LES of wake vortices in ground effect without and with wind (comparing different multiscale subgrid models)

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Outline

Computational Setup
- Numerical method
- Computational domain and mesh
- Initial condition

Head and cross winds generation

LES at Re = 20000 Results
- Without wind
- With cross-wind
- With head-wind

Comparison/Validation

Conclusions
Work description

- LES of a longitudinally uniform two-vortex system in ground effect at a Re = 20,000 with and without wind

- Work in close collaboration with the research team of Grégoire Winckelmans (UCL)

- Follow the work of M. Duponcheel et al. (UCL) that performed a DNS of a two-vortex system in ground effect at a Re = 5,000 without wind:
  - Smooth ground
  - Same simulation parameters and flow solver

- Investigate the influence of:
  - Reynolds number: LES at Re = 20,000 without wind
  - Atmospheric conditions: LES at Re = 20,000 with head- and cross-winds
Computational Setup: numerical method

- Fourth-order parallel finite differences incompressible flow solver for non-uniform cartesian meshes
  - Initially developed at the UCL
  - Central discretization without any artificial dissipation: $4^{\text{th}}$ order accurate kinetic energy conserving scheme (Vasilyev)

- Two different Subgrid scale (SGS) models
  - Smagorinsky model (standard model)
  - Filtered-Smagorinsky model (advanced model) where the eddy-viscosity is evaluated on a high-pass filtered velocity field: not dissipative in well-resolved scales of the flow
  - Each model is supplemented by a damping function (here a Piomelli damping function) in order to reach the good near-wall behaviour of the eddy-viscosity, $\nu_{sgs} = \mathcal{O} \left( (y^+)^3 \right)$
Computational Setup: mesh description

Domain description: $L_x = 4b_0$, $L_y = 8b_0$ and $L_z = 3b_0$

Mesh: $N_x = 256$, $N_y = 512$ & $N_z = 256$ (33x10$^6$ nodes)

- Uniform mesh in the $x$ and $y$ periodic directions
- Non-uniform mesh in the wall-normal direction $z$ in order to perform wall-resolved LES: no-slip condition at the wall and slip-wall condition on top
Computational Setup: initial condition (1)

- As in the simulation of Duponcheel et al. (UCL)
  - Two-vortex system initialized using a low-order algebraic profile
  - Initial vortex height is equal to $b_0$
  - In the simulations without wind, a 3D random perturbation is supplemented to the velocity field

\[
\omega(r) = \frac{\Gamma_0}{\pi} \frac{r_c^2}{(r^2 + r_c^2)^2}
\]

\[
\Gamma(r) = \frac{\Gamma_0}{(r^2 + r_c^2)}
\]

\[
u_\theta(r) = \frac{\Gamma(r)}{2\pi r}
\]

\[
\frac{r_c}{b_0} = 0.05
\]

\[
V_0 = \frac{\Gamma_0}{2\pi b_0}
\]
Computational Setup: initial condition (2)

- Initial condition of the two-vortex system without wind (two isosurfaces of vorticity)
Turbulent wind generation

Generation of the turbulent wind

- Half-channel flow simulation
- A pressure gradient is applied in the streamwise direction to drive the flow through the channel
- Pressure gradient such that:
  \[ R = \frac{\overline{U_{\text{wind}}}(h_0)}{V_0} \approx 1 \Rightarrow Re_r \approx 590 \]
- Potentially hazardous situation: upwind vortex stays above the runway after rebound
- Perform statistically-converged DNS of the half-channel flow at a \( Re_r = 590 \) (one for the head-wind and one for the cross-wind) on the same mesh (33,000,000 nodes). Flow statistics validated on the DNS of Moser et al.
Cross-wind streaks

- Vortex streaks detection using an isosurface of vorticity

- Wind structures detection using the \( \lambda \text{mdba}2 \) criterion
Initial vortices in cross wind

Vortical structures detected using the lambda2 criterion
LES at Re = 20000 without wind (1)

Different phases of the two-vortex system evolution

- 2D inviscid descent phase corresponding to hyperbolic trajectories
- Generation of boundary layers induced by the vortex system that finally separates through the effect of an adverse pressure gradient
- 2D secondary vortices orbiting around the primary system
- Secondary vortices unstable from short wavelength instabilities that finally interact with the primary system
- Generation of a complex three-dimensional flow that eventually becomes turbulent
LES at Re = 20000 without wind (2)
Different steps depicted using mean axial vorticity field
LES at $\text{Re} = 20000$ without wind (3)

Two-isosurfaces of vorticity
LES at $Re = 20000$ without wind (4)
LES at Re = 20000 without wind (5)
LES at Re = 20000 without wind (6)
LES at Re = 20000 without wind (7)
LES at Re = 20000 without wind (8)
LES at $Re = 20000$ without wind (9)

Animation for the Filtered Smagorinsky model

- Isosurface of vorticity
- Axial vorticity fluctuations
- Mean axial vorticity

Global diagnostics
LES at Re = 20000 without wind (10)

- Compared to Re = 5000, the LES at Re = 20,000 present strong similarities but
  - More complex three-dimensional structures are generated
  - The fast decay phase happens earlier
  - The fast decay phase presents a higher growth rate

- Comparing the SGS model, the Filtered Smagorinsky model outperforms clearly the Smagorinsky model as it is not dissipative in the laminar phase of the flow
LES at Re = 20000 with cross-wind (1)

Different steps depicted using the mean axial vorticity field
LES at Re = 20000 with cross-wind (2)

Two isosurfaces of vorticity
LES at $\text{Re} = 20000$ with cross-wind (3)
LES at Re = 20000 with cross-wind (4)
LES at Re = 20000 with cross-wind (5)
LES at Re = 20000 with cross-wind (6)
LES at Re = 20000 with cross-wind (7)
LES at $Re = 20000$ with cross-wind (8)
LES at Re = 20000 with cross-wind (9)

- Tilting phenomenon induced by the no-slip wall and the wind velocity profile
- Animation for the Filtered Smagorinsky model
  - Two iso-surfaces of vorticity
- Animation for the Filtered Smagorinsky model
  - Axial vorticity fluctuations
LES at $Re = 20000$ with head-wind (1)

Different steps depicted using the mean axial vorticity field
LES at Re = 20000 with head-wind (2)
LES at \( \text{Re} = 20000 \) with head-wind (3)
LES at Re = 20000 with head-wind (4)
LES at Re = 20000 with head-wind (5)
LES at $Re = 20000$ with head-wind (6)
LES at Re = 20000 with head-wind (7)
LES at Re = 20000 with head-wind (8)
LES at Re = 20000 with head-wind (9)

- Secondary vortices generated by the detached boundary layer are directly unstable through the effect of the head-wind
- Animation for the Filtered Smagorinsky model
  - Two iso-surfaces of vorticity
- Animation for the Filtered Smagorinsky model
  - Axial vorticity fluctuations
LES at Re = 20000 with wind (1)

Energy decay for the Filtered Smagorinsky

Evolution of the energy WVIGE (Re = 20000)

- 2D evolution no-wind
- Filtered Smagorinsky no-wind
- Filtered Smagorinsky head-wind
- Filtered Smagorinsky cross-wind
Global diagnostics: circulation for the Filtered Smagorinsky
LES at $Re = 20000$ with wind (3)

- Trajectory of the primary vortices: rebound phenomenon
Comparison of the delays between rebound and fast decay of the vortices

$\Delta \tau$ is the delay between the time, $\tau_{zmin}$ when the vortices are at their lowest position, and the fast turbulent decay starting time $\tau_{FD}$.

<table>
<thead>
<tr>
<th>Case</th>
<th>$\tau_{zmin}$</th>
<th>$\tau_{FD}$</th>
<th>$\Delta \tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R = 0$ No wind</td>
<td>1.2</td>
<td>2.8</td>
<td>1.6</td>
</tr>
<tr>
<td>$R = 1$ Head wind</td>
<td>1.2</td>
<td>1.8</td>
<td>0.6</td>
</tr>
<tr>
<td>$R = 1$ Upwind</td>
<td>1.4</td>
<td>1.8</td>
<td>0.4</td>
</tr>
<tr>
<td>$R = 1$ Downwind</td>
<td>1.0</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$R = 2$ Upwind (IMFT)</td>
<td>1.5</td>
<td>1.8</td>
<td>0.3</td>
</tr>
<tr>
<td>$R = 2$ Downwind (IMFT)</td>
<td>0.9</td>
<td>1.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

According to Proctor and Hamilton (AIAA 2000) ($R=0$) $\Delta \tau = 0.25$
LES at $Re = 20000$ with wind (4)

- Fast decay phases happen earlier and present significantly higher growth rates in presence of wind.

- Cross-wind more efficient than the head-wind regarding the $\Gamma_{5-15}$ decay rate.

- In the cross-wind LES, the downwind vortex is destroyed efficiently and significantly better than the upwind vortex.

- Delays between fast decay and rebound is decreasing when wind level increases.
Influence of the SGS model

- LES of Wake vortices IGE without wind:
- Comparison of diagnostics with an « advanced multiscale WALE model »

![Graphs showing comparison between RVMs-WALE (UCL) and Filtered Smagorinsky (CENAERO)]
Influence of the computational domain size

- In the case of a crosswind, the length of the computational box has been doubled in the wind direction: \( \frac{L_y}{b_0} = 8 \) increased to 16
- Computation was made by UCL using a multiscale WALE model.
Comparison with UPS/IMFT Results

- Filtered Smagorinsky no-wind
- Filtered Smagorinsky HW
- Filtered Smagorinsky CW R=1:upwind
- Filtered Smagorinsky CW R=1:downwind
- Dynamic Mix Model CW R=1:upwind
- Dynamic Mix Model CW R=1:downwind
- Dynamic Mix Model CW R=2:upwind
- Dynamic Mix Model CW R=2:downwind
Visualisation (Ly = 16 b0)

\[ \tau = 3.52 \]
Conclusions

- LES of a two-vortex system in ground effect with and without wind performed at a $Re = 20000$
  - Reynolds number effect analyzed by comparing the DNS at $Re = 5000$ of Duponcheel et al. (UCL)
  - Influence of the an head- and cross-wind also investigated

- Validation:
  - Differents SGS models
  - Influence of the domain size along the cross-wind direction

- Outcome:
  - Better understanding of the physics
  - Quantitative results on decay
  - Improvement of operational models (subtask 3.1.1)