Propeller Simulation with the DLR TAU-Code
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CFD Simulations of Propeller Flows

- Actuator Disc:
  - Modeling of the propellers as a disc
  - Assumption/specification of the propellers’ effect in terms of a pressure jump and outflow swirl angles
  - Coupling of the flow solver with an external propeller model (based on blade element theory or an airfoil properties database for example)
  - “Azimuthal Averaging”
- (Unsteady) 3D simulation of the rotating propeller
Simulation of the Rotating Propeller

- Steady or unsteady simulation of a single blade utilizing periodic boundary conditions
  - Geometry must be periodic/rotationally symmetric
  - Only axial flow (no AOA)
- Steady state simulation of entire geometry
  - Only axial flow (no AOA)
  - No relative motion
- Unsteady simulation using entire geometry
Simulation of the Rotating Propeller

- What is the benefit or the necessity of conducting the elaborate and expensive simulation of the rotating propeller?
  - Compute unsteady interactions of the propeller wake and aircraft components without simplifications or assumptions
  - Only possibility of obtaining propeller blade loads directly with CFD
  - Input/validation data for actuator disc computations

- Requirements:
  - Capability of modeling multiple rigid bodies in relative motion (Propeller rotating relative to the stationary nacelle/wing/aircraft-configuration)
  - Time-accurate simulation

- Capabilities available in the DLR TAU-code:
  - Chimera grids
  - Motion libraries
  - Dual time stepping
The DLR TAU-code

- Unstructured finite volume Euler/RANS-flow solver
- Dual-grid approach (edge-based data structure) enhances efficiency and enables handling of arbitrary mesh elements
- All standard state-of-the-art CFD techniques available:
  - Central and upwind schemes for spatial discretization
  - Matrix dissipation
  - Multistage Runge-Kutta time-stepping, LUSGS
  - Convergence acceleration through MG, implicit residual smoothing, local time-steps
  - 1- and 2-equation turbulence models (SAE, k-ω SST)
  - Rotational/Vortical correction
  - Preconditioning
- Efficiently parallelized for fast-turn around times through distributed computing
- Grid adaptation
AGARD Propeller: Geometries and Experimental Data Base

- Low-speed experimental investigations conducted in the 80s/90s
- Generic isolated and installed propeller configurations at 1:5-scale
  - Axissymmetric nacelle, wing with NACA 63(10)A-012 airfoil
- 4-bladed propeller designed for typical modern 30-seater regional turboprop, D=0.64m
- Variation of blade pitch, propeller AOA and side slip angles as well as advance ratios
- 5-hole probe measurements of propeller slipstream development, surface pressure measurements by taps on wing and nacelle and propeller force and moment measurements utilizing RSBs and the wind tunnel balance
AGARD Propeller: Grid Generation with Centaur

- Two-block Chimera grids exploit symmetry and periodicity of the geometry to ensure resolution of periodic fluctuations of the flow
- Nacelle/wing block:
  - Cylindrical hole at position of propeller
  - Mesh refined aft of propeller to enhance resolution of blade wakes and tip vortices
  - Mesh for half the geometry
AGARD Propeller:
Grid Generation with Centaur

- Two-block Chimera grids exploit symmetry and periodicity of the geometry to ensure resolution of periodic fluctuations of the flow

- Nacelle/wing block:
  - Cylindrical hole at position of propeller
  - Mesh refined aft of propeller to enhance resolution of blade wakes and tip vortices
  - Completion of nacelle grid
  - AGARD1 Euler: 1,415,770
  - AGARD1 NS: 2,002,442
  - AGARD2 Euler: 3,240,629
AGARD Propeller: Grid Generation with Centaur

- Two-block Chimera grids exploit symmetry and periodicity of the geometry to ensure resolution of periodic fluctuations of the flow.
- Nacelle/wing block...
- Propeller block:
  - Mesh refined aft of propeller to enhance resolution of blade wakes and tip vortices
  - 90°-slice of geometry
AGARD Propeller: Grid Generation with Centaur

- Two-block Chimera grids exploit symmetry and periodicity of the geometry to ensure resolution of periodic fluctuations of the flow
- Nacelle/wing block...
- Propeller block:
  - Mesh refined aft of propeller to enhance resolution of blade wakes and tip vortices
  - Completion of propeller mesh
  - Euler: 2,392,184
  - NS: 6,371,472
AGARD Propeller: Grid Generation with Centaur

- Two-block Chimera grids exploit symmetry and periodicity of the geometry to ensure resolution of periodic fluctuations of the flow
- Nacelle/wing block…
- Propeller block…
- Completed two-block Chimera grids:
  - AGARD1 Euler: 3.807.954
  - AGARD1 NS: 8.373.914
  - AGARD2 Euler: 5.632.813
AGARD Propeller: TAU Capabilities - Matrix Dissipation

- The use of matrix dissipation greatly enhances the resolution and sustainment of the propeller wake and blade tip vortices.
AGARD Propeller: TAU Capabilities – Rotational/Vortical Correction

TAU offers several models to correct for the turbulence models excessive production of eddy viscosity in vortex cores.

Initial tests show a small improvement in blade tip vortex resolution can be achieved, but more detailed investigations (in particular for the 2-equation turbulence models) are still in progress.
AGARD Propeller:
TAU Capabilities - Chimera Interpolation
AGARDP Propeller: TAU Capabilities - Grid Adaptation

- Grid adaptation in wake to improve vortex resolution based on gradients of total pressure, velocity and vorticity
- 50% point number increase specified for the slipstream region
- Appropriate refinement attained for tip vortices and blade wakes
AGARD Propeller: Unsteady Computations

- Simulation at wind tunnel conditions of $M=0.15$, $J=0.7$ ($n=39900\,\text{°/s}$), $\beta=29°$, $\alpha=0°$
- Unsteady computations “from scratch”, i.e. initialization with farfield conditions:
  - $1°/dt \rightarrow$ physical time step $dt=2.5062\times10^{-5} \, \text{s}$
  - 100 inner iterations per time step
- Central scheme, scalar dissipation ($k_2=0.5, k_4=1/64$), SAE turbulence model
- Parallel computation utilizing 16-32 processors of a Linux/Opteron-based cluster
- Periodic/converged solutions achieved after 4 complete propeller revolutions
- Run times:
  - AGARD1 Euler: 16 processors for ~129h
  - AGARD1 NS: 32 processors for ~245h
  - AGARD2 Euler: 32 processors for ~105h
- Data volumes per flowfield solution: ~700MB, ~1.7GB, ~1GB
AGARD Propeller: Propeller Slipstream Axial Velocities
AGARD Propeller: Propeller-Wing Interaction

- Increased velocities in propeller slipstream
- Swirl due to propeller rotation leads to an asymmetric flow, with positive local AOAs for the wing on the side of upward propeller rotation and negative local AOAs on the other → Locally positive or negative lift generation
- Airfoil section @ r/R=0.8125:
  - Unsteady fluctuations due to periodic passage of blade tip vortices
  - Good agreement of time-averaged CFD results with wind tunnel data
AGARD Propeller: Propeller-Wing Interaction
AGARD Propeller: Propeller Thrust Coefficients

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<th>Exp</th>
<th>TAU-Euler</th>
<th>TAU-NS</th>
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<tbody>
<tr>
<td>AGARD1</td>
<td>0.236–0.248 (0.242)</td>
<td>0.2598</td>
<td>0.2429</td>
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<tr>
<td>AGARD2</td>
<td>0.233–0.260 (0.2465)</td>
<td>0.2611</td>
<td>-</td>
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- Euler computations overpredict thrust by about 6-7% versus the mean experimental value.
- Navier-Stokes result shows a reduction of the thrust coefficient by 6% versus the Euler computations, bringing the value within the scatter of the experimental data.
Propeller Simulation with the DLR TAU-Code: Summary

TAU has successfully been applied to the simulation of propellers at both high- and low-speed conditions, greatly enhancing understanding of the complicated aerodynamics of propeller flows.

TAU delivers good results for the investigated isolated and installed propeller configurations:
- Good agreement with wind tunnel data demonstrated for the slipstream development, the aerodynamic interactions with aircraft components (wing pressure distributions) as well as overall propeller forces.

In addition to the essential Chimera and dual time capabilities, TAU features such as LUSGS, matrix dissipation and rotational/vortical corrections of turbulence model eddy viscosity production have either been successfully demonstrated or are in the process of being evaluated for their potential to improve the accuracy and efficiency of propeller simulations.
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