Development Lines of Improved Physical Modeling at DLR

Window on Science Seminar
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US Air Force Research Laboratory (AFRL)
Wright-Patterson Air Force Base, OH, USA

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DLR, Institute for Aerodynamic and Flow Technology
C²A²S²E, Turbulence & Transition Group

Center for Computer Applications in AeroSpace Science and Engineering

Wissen für Morgen
The German Aerospace Center - DLR

- Three primary functions
  - National aeronautics and space research center of the Federal Republic of Germany

- Germany’s space agency

- One (out of a number of) project management agencies for national research projects
The German Aerospace Center - DLR

- Three primary functions
  - National aeronautics and space research center of the Federal Republic of Germany
    - Personnel: ~ 6000
  - Germany’s space agency
    - Personnel: ~ 800
  - One (out of a number of) project management agencies for national research projects
    - Personnel: ~ 1200
The German Aerospace Center - DLR

- 6 research areas:
  - Aeronautics
  - Space
  - Energy
  - Transport
  - Digitalisation (new)
  - Security (new)

- Institute for Aerodynamic and Flow Technology

- 8100 employees in 40 institutes at 20 sites in Germany

Braunschweig: H. Blenk, A. Busemann, …

Göttingen: L. Prandtl, H. Schlichting, W. Tollmien, Th. von Kármán, …
Institute for Aerodynamic and Flow Technology

- Research and work areas
  - Software Development
  - Aircraft Aerodynamics
  - Aircraft Design and Assessment
  - Experimental Methods
  - Military Aircraft
  - Helicopter Aerodynamics
  - High-Speed-Configurations
  - Spacecraft
  - Aeroacoustics
  - Technical Flows
  - Flow Measurement Technology
  - Acoustic Measurement Technology
  - Hardware
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Outline

- Introduction
- Reynolds stress models (RSM)
- Scale resolving simulations (SRS)
- Transition prediction and modeling
- Turbulence modeling improvements
- Outlook
Introduction

Overview

- C²A²S²E – Numerical Methods Branch → CFD Code Development
  - TAU code – external aerodynamics, unstructured, FV, compressible
    → air vehicles
  - THETA code – internal/external flows, unstructured, FV, incompressible
    → combustion, wind turbines, two-phase flows (gas/liquid)
  - Flucs (FLexible Unstructured CFD Software) – external aerodynamics
    → DLR’s ‘next generation’ flow solver
    → unstructured, 2nd order FV branch + HO-DG-branch, compressible/incompressible
    → massive hybrid parallelization
    → flow-solver component of a multi-disciplinary simulation system FlowSimulator
    → development currently ongoing
    → 1st release planned for 12/2021

- Main Customers
  - Internal: Transport Aircraft, Helicopters (incl. Wind Turbines), High-Speed Configurations, Spacecraft
  - External: Airbus Operations

- Focus: Transport Type Aircraft
Our major driver: *The Digital Aircraft*

Numerical Analysis of Full Flight Envelope

- Extension of confidence region towards edge of flight envelope
  - Unsteady flows
  - Strong non-linearities
    - Separated flow regions
    - Strong shocks
    - Shock/boundary-layer interaction
    - …
  - CFD solver capabilities growing
    - Discretization schemes
    - Grid generation, higher resolution, geometrical complexity and details, …
    - HPC capacities and parallelization strategies
    - …

- Turbulence and transition models have to keep up with solver capabilities.
  - Coupling and extension of models needed.
Vision: **The Digital Aircraft**

**Future goal for CFD**

- Aircraft design and analysis based strongly on numerical simulation
- Bring down number of computations necessary and free from current configuration knowledge
- Two basic concepts
  - Time accurate maneuver simulations: *Flying the equations*
  - Generation of aerodynamic/aeroelastic data: *Flying through the data base*
Vision: The Digital Aircraft

Future goal for CFD

- Aircraft design and analysis based strongly on numerical simulation
- Bring down number of computations necessary and free from current configuration knowledge
- Two basic concepts
  - Time accurate maneuver simulations: *Flying the equations*
  - Physical Modeling for High Fidelity CFD
  - Generation of aerodynamic/aeroelastic data: *Flying through the data base*
Vision: The Digital Aircraft

Future goals for CFD:
- Aircraft design and analysis based strongly on numerical simulation
- Bring down number of computations necessary and free from current configuration knowledge
- Two basic concepts:
  - Time accurate maneuver simulations: Flying the equations
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Vision: The Digital Aircraft

Numerical Analysis of Full Flight Envelope

- For accurate predictions, besides high grid resolution and accurate numerical handling of the equations, physical modeling is a key issue.

- **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. Transition prediction and modeling
     - Necessary condition for accurate results of turbulence models within the full flight envelope
  4. Turbulence modeling improvements
     - Targeted experimental (physical & numerical) investigations for specific flow phenomena
Reynolds stress models

Differential RSM (DRSM)

- DRSM represent highest level of RANS-modeling
  - Individual equations for stress components
  - Anisotropy of turbulence inherently accounted for
  - Effects of rotation and streamline curvature included
    - No corrections for free vortices necessary
  - No stagnation point anomaly
  - 7 model equations
- Sometimes lack of robustness for complex configurations
- DRSM in TAU
  - SSG/LRR-ω model (standard model)
    - Based on Menter’s BSL ω-equation
    - Exact transformation to $g = 1/\sqrt{\omega}$ and to $\tilde{\omega} = ln(\omega)$
    - Higher numerical stability + no near wall grid dependence
  - $\varepsilon^h$-JHh-v2 model (Jakirlic-Hanjalic + ISM of TU-BS)
    - Based on homogeneous dissipation rate $\varepsilon^h$
    - Advanced near-wall treatment + anisotropic dissipation
Reynolds stress models
Application of Reynolds Stress Models

Realistic aircraft configuration
Re = 40 × 10^6, M = 0.85, \( \alpha = 2.0^\circ \)

- Significant better shock prediction
- Very different separation pattern
Reynolds stress models

Application of Reynolds Stress Models

NASA Common Research Model (CRM), DWP-4

Re = 5 × 10^6, M = 0.85, α = 2.0, 2.75, …, 4.0

Grids: L3(5M), L4(17M)

RSM shows very low grid dependence
Reynolds stress models

Application of Reynolds Stress Models

NASA Common Research Model (CRM)

\[ \frac{Re}{Ma} = 5 \times 10^6 / 0.85 \]

Reynolds stress models
Application of Reynolds Stress Models

Flow-through nacelle at stall
Re = 1.3 \times 10^6, M = 0.11

- URANS combined with e^N method
- Measured separation onset around \( \alpha \geq 24^\circ \)
- Improvement by DRSM
- In particular \( \varepsilon^h \)-JHh-v2 model
  - Coefficients depend on turbulence quantities
  - Uses \( \varepsilon^h \) instead of \( \varepsilon \): by targeted calibration matching with DNS data near walls achieved

Source: PhD thesis A. Probst

Oil-flow picture (left) and JHh-v2 RSM (right)
Scale resolving simulations

Basic approach

- Classical hybrid RANS/LES models
  - Detached-Eddy Simulation (DES, 1997)
  - Delayed DES (DDES, 2006)
  - Improved DDES (IDDES, 2008)
  - Coupled with SA or $k-\omega$ type RANS models

- Numerics
  - 2nd order central spatial discretization of all equations
  - 4th order matrix artificial dissipation with $k^{(4)} = 1/128$
  - Skew-symmetric convective fluxes (for kinetic energy conservation)
  - Low Mach number preconditioning (LMP) for $M < 0.3$
  - 2nd order dual-time stepping

- Range of applicability
  - Flows with massive local separations
  - Clear distinction between attached (stable) and separated (unstable) regions

NASA CRM at low speed and high AoA

DLR-F15
3-element high-lift airfoil near maximum lift
Scale resolving simulations
Sample applications of basic approach

NASA tandem cylinder

TAU results: green

Mean pressure

Pressure fluctuations

- Good prediction all approaches on both cylinders
- Influence of numerical method and underlying RANS model small

Experimental setup in WT

- \( L/D = 3.7 \)
- \( M = 0.1285 \)
- \( Re_D = 1.66 \times 10^5 \)

• k-ω based models too "noisy"
→ Reason unclear
Scale resolving simulations
Sample applications of basic approach

**SA-DDES**

**URANS with different turbulence models**

- BART Experiment, trip 70-80°
- UniMan, KE URANS
- UniMan, LPKE URANS
- UniMan, SST URANS
- UniMan, EBRSM URANS

**Turbulence simulations of NASA tandem cylinder**

**Experimental setup in WT**

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- \( M = 0.1285 \)
- \( \text{Re}_D = 1.66 \times 10^5 \)

**Pressure fluctuations**

- Influence of numerical method and underlying RANS model small

- \( \text{k-}\omega \) based models too “noisy”

\( \rightarrow \) Reason unclear
Scale resolving simulations

Extended approach

- Improved Numerics
  - Better satisfying general LES requirements
    -> Very high accuracy -> low dissipation (LD) and low dispersion (LD2)
  - LD2-scheme: 2nd-order central scheme with
    - Reduced dissipation settings (optimized)
    - Reduced dispersion by appropriate flux reconstruction
  - Test with pure LES applications, e.g. periodic 2D channel flow
  - Switch of standard RANS scheme into LD2 scheme for LES: apply optimized numerics in LES regions only
    -> Adaptive numerical scheme for hybrid RANS/LES computations

<table>
<thead>
<tr>
<th></th>
<th>$Re_\tau$</th>
</tr>
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<tbody>
<tr>
<td>DNS</td>
<td>395</td>
</tr>
<tr>
<td>Ref. Num.</td>
<td>358</td>
</tr>
<tr>
<td>LD</td>
<td>389</td>
</tr>
<tr>
<td>LD2</td>
<td>393</td>
</tr>
</tbody>
</table>

WR-LES: given $Re_\delta$ (mass flow), target quantity $Re_\tau$ (wall shear stress)

Velocity profile

Resolved Reynolds stresses

2D-Channel, $Re_\tau = 6875$

LES-WALE
Scale resolving simulations
Sample applications of extended approach

Flow separation at backward facing step (BFS)

- SA-DDES of backward-facing step; Re_h = 38,000
- Optimized scheme in LES region, standard stable scheme in RANS region
- Switch based on suitable sensor function (l_{hyb}/l_{RANS} sensor)

Standard scheme

Optimized scheme: adaptive RANS/LES numerics

grey: Optimized LES-scheme in separated/re-attachment region

white: RANS-scheme in attached flow

Improved resolution in LES region (Q-criterion)
Scale resolving simulations
Sample applications of extended approach

Aircraft nacelle in side wind (1)

⇒ SST-IDDES + adaptive scheme with LD2

\[ DC60 = \frac{P_{tot}(60^\circ) - P_{tot}(360^\circ)}{q_\infty} \]
Scale resolving simulations
Sample applications of extended approach

Aircraft nacelle in side wind (2)
→ SST-IDDES + adaptive scheme with LD2

Intake Distortion Measure
(Values in percentage of target operating point)

- RANS k-w SST
- IDDES k-w SST

Shock-induced separation
LD2 scheme
Reference scheme
Scale resolving simulations

Extended approach

→ Improved Modeling → *Towards extension of the applicability range from massive to incipient separation*

→ Three areas
  1. RANS/LES sensors for pressure-induced separation
  2. Acceleration of transition from RANS to LES (→ „grey area“ mitigation)
  3. Underlying RANS model (→ better representation of separation point)

1. RANS/LES sensors for pressure-induced separation

→ Shortcomings of DDES
  → No reliable “shielding” of attached BLs
  → No clear RANS/LES interface at separation

→ DLR development Algebraic DDES (ADDES)
  → Boundary-layer (BL) detection
  → Separation detection
  → Algebraic RANS/LES sensor
Scale resolving simulations

Extended approach

- Improved Modeling → ADDES

  1. **RANS/LES sensors for pressure-induced separation**

  - BL detection
    - algebraic BL criteria for $U_{\text{edge}}$
    - search algorithm to detect $\delta_{99}$

  - Separation detection
    - Shape factor $H = \delta^*/\Theta \rightarrow H_{\text{crit}}$ as separation criterion (Castillo et al., 2004)
    - $H_{\text{crit}}$ RANS-model dependent
      → calibration necessary

  - Algebraic RANS/LES sensor
    - RANS mode if: $d_w < \delta_{99}$ and $H < H_{\text{crit}}$
    - LES mode if: $H > H_{\text{crit}}$
Scale resolving simulations

Extended approach

- Improved Modeling → ADDES

Demonstration of separation detection

- Automatic injection of synthetic turbulence under development
Scale resolving simulations

Extended approach

2. Acceleration of transition from RANS to LES

- Hybrid RANS/LES of incipient separation suffers from “grey area”:
  - Weak separations rather stable w.r.t. outer disturbances
  - Hybrid RANS/LES switches to LES mode, but resolved turbulence is delayed
- Undefined modelling state with low total (modelled + resolved) turbulent stress

Techniques for grey area mitigation considered in TAU code:

1. **Stochastic forcing** of modeled turbulence
2. Modified **LES scale** considering **local vorticity** vector
   - Both 1. and 2. applicable to rather unstable separation or free shear flow
3. **Synthetic turbulence** generated from RANS data
   - Complex approach, but applicable to weakly separated or attached flow
Scale resolving simulations

Extended approach

1. Improved Modeling → Synthetic turbulence (RANS → LES)

2. Acceleration of transition from RANS to LES

- Initial implementation of Synthetic Eddy Method (SEM, 2006)
  - Artificial fluctuations generated from given turbulence statistics
  - First tests with SEM applied at inflow boundary:
    - 2D channel flow
    - Rounded step with separation:

<table>
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<tr>
<th>Method</th>
<th>$x_{\text{separation}}$</th>
<th>$x_{\text{reattachment}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDDES</td>
<td>1.15</td>
<td>6.04</td>
</tr>
<tr>
<td>IDDES + SEM</td>
<td>0.72</td>
<td>4.99</td>
</tr>
<tr>
<td>LES (reference)</td>
<td>0.83</td>
<td>4.36</td>
</tr>
</tbody>
</table>

- Ongoing:
  - Full integration in hybrid RANS/LES (i.e. combination with ADDES)
Scale resolving simulations

Extended approach

- Improved Modeling → Synthetic turbulence (RANS → LES)
  - 2D wall-mounted hump

Snapshot of: $\lambda_2 = 5 \cdot (U/c)^2$
(SST-IDDES + SEM(x=-1); mand. time step)
Scale resolving simulations

Extended approach

- Improved Modeling → Synthetic turbulence
- DLR-F15 at $Re = 2 \times 10^6$ and $\alpha = 6$

Snapshots:

RANS/LES interfaces + synth. turb.

Specifically adapted grid

- Embedded WM-LES:
  1) Restricted to flap region
  2) SEM at interfaces
  3) Large grid-point savings possible:
     - high-resolution structured grid in LES region (flap + wake)
     - coarser unstructured outer part
     → -62% grid points (baseline grid: 27 mio. points)
Scale resolving simulations

Extended approach

- Improved Modeling → Synthetic turbulence
- DLR-F15 at \( Re = 2 \times 10^6 \) and \( \alpha = 6 \)

Cross-comparison with project partners from EU project Go4Hybrid

Mean surface pressure:

Mean skin friction:

- reasonable agreement between different „zonal“ approaches
Scale resolving simulations

Extended approach

- Improved Modeling → Modified LES scale using local vorticity vector ($\mathbf{\Omega}$)
- Transition from RANS to LES: Take into account local orientation of vortices

\[ \Delta_\omega = \sqrt{N_x^2 \Delta_{y,max} \Delta_{z,max} + N_y^2 \Delta_{x,max} \Delta_{z,max} + N_z^2 \Delta_{x,max} \Delta_{y,max}} \]

Transonic nozzle jet flow: $\Delta_{max}$ vs. $\Delta_\omega$
Scale resolving simulations

Extended approach

→ Improved Modeling → Modified LES scale

Engine line:

- axial oscillations (Ma-cells) captured by all simulations
- "wave length" better predicted by HRLM (increasing phase shift with RANS)

Fan line:
Scale resolving simulations

Extended approach

3. Underlying RANS model

- RANS model determines inflow boundary and location of LES region
- DDES solution sensitivity w.r.t. RANS model
  - Low for flows with massive separation, e.g. airfoils at deep stall, step flows, …
  - Large for more practical flows, e.g. airfoil near stall, distorted intake flow, …

- Example: ONERA-A airfoil at maximum lift (Re = 2 Mio.)

- DDES at flight boundaries requires more advanced RANS models, i.e. Reynolds-stress models (RSM)

<table>
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<th>Experiment</th>
<th>$x_{sep/l}$</th>
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<tbody>
<tr>
<td>Experiment</td>
<td>0.83</td>
</tr>
<tr>
<td>SA</td>
<td>0.96</td>
</tr>
<tr>
<td>SSG/LRR RSM</td>
<td>0.89</td>
</tr>
<tr>
<td>$\varepsilon^h$-RSM</td>
<td>0.88</td>
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Scale resolving simulations

Extended approach

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\[ x_{sep}/l = \text{Experiment} 0.83, \text{SA} 0.96, \text{SSG/LRR RSM} 0.89, \epsilon_{h-RSM} 0.88 \]

François, Radespiel (ISM, TU-BS), Probst (DLR), 2014

Synthetic turbulence generator (STG)
- Synthetic turbulence generated from RANS data
- ADDES + RSM + STG
- for „locally unstable“ and „stable“ flow cases
Transition Prediction and Modeling

Transition Prediction Module

- $e^N$ method
- Local, linear stability code
- 2-N-factor-method: $N_{TS}$, $N_{CF}$

- Line-in-flight cuts
  - Swept tapered wings

- Inviscid streamlines
  - Necessary for fuselages, nacelles etc.
  - Start at attachment line

- Execution of the stability code along these lines
  - One single transition point per cut/line.
  - Transition line is a polygonal line on the surface.

Automated local, linear stability code
- Frequency estimator for range of frequencies $f$
- Wave length estimator for range wave lengths $\lambda$

High grid resolution

Low grid resolution

Inviscid streamlines at BL-edge
Spanwise sections for BL code

Conical laminar BL code
Swept, tapered wings
Transition Prediction and Modeling

Application of Transition Prediction Module

**NASA trapezoidal wing, 1\textsuperscript{st} HiLiPW**

\[ M = 0.2, \quad Re = 4.3 \times 10^6, \quad \alpha = 6^\circ - 36^\circ \]

\[ N_\text{TS} = 8.5, \quad N_\text{CF} = 8.5 \]
Transition Prediction and Modeling
Application of Transition Prediction Module

**DLR A320 D-ATRA high-lift landing configuration**

- $M = 0.2, \text{Re} = 17 \times 10^6$
- Two different grids

$\alpha = 10.0^\circ$

$\Delta C_L$ between computations:
- fully-turbulent vs.
- predicted transition
Transition Prediction and Modeling

**Transport equation model – $\gamma$-Re$_{th}$ model**

- Basic model covers TS-, bypass- and separation induced transition
- **DLR development:** CF-extension of the basic model $\rightarrow$ $\gamma$-Re$_{th}$-CF model
- Coupled to Menter SST k-$\omega$ and SSG/LRR-$\omega$/g turbulence models

**Validation**

- Inclined prolate 6:1 spheroid
- Re = 6.5x10$^6$, Ma = 0.13, $\alpha$ = 10.0°
- Mixed T-S/CF transition
Transition Prediction and Modeling
Application of Transition Equation Model

**DLR-F4 Wing-Body**

\[ \text{Rec}_{\text{cm}} = 6.0 \times 10^6 \]
\[ C_L = 0.4 \ (\alpha = -1.58) \]
\[ M = 0.785 \]

\[ \gamma - \text{Re}_\theta - \text{CF} + \text{RSM} \]

TU Braunschweig
Sickle Wing
Transition Prediction and Modeling
Application of Transition Equation Model

**DLR-F4 Wing-Body**

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\[ C_L = 0.4 \ (\alpha = -1.58) \]
\[ \text{M} = 0.785 \]

**Ongoing and future activities**
- Getting rid of this malfunction
- Extension to rotating systems
- Hybrid laminar-flow control (HLFC)
- Coupling to hybrid RANS/LES methods

**TU Braunschweig**
Sickle Wing
Turbulence modeling improvements

Need for better RANS turbulence models

- Today, simulation of *moderately separated* flows **not reliable**, neither with RANS, nor with hybrid RANS/LES methods (HRLM).
- RANS models needed for next decades
  - Due enormous computational costs for LES
  - Pure RANS → highly complex configurations
  - HRLM → components of aircraft or special configurations (fighter)
- Technology gap **must be closed**
  - Insignificant unsteadyness → RANS
  - Significant unsteadyness → hybrid RANS/LES
- Identification of significant physical phenomena necessary
  - Flow separation, boundary-layer representation, shock/BL interaction
  - Transition
  - Wake modeling, vortical flows
  - Engine jet flows, …

⇒ Dedicated RANS turbulence modeling improvements for specific flow phenomena
Turbulence modeling improvements

Change of current turbulence modeling paradigm

- Focus **not** on validation of existing models using experiments
- **Instead:** use experiments to derive specific model modifications
- **Twofold approach**
  - **Identify** significant physical **quantities and laws** for specific identified phenomena
  - Derive models satisfying identified laws
- **Design of experiments** for phenomenon specific flows of major relevance
  - Dedicated physical experiments in wind tunnel
  - Numerical experiments using LES/DNS
- Finally, go back to traditional validation using more complex cases.
Turbulence modeling improvements

Ongoing: Improvement for incipient separation

Step I: Establish a high-quality data base from experiments & DNS

Step II: Find law-of-the-wall for mean velocity and Reynolds stresses at dp/dx > 0

Step III: Use new wall-laws to improve RANS models

Reduction of „Karman constant“ with increasing adverse pressure gradient
Turbulence modeling improvements

Ongoing: Improvement for incipient separation

Step I:

A very first step towards validation:

Step II:

Step III:

Reduction of „Karman constant“ with increasing adverse pressure gradient

HGR-01 airfoil (VTP)

$\alpha=12.0^0$, $Re=0.65\times10^6$

$M=0.07$

separation point from exp.

standard models

new model
Turbulence modeling improvements

Further modeling activities

- **Improvements for general shear layer flows**
  - Based on experimental data from literature
  - Different data sets defining the anisotropy of the Reynolds shear-stresses
  - Boundary layer, plane jet, axisymmetric jet, plane mixing layer
  - Resolves the round-jet/plane-jet anomaly → both correct using the corresponding data set
  - Theory ready, implementation ongoing

- **Improvements for turbulent wake under APG**
  - Collaboration with Braunschweig University and NTS (St. Petersburg, Russia)
  - Braunschweig University carries out experiment
  - NTS does IDDES for the exp. test case
  - Recently started

- **Data-driven approaches for model augmentation**
  - Planned to start next year
Turbulence modeling improvements

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