Wake Vortices generated by an Aircraft Fuselage: Comparison of Wind Tunnel Measurements on the TAK Model with RANS and RANS-LES Simulations

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Flow around a generic aircraft fuselage

- Work within the European Union funded FAR-Wake project (Fundamental Research for Aircraft Wake Phenomena)
- Investigate the proper influence of each aircraft element on the wake structure
- Generic four-engines civil aircraft, the TAK-model of the university of Munich (TUM)
  - Hot wire measurements in the TUM wind tunnel
  - RANS simulations of the DLR for different configurations using the « Tau » code
  - RANS and RANS-LES simulations by Cenaero but on the fuselage only and using « Argo » flow solver
TAK geometry & experimental setup at TUM

- Hot-wire measurements at TUM
- RANS at DLR
TAK geometry & experimental setup at TUM

WTV: Wing Tip Vortex

OFV: Outboard Flap Vortex

ONV: Outboard Nacelle Vortex

INV: Inboard Nacelle Vortex

WFV: Wing Fuselage Vortex

HTV: Horizontal Tailplane Vortex

- Hot-wire measurements at TUM
- RANS at DLR
TAK fuselage geometry

- Wind-tunnel experiment (TUM)
- RANS using $k-\omega$ and RSM (DLR)
- RANS using SA and DES (Cenaero)
Turbulence modelling strategy

• **RANS models (steady simulation)**:
  • Cenaero: one equation high-Reynolds Spalart-Allmaras model (SA)
  • DLR: Two equation $k-\omega$ SST model
  • DLR: Reynolds Stress Model (RSM)

• **Hybrid RANS-LES (unsteady simulation)**: DES97
  • Detached-Eddy Simulation (DES) in its standard version
  • RANS model near the body: ideally includes the attached boundary layer
  • LES away from the solid walls
  • Switch between RANS and LES zones governed by the streamwise grid resolution at the wall
Discretization strategy

- **Argo meshes**: tetrahedra
  - Anisotropic boundary layer mesh: tetrahedra
  - Isotropic volume mesh: tetrahedra
- **Tau (Centaur) meshes**: prisms + tetrahedra
  - Anisotropic boundary layer mesh: prisms
  - Isotropic volume mesh: tetrahedra
- **RANS steady simulations**: 
  - Cenaero: AUSM+up scheme (everywhere)
  - Cenaero: hybrid scheme (AUSM+up & K-scheme)
  - DLR: central scheme
- **DES unsteady simulations**: 
  - Cenaero: hybrid scheme (AUSM+up & K-scheme)
• Coarse mesh: generated by DLR and used by both codes Argo and Tau (500k nodes)

• Fine mesh: generated by Cenaero and used by Argo only (6M nodes)
Different meshes at measurement station $x/b = 0.2$

- Coarse mesh: generated by DLR and used by both codes (500k nodes)

- Fine mesh: generated by Cenaero and used by Argo only (6M nodes)
Different meshes at measurement stations $x/b = 0.37$

- Coarse mesh: generated by DLR and used by both codes (500k nodes)
- Fine mesh: generated by Cenaero and used by Argo only (6M nodes)
Adapted hybrid mesh

- DLR starting from the coarse mesh, 10-times adapted
- 500k → 2.5M nodes
- Compare: fine mesh from Cenaero 6M nodes
Flow conditions and computational setup

- Wind tunnel conditions and CFD flow parameters
  - \( \text{Re} = U_\infty \frac{b}{v} = 5.3 \times 10^5 \)
  - Mach number = 0.07 (« low-mach » application)
  - Angle of attack (AOA) : \( \alpha = 7^\circ \)
  - Half-model with peniche (wind tunnel)
  - Half-model without peniche and a symmetry plane (CFD)

- Using Argo: coarse and fine grids
  - RANS-SA with AUSM+up scheme
  - RANS-SA with Hybrid scheme (K-scheme & AUSM+up)
  - DES97 with Hybrid scheme (K-scheme & AUSM+up)

- Using Tau: coarse and adapted grids
  - RANS k-w with DLR-central scheme
  - RANS RSM with DLR-central scheme
RANS results: Mesh & TU-Model influence (1)

Streamwise vorticity at measurement station $x/b = 0.37$

Experiment  |  TAU + $k-\omega$  |  TAU + $k-\omega$ (adapted)
RANS results: Mesh & TU-Model influence (1)

Streamwise vorticity at measurement station $x/b = 0.37$

Significant influence of the mesh discretization

Experiment TAU + $k-\omega$ TAU + $k-\omega$ (adapted)
RANS results: Grid & TU-Model influence (2)

Streamwise vorticity at measurement station $x/b = 0.37$
RANS results: Grid & TU-Model influence (2)

Streamwise vorticity at measurement station $x/b = 0.37$

Significant influence of the Turbulence model
RANS results : Coarse grid & Flux functions (1)

Streamwise vorticity at measurement station $x/b = 0.2$

SA-AUSM  
\textbf{k-}\omega\text{-DLR}  
SA-Hybrid  
experiments
RANS results: Coarse grid & Flux functions (2)

Streamwise vorticity at measurement station $x/b = 0.37$
RANS results: Coarse grid & Flux functions (2)

Streamwise vorticity at measurement station $x/b = 0.37$

Major influence of the discretization method
Results: Grid refinement investigations (Part II)

Streamwise vorticity at measurement station \( x/b = 0.2 \)

SA Hybrid (coarse)  SA Hybrid (fine)  RSM (adapt.)  Experiment
Results: Grid refinement investigations (Part II)

Streamwise vorticity at measurement station $x/b = 0.2$

Again - Significant influence of the mesh discretization

SA Hybrid (coarse)  SA Hybrid (fine)  RSM (adapt.)  Experiment
Results: DES97 versus RANS-SA

Streamwise vorticity at measurement station x/b = 0.2

SA-Hybrid (fine)  DES97 (fine)  Experiment
Results: DES97 versus RANS-SA

Streamwise vorticity at measurement station $x/b = 0.2$

No significant differences as the wake is steady
Vortical structures: iso-surface of $\lambda_2$

- Two main vortices originating from:
  - Slowly separating boundary layer from the back of the fuselage
  - Separating boundary layer from the wing box
Vortical structures: vorticity field cuts

- Two main vortices originating from:
  - Slowly separating boundary layer from the back of the fuselage
  - Separating boundary layer from the wing box
Conclusion (Part I) – Isolated Fuselage

- The large structures of the flow are steady
  - Low angle of attack and slender body
  - No improvement using DES97 compared to RANS
- Numerical dissipation effects due to numerical scheme and mesh discretization can be more important than the selected turbulence model for this kind of low-mach application
- Good agreement between the experiment and the numerical methods, in terms of vortex magnitude and location
- Two major vortices generated by:
  - Slightly detaching boundary layer from the fuselage back
  - Detaching boundary layer from the wing box
Complete TAK Configuration (1)

- **Work performed on the TAK configuration:**
  - Grid generation for TAK-model in free-flight & wind-tunnel
  - RANS flow-simulation for full-model (free-flight):
    - Fuselage (LoRe & HiRe)
    - Fuselage & HTP (LoRe & HiRe)
    - Fuselage & Wing (LoRe & HiRe)
    - Fuselage & HTP & Wing (LoRe & HiRe)
  - RANS flow-simulation for half-model in wind-tunnel (TUM-AER) with Peniche & Fuselage & HTP & Wing (LoRe)
  - Analysis of CFD & Wind tunnel results
Complete TAK Configuration (2)

- **Work performed: Analysis of Flow Topology**
  - Example: Figure: color gives rotational direction, Configuration with all elements
  - Vortices analysed:
    - Fuselage
    - Belly
    - Junction(s)
    - Tail
Complete TAK Configuration (3)

- **Work performed: Wind Tunnel Effect (Additional)**
  - Comparison of vortex sheet in wind tunnel (red) and in free flight (blue), view from behind the complete configuration
  - Effect: changes in vortex position & additional lift in wind tunnel case

- **Work performed: Peniche Effect (Additional)**
  - Peniche effect: additional angle of attack on inboard wing
  - Wind tunnel effect: additional angle of attack over complete wing span
Complete TAK Configuration (4)

• Work performed: Reynolds Number Effect (Additional)
  • Picture: Vortices of High Reynolds number case in red, Low Reynolds number case in blue
  • Main changes on inboard section:
    - additional vortices / change of position
    - Outboard wing: nearly unchanged
Conclusion (Part II) – Complete TAK Configuration

- **Position of vortices significantly influenced by**
  - Wind tunnel walls
  - Reynolds number

- **Wind tunnel & peniche influence (half model):**
  - Peniche effect: additional angle of attack on inboard wing
  - Wind tunnel effect: additional angle of attack over complete wing span
Questions?