Roll-up of wing and propelled-wing wakes: time- and space-developing LES including comparison to experiments

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Context

FAR-Wake: Fundamental Research on Aircraft Wake Phenomena

- WP2: Vortex Interactions with Jets and Wakes
  - UCL contributions:
    LES of wing wake roll-up

Effect of velocity deficit and engine-jets,
Simulation of realistic wakes using Airbus wind-tunnel data

TR222-3 part of D222-2:
Roll-up of a temporally-evolving wing wake with velocity deficit

TR211-6:
Roll-up of a temporally-evolving wing wake in presence of jets

Contribution to D211-3:
Cold-jet effects in relevant multi-vortex configurations, including wake roll-up
Outline

Numerical Tool: The VICPFM Code

I. Roll-up with velocity deficit
   - Wake Model & numerical set-up
   - Results
   - Conclusions

II. Roll-up in presence of jets
   - Initial condition
   - Results & conclusions

III. Realistic multi-vortex wake simulation with comparison to experiments
   - Initial condition: experimental data
   - Results & comparison

Synthesis & Perspectives
Numerical Tool: The VIC-PFM code

Combination of Vortex-In-Cell and Parallel Fast Multipole methods

- **Vortex-In-Cell method:**
  - Combination of *Lagrangian* and *Finite Difference* methods
  - *Vortex Element Methods*: negligible numerical dispersion / dissipation

- **Fast Multipole method:**
  - *Exact* unbounded condition
  - *Compact* computational domain (tight to the vorticity field)
  - *Parallel* implementation: the PFM method

- **LES modelling**
  - UCL’s *Regularized Variational Multiscale (RVM)* subgrid-scale model
  - *Actes* only on the small scale part of the LES field
  - *Preserves* the inertial range
  - Provide *dissipation* to high wavenumbers
  - *Active* in complex phases & *inactive* in laminar / well-resolved regions
Numerical Tool: The VIC-PFM code
Combination of Vortex-In-Cell & Parallel Fast Multipole methods

- **Time-Developing (TD) LES:**
  - Periodic boundary condition in the longitudinal direction
  - 2D (without perturbation) initial condition

- **Space-Developing (SD) LES:**

  ![Diagram of computational domain with labeled regions: Lifting Line, Inflow plane, Outflow plane, Top view, Side view, Ground plane.](image)

  No through-flow symmetry:
  
  \[
  \omega_n(-x, y, z) = \omega_n(x, y, z) \\
  \omega_t(-x, y, z) = -\omega_t(x, y, z)
  \]

  Vortex- / lifting line-induced velocities
  Freestream velocity

  Space-Time dynamic evolution

  e.g.: wing wake roll-up IGE Daeninck et. al (FW-T.R. 3.1.2-4)
I. Roll-up with velocity deficit
Wake Model: vortex sheet + velocity deficit

Vortex sheet
⇔ axial vorticity field

- Prandtl lifting-line theory applied to an elliptic wing
- Gaussian regularization to obtain a regular, yet thin, vortex sheet

\[
\frac{\sigma}{b} = \frac{1}{75}
\]

Velocity deficit:

- Elliptic spanwise distribution, same regularization parameter
- Maximal velocity deficit parameter: compensates the freestream velocity to respect the no-slip condition at the trailing edge (center of the sheet)
- Corresponding transverse vorticity field (norm):
Simulation Set-Up

<table>
<thead>
<tr>
<th></th>
<th>TD LES</th>
<th>SD LES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Numerical Resolution</strong></td>
<td>$\frac{h}{b}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\frac{1}{200}$ ($14 \times 10^6$ grid points)</td>
<td>$\frac{1}{160}$ ($105 \times 10^6$ grid points)</td>
</tr>
<tr>
<td><strong>Computational domain length</strong></td>
<td>$L_x = 0.5 \ b$</td>
<td>$L_x = 10 \ b$</td>
</tr>
<tr>
<td><strong>Wing aspect ratio</strong></td>
<td>$Ar = 7.5$</td>
<td>$Ar = 7.5$</td>
</tr>
<tr>
<td><strong>Lift coefficient</strong></td>
<td>$C_L = 1.5$</td>
<td>$C_L = 1.5$</td>
</tr>
<tr>
<td>$Re_\Gamma = \frac{\Gamma}{\nu}$</td>
<td>$10^4 ; 10^6$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>$\tau_{max} = \frac{t_{max}}{t_0}$</td>
<td>1 ; 0.75</td>
<td>0.33</td>
</tr>
<tr>
<td>$\frac{x_{max}}{b}$</td>
<td>30.4 ; 22.8</td>
<td>8</td>
</tr>
</tbody>
</table>
Results: 3D Dynamics \( \text{Re}_\Gamma = 10^6 \)

\[ \tau = 0.01 ; \left( \frac{x}{b} \right) = 0.3 \]
Results: 3D Dynamics - $Re_\Gamma = 10^6$

$\tau = 0.05 ; \left(\frac{x}{b}\right) = 1.5$
Results: 3D Dynamics - $\text{Re}_\Gamma = 10^6$

$\tau = 0.07 ; \left( \frac{x}{b} = 2.1 \right)$
Results: 3D Dynamics - $Re_{\Gamma} = 10^6$

$\tau = 0.25 ; (\frac{x}{b} = 7.6)$
Results: 3D Dynamics - $Re_\Gamma = 10^6$

$$\tau = 0.75 ; \left(\frac{x}{b}\right) = 22.8$$
Results: time evolution of averaged quantities

Vortex Trajectory

Circulation

Vortex core size

- Vortex sheet at $Re_\Gamma = 10^4$
- Wake model at $Re_\Gamma = 10^4$
- Wake model at $Re_\Gamma = 10^6$

$\Delta \Gamma \approx 7.5 \%$
Results: Vortex Structure

\[ \tau = 0.5 ; \left( \frac{x}{b} \right) = 15.2 \]

Circulation

Tangential velocity

Perturbation field of axial vorticity in a cross-section:

Vortex Core Deformation

Axial velocity
Conclusions

Effect of the velocity defect due to boundary layers on the wing wake roll-up and resulting vortex system:

- Early stages of the roll-up dynamics greatly affected:
  - Development of successive instabilities
  - Generation of vortical structures surrounding the vortex core
  - Helical vortex core deformation
- Vortex trajectory not affected
- Average resulting vortex structure (after roll-up):
  - Core radius, circulation and tangential velocity profiles not significantly affected
  - Significant axial velocity component inside the vortex core
  - ~7.5% reduction in the circulation $\Gamma_{5-15}$
II. Roll-up with velocity deficit in presence of jets
Initial condition & Numerical set-up

- Same wake model with velocity deficit (same wing wake parameters) with 2 added jets in a cruise configuration:
  - Large initial jet/wing tip distance
  - Medium jet to vortex strength ratio: $R = 0.82$
  - Total jet thrust = induced + viscous drag
    (see TR 2.1.1-6 & D 2.1.1-3)

<table>
<thead>
<tr>
<th>TD LES</th>
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</thead>
<tbody>
<tr>
<td>$\frac{h}{b} = \frac{1}{400}$</td>
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<tr>
<td>(96 $10^6$ grid points)</td>
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<tr>
<td>$L_x = 0.5 \ b$</td>
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<tr>
<td>$Re\Gamma = 10^6$</td>
</tr>
<tr>
<td>$\tau_{max} = 0.75$</td>
</tr>
<tr>
<td>$\frac{x_{max}}{b} = 22.8$</td>
</tr>
</tbody>
</table>
Results: 3D Dynamics

\[ \tau = 0.05 \; ; \; \left( \frac{x}{b} = 1.5 \right) \]
Results: 3D Dynamics

\[ \tau = 0.25 ; \left( \frac{x}{b} = 7.6 \right) \]
Results: 3D Dynamics

\[ \tau = 0.75 ; \left( \frac{x}{b} = 22.8 \right) \]
Results & Conclusions

- Similar dynamics to that without jets: jets and velocity deficit have similar 3D effects (instabilities, vortical structures, core deformation)
- The jet fluid does not penetrate the vortex core: the resulting vortex structure is not significantly affected
III. Roll-up of an experimental multi-vortex wake configuration including jets
Initial condition & Numerical set-up

- Multi-vortex wake wind tunnel data (provided by Airbus):
  - Thrust for level flight: total thrust = total drag
  - Deflected flap $\rightarrow$ multi vortex wake

- 3 components of velocity at two downstream positions:
  $\frac{x}{b} = 0.3 ; 1.3$
  $(\tau = 0.007 ; 0.03)$

<table>
<thead>
<tr>
<th></th>
<th>Numerical Resolution $\frac{h}{b}$</th>
<th>Computational domain length</th>
<th>$\tau_{\text{max}} = \frac{t_{\text{max}}}{t_0}$</th>
<th>$\frac{x_{\text{max}}}{b}$</th>
<th>$\text{Re}_\Gamma = \frac{L}{\nu}$</th>
<th>Lift Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expe.</td>
<td>$\frac{1}{100}$</td>
<td>—</td>
<td>0.03</td>
<td>1.3</td>
<td>$2 \times 10^6$</td>
<td>1.76</td>
</tr>
<tr>
<td>TD LES</td>
<td>$\frac{1}{200}$</td>
<td>$L_x = b$</td>
<td>1.1</td>
<td>35.1</td>
<td>$2 \times 10^6$</td>
<td>1.76</td>
</tr>
<tr>
<td>(24 $10^6$ grid points)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SD LES</td>
<td>$\frac{1}{200}$</td>
<td>$L_x = 5 , b$</td>
<td>0.16</td>
<td>5</td>
<td>$2 \times 10^6$</td>
<td>1.76</td>
</tr>
<tr>
<td>(45 $10^6$ grid points)</td>
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</tbody>
</table>
Results: 3D TD Dynamics \[ \tau = 0.03 ; \left( \frac{x}{b} \right) = 1.3 \]
Results: 3D TD Dynamics

$\tau = 0.09$ ; $(\frac{x}{b} = 3.1)$
Results: 3D TD Dynamics \[ \tau = 0.22 \; ; \; \left( \frac{x}{b} \right) = 7.3 \]
Results: 3D TD Dynamics

\[ \tau = 0.63 \; ; \; \left( \frac{x}{b} \right) = 20.2 \]
Results: 3D SD Dynamics

SD vs. TD
Averaged axial vorticity & velocity fields at $\frac{x}{b} = 4.3$
Comparison Expe. / TD LES / SD LES

\[ \frac{x}{b} = 1.3 \]

TD – Space averaged vs. expe.

SD – Time averaged vs. expe.

Axial vorticity

Axial velocity

Transverse vorticity norm
Comparison of the averaged vortex structure

- LES inboard vortex
- LES outboard vortex
+ Expe. inboard vortex
● Expe. outbound vortex
Synthesis & Perspectives

Roll-up & vortex interaction with wing wakes and jets

- Both jet and deficit highly unstable during roll-up in both wake model and experimental multi-vortex wake: 3D dynamics, vortical structures, core deformation
- Resulting averaged vortex structure weakly affected except the strong axial velocity component concentrated in the vortex core

Numerical method: the VIC-PFM code

- Hight quality of both TD and SD simulations ➔ predictive tool
- SD: more suitable for highly spatially-evolving flows (➔ axial velocity): jets, early stages of wake roll-up
- TD: relative low cost, gives access to the “FAR-Wake” dynamics
- Further developments to include immersed-boundary methods for simulations of flows past bodies (ongoing work, T. Lonfils)