Development and Application of SST-SAS Turbulence Model in the DESIDER Project

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Outline

• Scale-Adaptive Simulation (SAS) concept
• SST-SAS turbulence model
• Aerodynamic applications
  – NACA0021 airfoil beyond stall
  – Delta wing
  – Full aircraft configuration
  – 3-D acoustic cavity
SAS concept

- **URANS**: unphysical single mode unsteady behaviour
- **LES**: too expensive
- **DES**:
  - 1\textsuperscript{st} industrial model of high Re flows with LES content
  - Explicit mix of RANS & LES $\rightarrow$ grid sensitivity
- **SAS**: provides URANS with LES content in unsteady regions
• **Two scales** required for statistical description

- **L, T**

- **Two equations → two scales?**
SAS concept. 2-eq RANS models

- $k$-$\omega$ model
- One local scale: $S$
- 2nd scale:
  - Shear layer thickness via diffusion: $L = \kappa \cdot y$, $L = \delta$
  - Too dissipative to resolve the energy cascade
  - Homogeneous turbulence, frozen LES velocity field:

No diffusion → **Contradiction:**

\[
\frac{Dk}{Dt} = \nu_t \left( S^2 - c_\mu \omega^2 \right) + \text{Diff} \left( k \right)
\]

\[
\frac{D\omega}{Dt} = \alpha S^2 - \beta \omega^2 + \text{Diff} \left( \omega \right)
\]

\[
S^2 = c_\mu \omega^2
\]

\[
\alpha S^2 = \beta \omega^2
\]
• Rotta’s transport eq. for spatial correlation-based $L$
• $2^{nd}$ scale from $\partial^2 U/\partial y^2 \rightarrow$ von Karman length scale
• New RANS model for $k$ and $\Phi = \sqrt{kL}$

\[
\frac{D\Phi}{Dt} = \frac{\Phi}{k} P_k \times \left[ \zeta_1 - \zeta_2 \left( \frac{L}{L_{vK}} \right)^2 \right] - \zeta_3 k + \text{Diff}(\Phi)
\]

\[
P_k = \nu_t S^2, \quad L_{vK} = \kappa S / |\nabla^2 U|
\]

• Two natural local scales: $S$ and $L_{vK}$
SAS concept. SAS and RANS

- \( U(y) = U_0 \sin\left(\frac{2\pi \cdot y}{\lambda}\right) \), \( \lambda \) - natural scale, ignored by RANS

- Two domains:
  \( \delta = 4\lambda \)
  \( \delta = 8\lambda \)

- RANS:
  \( L \sim \delta \)

- SAS:
  \( L \sim \lambda \)
SAS concept. SAS and DES

- DES enforces LES-behaviour via explicit grid influence
- SAS detects resolved structures and adjusts accordingly

DES: RANS LES based on $\Delta$

SAS: RANS “LES” based on $L_{vK}$
SAS concept definition

- SAS: 2\textsuperscript{nd} flow scale in the source terms typically via 2\textsuperscript{nd} velocity derivative

- Requirements:
  - Proper \textbf{RANS performance} in stable flow region
  - Break-up of large unsteady structures into a \textit{turbulent spectrum}
  - Proper energy dissipation at small scale (\textit{high wave number damping})

No grid & time step dependence

Based on the grid spacing $\Delta$
SST-SAS turbulence model

- Experimental $k$-$\Phi$ model
- Transformation to $k$-$\omega \rightarrow$ SST-SAS model

\[ \frac{Dk}{Dt} = \nu_t \left( S^2 - c_\mu \omega^2 \right) + \text{Diff}(k) \]

\[ \frac{D\omega}{Dt} = \alpha S^2 - \beta \omega^2 + Q_{\text{SAS}} + \text{Diff}(\omega) + \frac{2 \cdot (1 - F)}{\sigma_{\omega^2 \omega}} \nabla k \nabla \omega \]

\[ Q_{\text{SAS}} = \max \left[ \zeta_2 \kappa S^2 \left( \frac{L}{L_{vK}} \right)^2 - C \cdot \frac{2k}{\sigma_\Phi} \max \left( \frac{\left| \nabla \omega \right|^2}{\omega^2}, \frac{\left| \nabla k \right|^2}{k^2} \right) , 0 \right] \]
SST-SAS turbulence model

- Decay of isotropic turbulence

High wave number damping in SAS:
- off
- on
- LES

Turbulence length scale / grid cell size

Ek

- Experiment
- LES, Cs=0.215
- k-epsilon
- SST-SAS, Lvk limiter
- SST-SAS, no Lvk limiter
NACA0021 airfoil beyond stall

- NACA0021 at 60° AoA, experiment by Swalwell et al., 2003
- Re = 2.7 \cdot 10^5, low Mach number, domain span-size 4 chords
- O-grid: courtesy of NTS, Russia, 1.9 million elements, $y^+ \approx 1$

Contours of $L / \Delta \in [0, 0.5]$

Isosurface of $Q = \Omega^2 - S^2$
NACA0021 airfoil beyond stall

- Mean values and PSD spectra of forces

<table>
<thead>
<tr>
<th></th>
<th>$C_L$</th>
<th>$C_D$</th>
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<tbody>
<tr>
<td>SST-SAS</td>
<td>0.915</td>
<td>1.484</td>
</tr>
<tr>
<td>Experiment</td>
<td>0.931</td>
<td>1.517</td>
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</tbody>
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Mean pressure

PSD of $C_L$

PSD of $C_D$
Delta wing

- Sweep angle 76°, experiment by Laschka et al., 1995
- AoA = 35°, Re = 1.07 · 10^6, low Mach number
• Hybrid unstructured grid, 50 million elements, \( y^+ \approx 0.5 \)
  – Courtesy of EADS Deutschland GmbH, Military Air Systems
Delta wing

- Delayed bursting of vortices predicted: numerical diffusion?
Full aircraft configuration

- Delta-canard FA-5, exp. by Laschka et al., 1995
- \( \text{AoA} = 15^\circ, \text{Re} = 2.78 \cdot 10^6 \), low Mach number
- Hybrid unstructured grid, 36 million elements, \( y^+ \approx 0.8 \)
  - Courtesy of EADS Deutschland GmbH, Military Air Systems
  - Half of the airplane, symmetry BC
Full aircraft configuration

- SAS vs. URANS
Full aircraft configuration

- Resolution details

$L / \Delta$
Full aircraft configuration

- Cross planes at $x/c = 0.2, 0.4, 0.6, 0.8, 1$

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<tr>
<th>$U/U_0$</th>
<th>Experiment</th>
<th>SST-SAS</th>
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| Resolved+Modelled $TKE/U_0^2$ | Experiment | SST-SAS |

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3-D acoustic cavity

- M219 test cavity, exp. by QinetiQ, Henshaw, 2000
- Shallow cavity: Length × Width × Depth = 5 × 1 × 1, 1 = 4"
- \( \text{Re}_D = 1.37 \times 10^6 \), \( M_\infty = 0.85 \) – local transonic zones
- Coarse grid, 1.1 million elements
- 90 \( \Delta t \) per convective unit
- 100 units run for statistics
3-D acoustic cavity

- Resolved turbulent structures
- Pressure spectrum at cavity bottom near the downstream wall (K29)
Other DESIDER tests simulated

- Bump in a duct, experiment by ONERA
- Generic car mirror, exp. by Höld et al., 1999