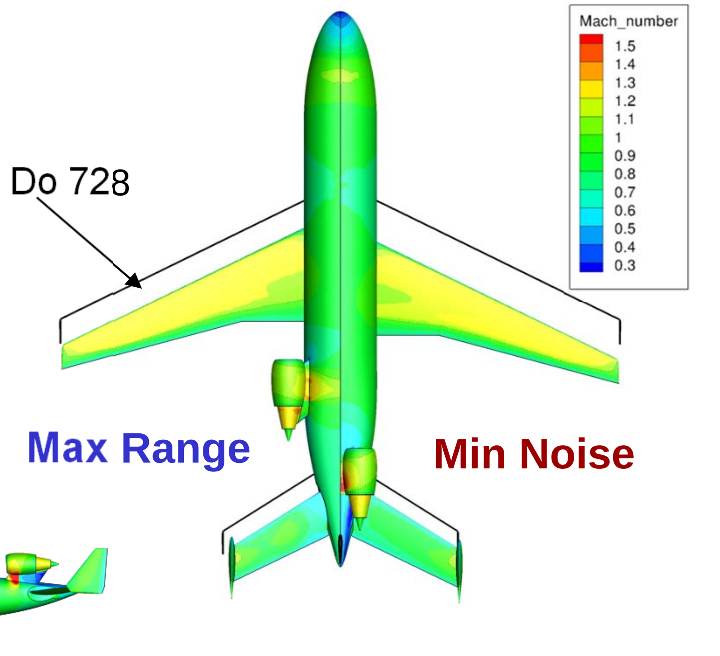
High-Fidelity MDO Key Enabler for Future Aircraft Design

- 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

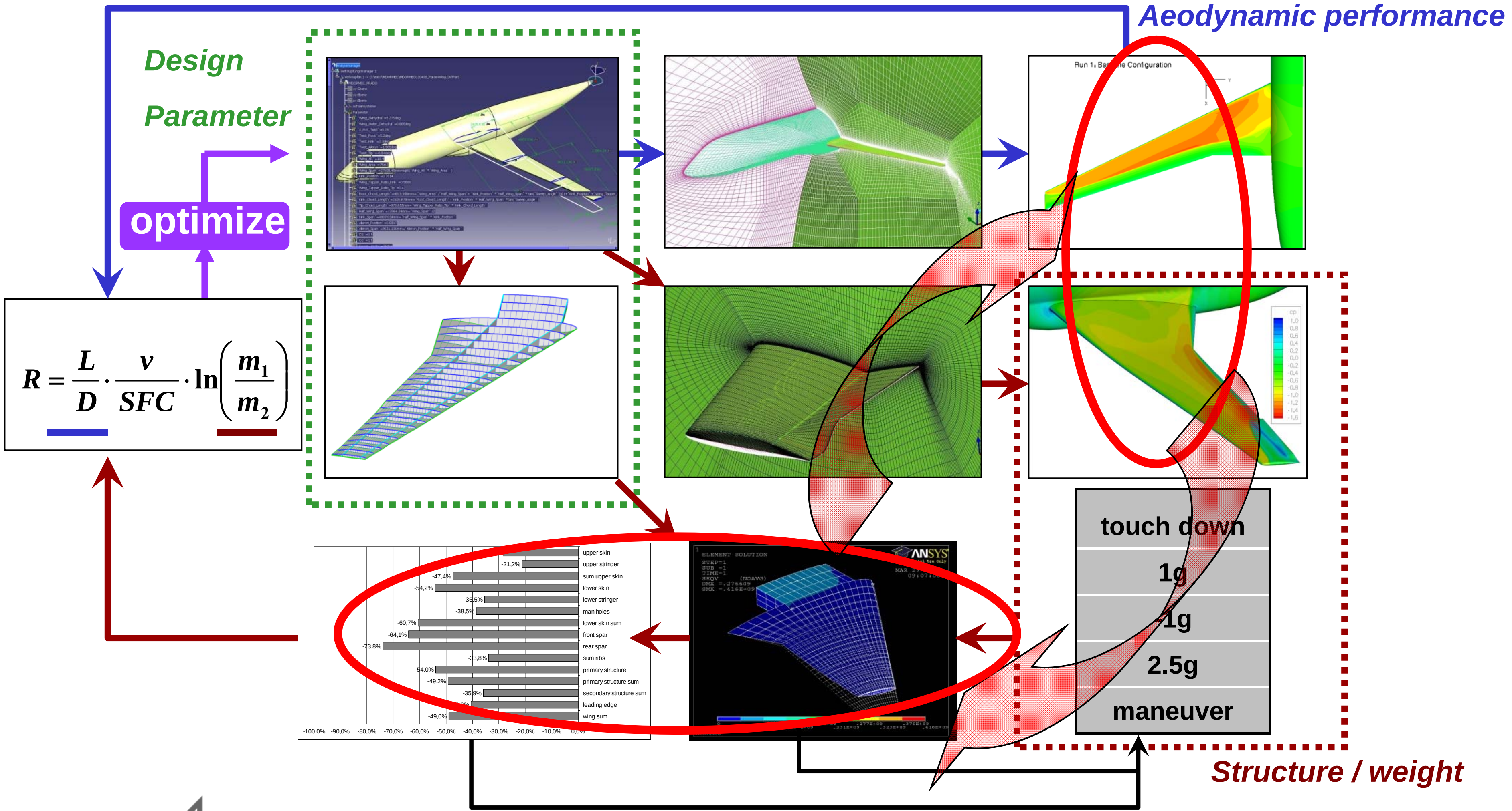




Multi-Disciplinary Optimization

Detailed Design

Status: Aero-Structural Wing Planform Optimization



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Multi-Disciplinary Optimization

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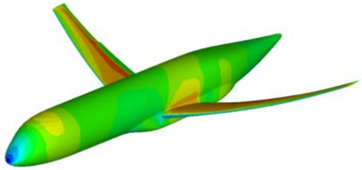
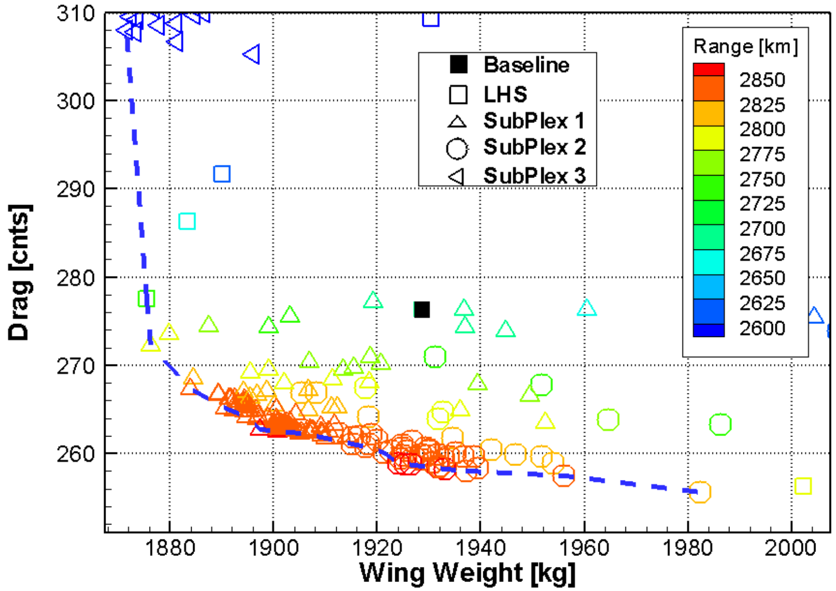


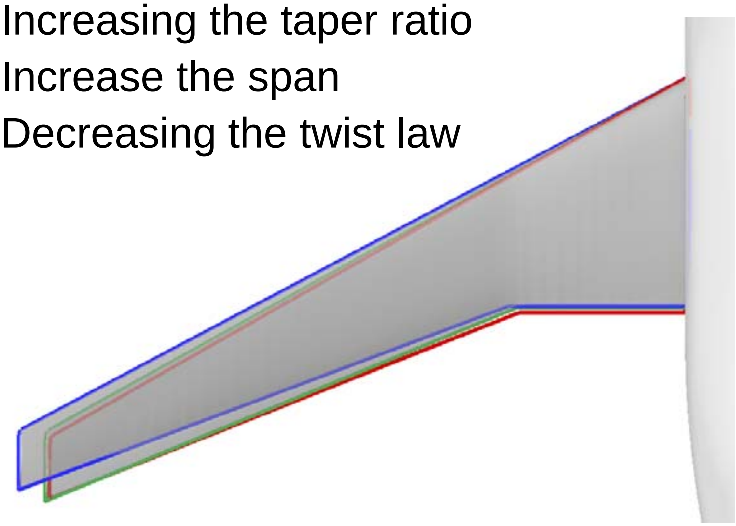
Status: Aero-Structural Wing Planform Optimization

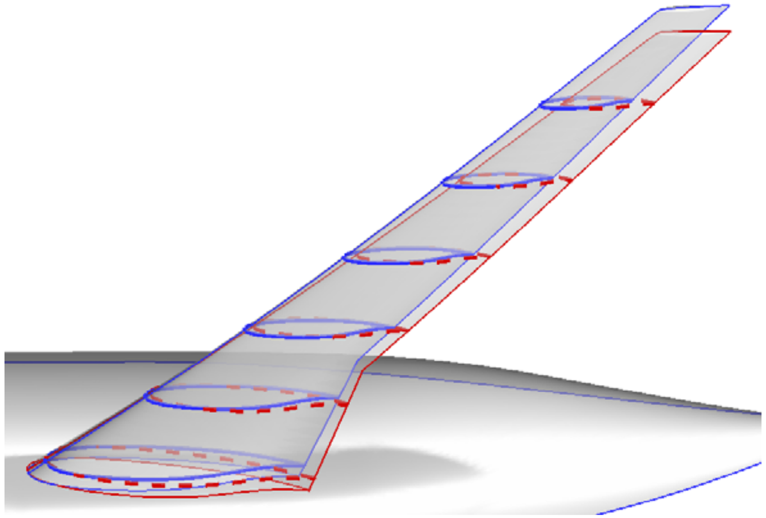
- 7 Design parameters
  - Aspect and taper ratios
  - Sweep angle
  - Twist at 4 sections
- Structure sizing
  - 27 Ribs, 2 Spars, Lower & Upper Shell
  - 4000 nodes



Result:

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

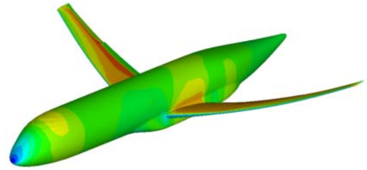




A. Ronzheimer

Multi-Disciplinary Optimization

Detailed Design



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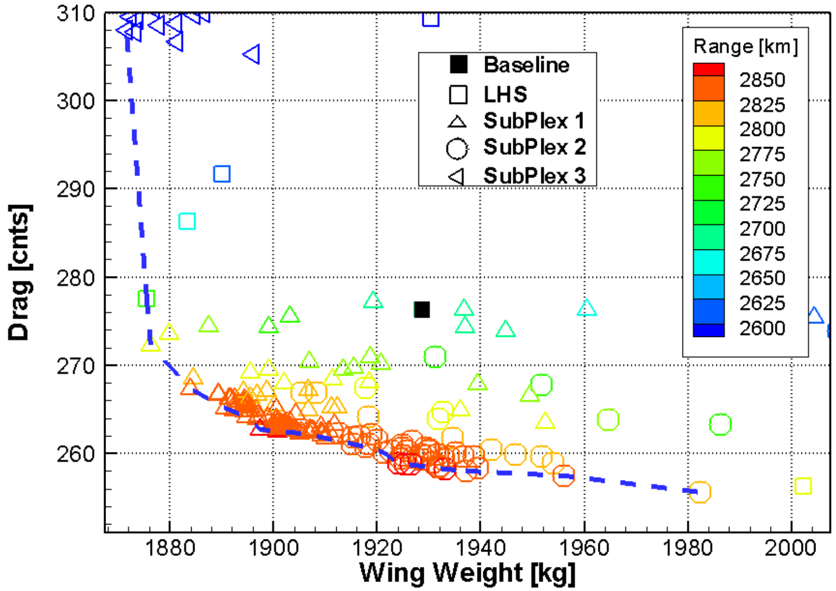

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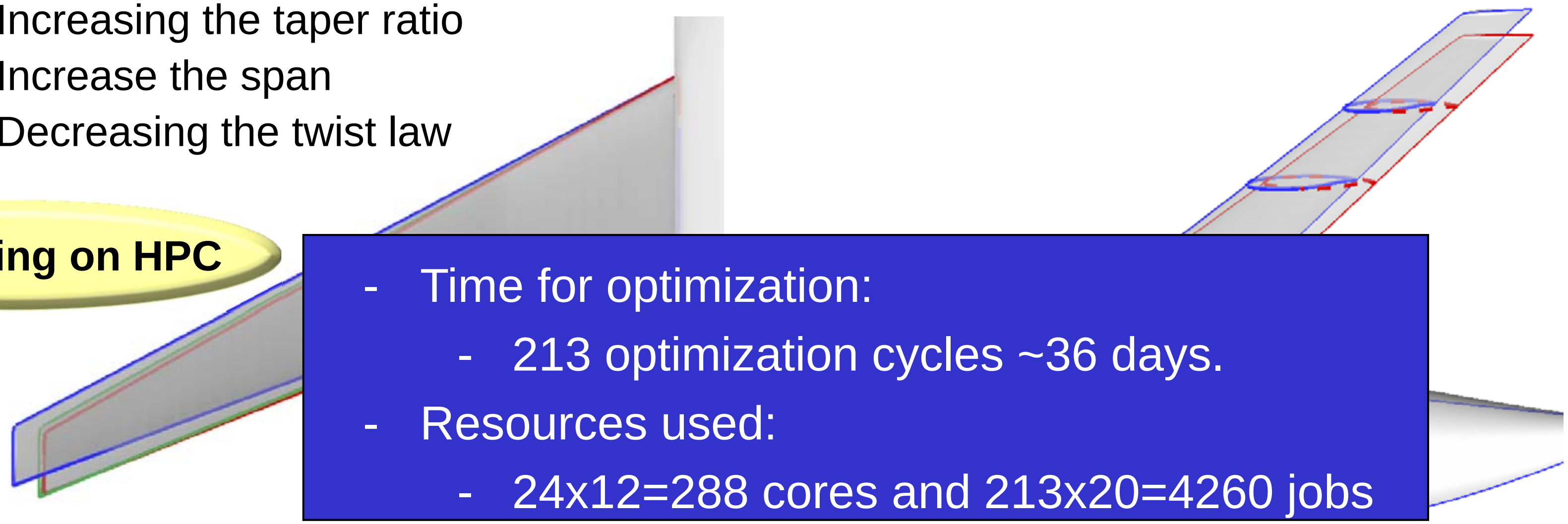


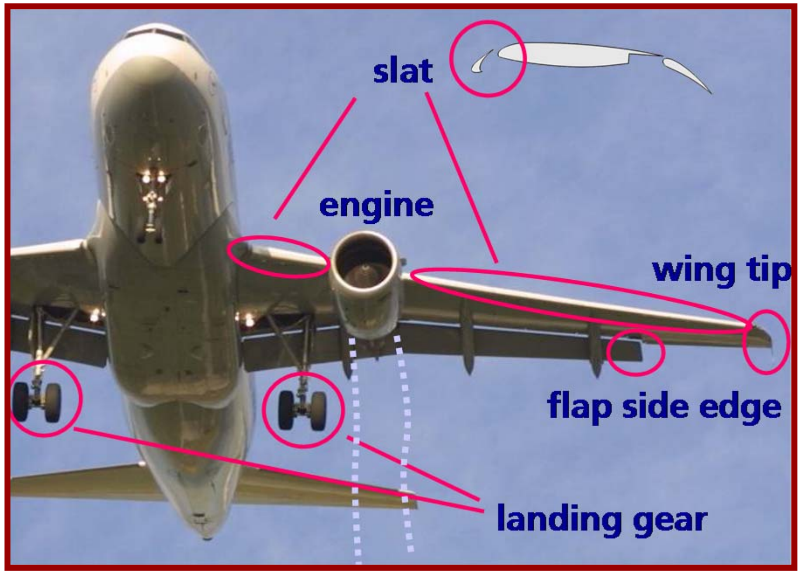
➡ farming on HPC

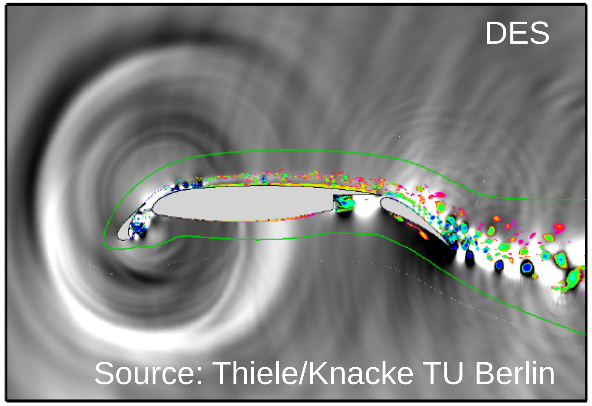
- Time for optimization:
  - 213 optimization cycles ~36 days.
- Resources used:
  - 24x12=288 cores and 213x20=4260 jobs

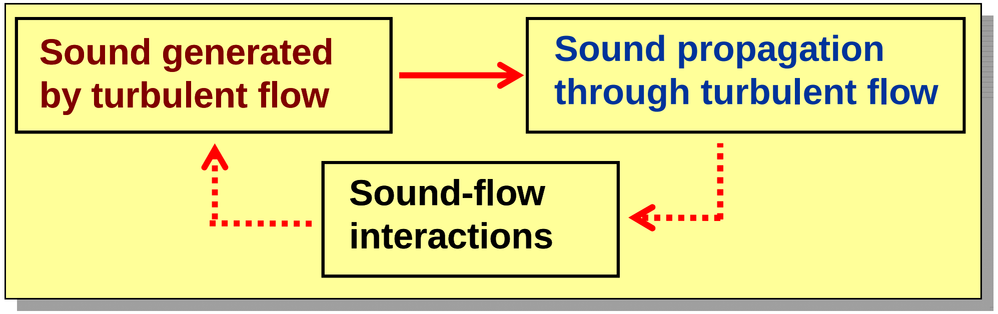
A. Ronzheimer

Aero-acoustic Simulation
Airframe Noise

A/C turbulent source 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

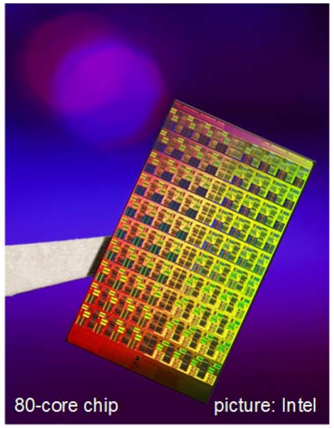
Scattering of engine sound in boundary layer
- 10^{11} degrees of freedom required to resolve aero-acoustics around A/C

→ **Excessive computational cost**

→ **weak scaling**

HPC for Aircraft Design

The "Manycore Shift" in HPC Hardware & Software



Multiple levels of explicit parallelism in cluster hardware

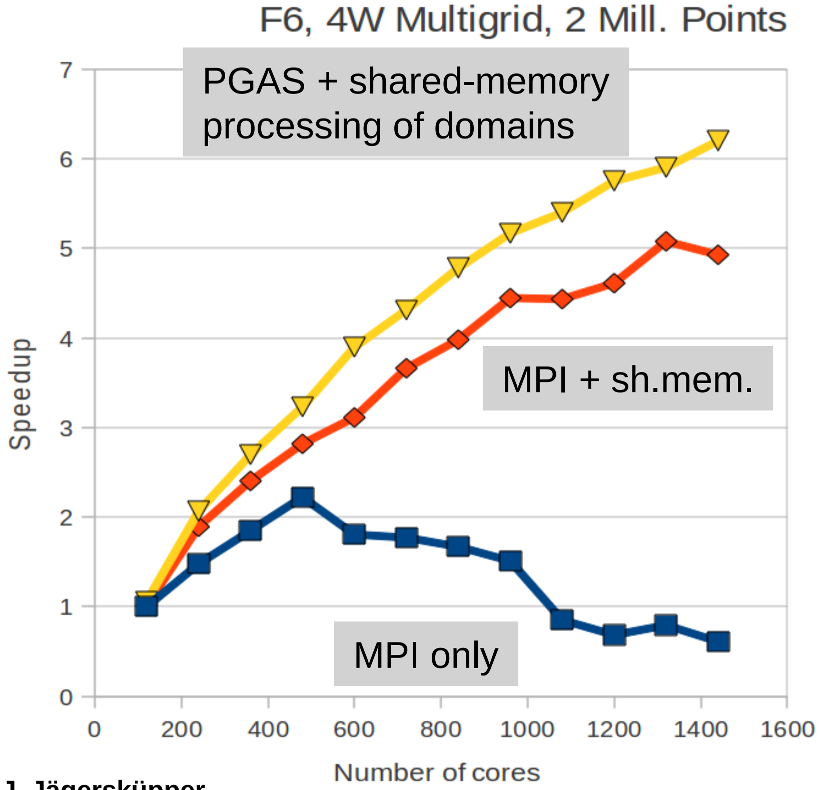
1. nodes — *message passing (MPI)*
2. sockets (multiple CPUs)
3. multi-core CPUs — *task parallelism*
4. symmetric multi-threading
5. SIMD (vector) units — *data parallelism*

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



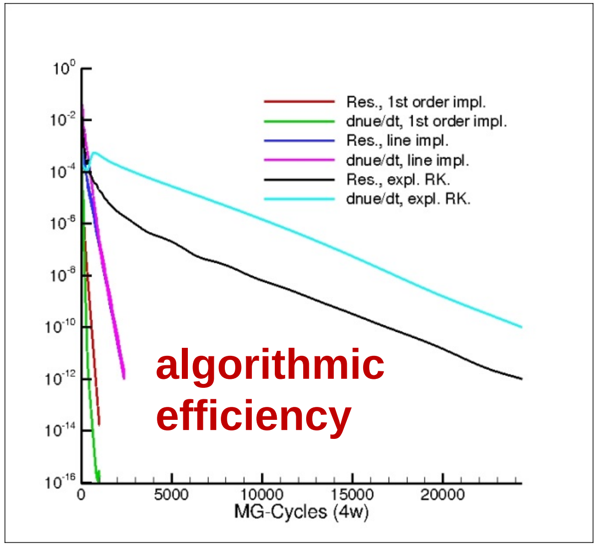
J. Jägersküpper

DLR

HPC for Aircraft Design

The "Manycore Shift" in HPC Hardware & Software

- 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



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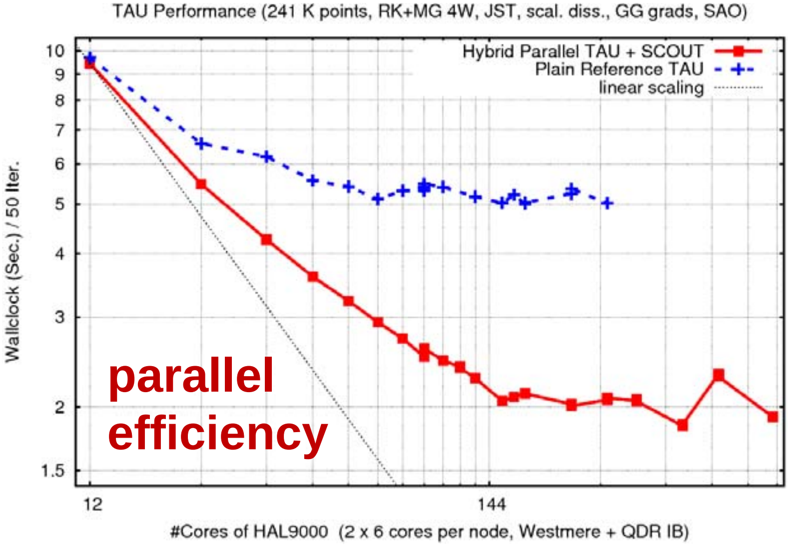

Target: #iterations x wall clock / iteration

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HPC for Aircraft Design

Advanced Solution Strategies

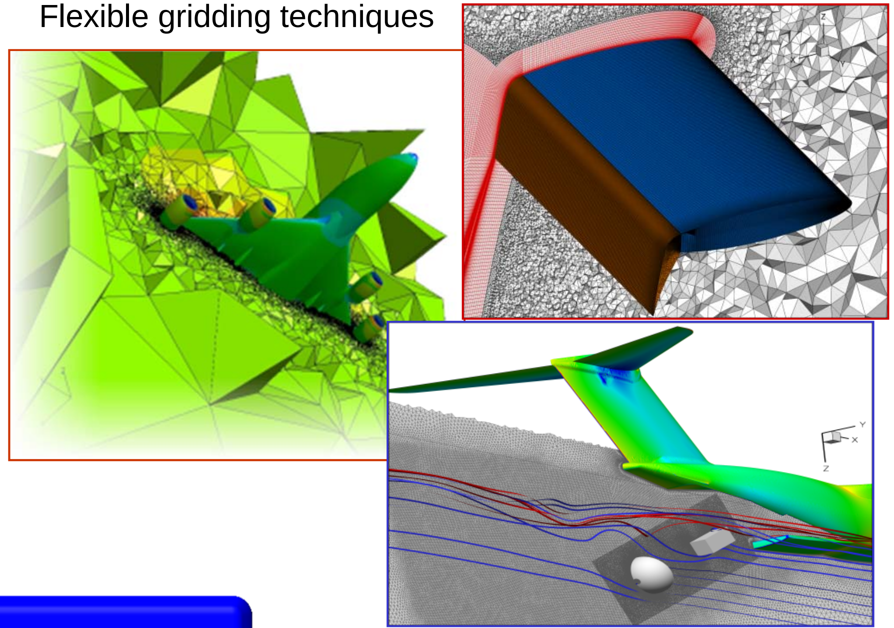
Gridding techniques for complex configurations

- Flexible, high quality
- Automatic for complex geometries

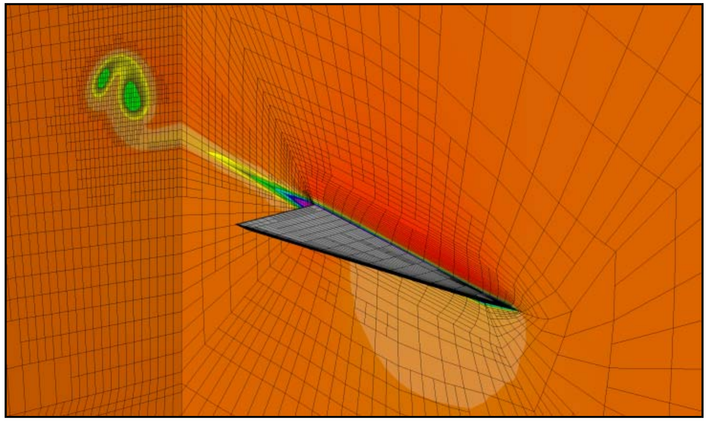
Solution strategies

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

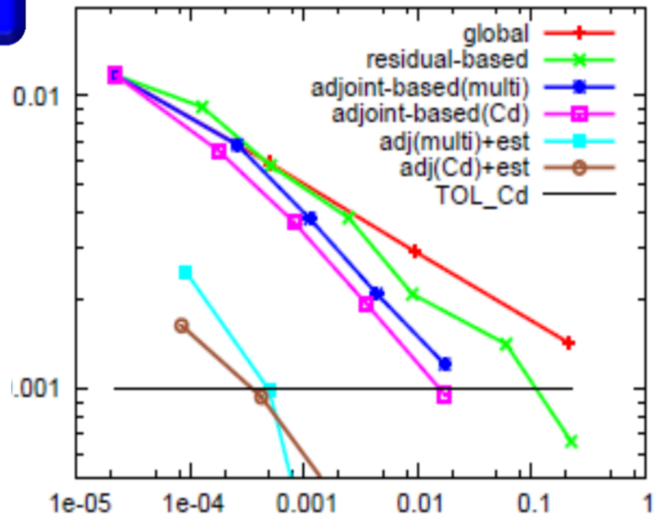
Flexible gridding techniques



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



adaptive higher-order method



computational time

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

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Contributions from DLR colleagues:

O. Brodersen, R. Ewert, R. Heinrich,
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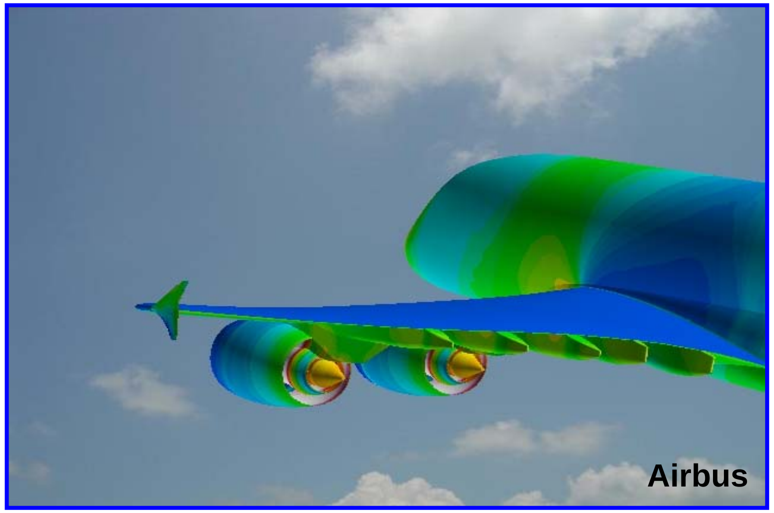
M. Mifsud, A. Ronzheimer



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- 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

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