Comparison of different approaches for modeling of atmospheric effects like gusts and wake-vortices in the CFD Code TAU

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Comparison of different approaches for modeling of atmospheric effects in the CFD Code TAU

Overview
- Motivation
- CFD code TAU of DLR
- Methods for modeling of atmospheric effects in TAU
  - „Highly accurate“ method: Resolved Atmosphere Approach (RAA)
  - Simplified method: Disturbance Velocity Approach (DVA)
- Comparison of DVA and RAA
  - Gust encounter
  - Wake vortex encounter
- Application
- Summary and outlook
Motivation

Hamburg, 3rd of March 2008, amateur video
strong winter storm “Emma”
Motivation

- It would be very beneficial, to simulate such scenarios long before the first flight of an aircraft with high accuracy (virtual flight tests)
  - Chance to detect deficiencies in the design
- For the design and the assessment of an aircraft the additional loads due to gusts / wake vortices have to be taken into account
  - Important for the design of the structure
  - Important for the design of control surfaces and the flight control system

Aim

- Development and realization of a strategy enabling to simulate the interaction of an aircraft with gusts / wake vortices based on HiFi CFD solver TAU
- Take into account the reaction of the aircraft by coupling to relevant disciplines
CFD Code TAU of DLR

**Grid strategy**
- unstructured/hybrid grids
- overset grids (Chimera)
- deforming grids
- grid adaptation (refinement, de-refinement)

**Physical model**
- 3D compressible Navier-Stokes equations
- state-of-the-art turbulence models
- arbitrarily moving bodies
- steady and time accurate flows

**Numerical algorithms**
- 2nd order finite volume discretization based on dual grid approach
- central and upwind schemes
- multigrid based on agglomeration
- Runge-Kutta or LU-SGS scheme
- implicit schemes for time accurate flows (dual time stepping)
- MPI parallelization
CFD Code TAU

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- **overset grids (Chimera)**
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Chimera technique with automatic hole cutting for simulation of moving spoilers
CFD Code TAU

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Mesh deformation for modeling of movables
CFD Code TAU

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Methods for modeling of atmospheric effects in TAU
Resolved Atmosphere Approach (RAA)

- Implementation of an unsteady boundary condition, to feed the atmospheric disturbances into the discretized flow domain

Discretized flowfield

Additional inflow velocity prescribed at the boundary
Methods for modeling of atmospheric effects in TAU Resolved Atmosphere Approach (RAA)

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Discretized flowfield
Methods for modeling of atmospheric effects in TAU
Resolved Atmosphere Approach (RAA)

- Implementation of an **unsteady boundary** condition, to feed the atmospheric disturbances into the discretized flow domain

**Advantage:**
- Allows to capture mutual interaction of atmospheric disturbance and aircraft

**Disadvantage**
- A high spatial resolution of the COMPLETE flowfield is required, to transport e.g. gusts without significant numerical losses
- Very expensive . . . do exist alternatives??
Methods for modeling of atmospheric effects in TAU

**Disturbance Velocity Approach (DVA)**

- A popular method found in literature is the **Disturbance Velocity Approach***

\[
\frac{d}{dt} \int_{V(t)} \rho \, dV + \int_{S(t)} \rho (\vec{v} - \vec{v}_B - \vec{v}_i) \cdot d\vec{S} = 0
\]

additional disturbance velocity induced by e.g. gusts / wake vortices, which can be prescribed as function in space and time

*) Other names for this method: *Field-Velocity-Approach* or *Artificial-Velocity-Approach*
Methods for modeling of atmospheric effects in TAU

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\[
\frac{d}{dt} \int_V \rho \, dV + \int_{S(t)} \rho \left( \bar{v} - \bar{v}_B - \bar{v}_l \right) \cdot dS = 0
\]

- Advantage: Easy to implement + standard grids can be used
- Disadvantage: Takes into account the influence of gusts on the aircraft, but not vice versa! → Errors expected especially for e.g. gusts of short wave length

- **Question:** How good is the DVA compared to a method resolving atmospheric disturbances??
  - A 2D study has been compiled in 2013 (see Heinrich, R., Reimer, L.: *Comparison of Different Approaches For Gust Modelling in the CFD Code TAU, IFASD 2013, Bristol*)

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Methods for modeling of atmospheric effects in TAU
Comparison of DVA and RAA for gusts

Results of 2D study
- NACA wing-HTP configuration
- Ma = 0.25; Ma = 0.75
- Viscous and inviscid
- λ / cref = 1, 2, 4

\[
\text{err}_{C_{L,max}} = \left| \frac{C_{L,max,RGA} - C_{L,max,DVA}}{C_{L,max,RGA}} \right| \times 100\% 
\]

<table>
<thead>
<tr>
<th>λ / cref</th>
<th>err_{C_{L,max}} [%]</th>
<th>Ma = 0.25</th>
<th>Ma = 0.75</th>
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<tr>
<td></td>
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<td>NS</td>
<td>Euler</td>
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<td>1,96</td>
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</tr>
<tr>
<td>4</td>
<td>0,21</td>
<td>0,47</td>
<td>0,42</td>
</tr>
</tbody>
</table>

RAA & DVA results are very similar for \(\lambda_{gust} / c_{ref} \geq 2\) (for vertical gusts in 2D)!

Ma = 0.25, Re = 5 x 10^6
Solid : RAA
Dashed : DVA
Methods for modeling of atmospheric effects in TAU
Comparison of DVA and RAA for gusts

Extend study to 3D
- Usage of configuration with forward swept wing
  - \( Ma = 0.78 \)
  - \( Re = 26.4 \times 10^6 \)
  - \( \alpha = 0.0^\circ \)
  - \( \lambda_{\text{gust}} / c_{\text{ref}} = 1, 2, 4 \)
  - \( v_{\text{gust}} / v_{\text{inf}} = 0.1 \)
  - Altitude \( h = 11 \) km
  - Basic grid: \( 11.2 \times 10^6 \) nodes
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- Altitude $h = 11 \text{ km}$
- Basic grid: $11.2 \times 10^6$ nodes
- Create nearfield grid based on basic grid
- Embed this into a Cartesian background mesh

$\Delta x = 0.05 \ c_{ref}$
Methods for modeling of atmospheric effects in TAU
Comparison of DVA and RAA for gusts

Extend study to 3D
- Usage of configuration with forward swept wing
  - Ma = 0.78
  - Re = 26.4 x 10^6
  - \( \alpha \) = 0.0°
  - \( \frac{\lambda_{gust}}{c_{ref}} = 1, 2, 4 \)
  - \( \frac{v_{gust}}{v_{inf}} = 0.1 \)
  - Altitude h = 11 km
  - Basic grid: 11.2 x 10^6 nodes
  - Create nearfield grid based on basic grid
  - Embed this into a Cartesian background mesh
  - Add fine resolved gust transport mesh
  - In total 17.3 x 10^6 nodes

\( \Delta x = 0.01 \lambda_{gust} \)
\( \Delta x = 0.05 c_{ref} \)

\( t = 0; \) gust in front of flow domain
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$\Delta x = 0.05 \text{c}_{\text{ref}}$

$t = 1.5 \lambda_{\text{gust}} / u_{\text{inf}}$, gust centered in transport grid
Methods for modeling of atmospheric effects in TAU
Comparison of DVA and RAA for gusts

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<th>$\text{err}_{CL,\text{max}}$</th>
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<tbody>
<tr>
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<td>1.42%</td>
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$\text{err}_{CL,\text{max}} = \left| \frac{c_{L,\text{max},\text{RAA}} - c_{L,\text{max},\text{DVA}}}{c_{L,\text{max},\text{RAA}}} \right| \times 100\%$
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3D results show similar trends compared to 2D simulations.

DVA is sufficient accurate for gust load prediction down to \( \lambda_{\text{gust}} / c_{\text{ref}} = 2 \)
Methods for modeling of atmospheric effects in TAU
Comparison of DVA and RAA for wake vortex encounter problems

DVA and RAA can now also be applied for simulation of wake vortex encounters

- Analytical function according to Burnham-Hallock
  \[ V_i(r) = \frac{\Gamma}{2\pi} \frac{r}{r_c^2 + r^2} \]

- Disturbance velocity field is created by superposition of two counter rotating vortices with circulation \( \Gamma \) and distance \( b \)
Methods for modeling of atmospheric effects in TAU
Comparison of DVA and RAA for wake vortex encounter problems

Comparison of DVA and RAA
- LANN wing, span of 32 m
- Interacts with a single vortex of a heave aircraft (190 t)
  - $\Gamma = 486 \text{m}^2/\text{s}$
  - $r_c = 2.412 \text{m}$
  - $Ma = 0.78$, $\text{AoA} = 0^\circ$
- A nearfield grid around LANN wing is embedded into a Cartesian background grid
- **Question**: Which resolution is required, to transport the vortex from the inflow boundary to the wing?
Comparison of DVA and RAA

- LANN wing, span of 32 m
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- A nearfield grid around LANN wing is embedded into a Cartesian background grid

**Question**: Which resolution is required, to transport the vortex from the inflow boundary to the wing?

- Perform a mesh density study

| Mesh Density | 10 cells to resolve $r_c$ | 5 cells to resolve $r_c$ | 2.5 cells to resolve $r_c$ |
Methods for modeling of atmospheric effects in TAU
Comparison of DVA and RAA for wake vortex encounter problems

- Results of mesh conversion study

![Lines of constant z-velocity (w)](image)

- fine
- medium
- coarse

- inflow boundary (prescribed)
- outflow boundary
Methods for modeling of atmospheric effects in TAU
Comparison of DVA and RAA for wake vortex encounter problems

- Results of mesh conversion study (results on a ray through the vortex core)
Methods for modeling of atmospheric effects in TAU
Comparison of DVA and RAA for wake vortex encounter problems

- Results of mesh conversion study (results on a ray through the vortex core)

\[
\text{err}_{\text{mean}} = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{w_{\text{out,}i} - w_{\text{in,}i}}{w_{\text{in,}\text{max}}} \right) \times 100\%
\]

\[
\text{err}_{\text{max}} = \max \left( \frac{w_{\text{out,}i} - w_{\text{in,}i}}{w_{\text{in,}\text{max}}} \right) \times 100\%
\]

<table>
<thead>
<tr>
<th>Mesh Type</th>
<th>Fine mesh</th>
<th>Medium mesh</th>
<th>Coarse mesh</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{err}_{\text{max}}</td>
<td>0.90%</td>
<td>4.95%</td>
<td>15.88%</td>
</tr>
<tr>
<td>\text{err}_{\text{mean}}</td>
<td>0.11%</td>
<td>0.64%</td>
<td>2.57%</td>
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- To be on the safe side, the fine resolution has been selected for the computation of wake vortex encounter of the LANN wing
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  - $r_c = 2.412\text{ m}$
- $Ma = 0.78$, $AoA = 0^\circ$
- Nearfield grid around LANN with $4.8 \times 10^6$ nodes
- Cartesian background mesh with $2.8 \times 10^6$ nodes
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- $M_a = 0.78$, $\text{AoA} = 0^\circ$
- Variation of core position from tip to tip
- The prediction error of lift and rolling moment coeff. is below 1%!

DVA is well suited for wake vortex encounter studies
Application

Wake vortex encounter of transport aircraft

- Transport aircraft (70 t) flying through wake vortices of heavy aircraft (190 t)
- $Ma = 0.78$, $h = 37.000$ ft
- Usage of DVA for modeling of wake of leading aircraft
  - $\Gamma = 486 m^2/s$
  - $r_c = 2.412$ m
  - $b = 47.36$ m

- Perform unsteady CFD simulation (guided motion)
- Perform unsteady coupled simulation (CFD-FM)
Application
Wake vortex encounter of transport aircraft
Application
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Wake vortex encounter of transport aircraft

![Diagram showing wake vortex encounter of transport aircraft](image-url)
Application

Wake vortex encounter of transport aircraft
Application
 Wake vortex encounter of transport aircraft

\[ uz: \ -12 \ -8 \ -4 \ 0 \ 4 \ 8 \ 12 \ 16 \]
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*) Disturbance Velocity Approach

Comparison of monodisciplinary and multidisciplinary simulation

![Graph showing comparison of CFD and CFD-FM simulations with time [s] on the x-axis and C-lift on the y-axis.](image)
Summary

- Two methods for modeling of atmospheric disturbances are available in TAU now:
  - Simplified approach: DVA
  - A „highly-accurate“ method allowing to simulate the mutual interaction of aircraft and atmospheric disturbances: RAA
- Comparison of both methods in terms of global loads show that:
  - DVA achieves results comparable to results of „highly-accurate“ method down to \( \frac{\lambda_{\text{gust}}}{c_{\text{ref}}} \geq 2.0 \) for viscous and inviscid flow in 2D and 3D for vertical gusts
  - Very good agreement of DVA and RAA for gust encounter problems
Next steps

- Perform similar investigation for lateral gusts
  - Maybe the interaction of the lateral gust with the tip vortices have a significant impact on the results, which cannot be captured by the DVA

Acknowledgement

- The research leading to these results has partly been supported by the AEROGUST project funded by the European Commission under grant agreement number 636053 and the German research project FOR1066 “Simulation des Überziehen von Tragflügeln und Triebwerksgondeln” funded by the “Deutsche Forschungsgemeinschaft DFG”
Thank you for your attention!