Aircraft Wake-Vortex Evolution in Ground Proximity: Analysis of Field Measurement Data and Parameterization

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• Analysis of WakeFRA measurements of IGE vortices
  (Airbus, DFS, DLR, Fraport, METEK, 2004)

• Parameterization & performance of P2P model

WakeFRA site & 2004 campaign

Runway 25R:
127 approaches
z = 61 m

Runway 25L:
110 approaches
z = 55 m

A340-300  A340-600  B747-400

28 Sept 2004
73 approaches
25 a/c types
checks of data consistency

⇒ good quality of measurement data

initial circulation strength as function of initial observation time

initial circulation strength as function of headwind at $z = 40\,\text{m}$
circulation evolution - statistics 25R (127 cases)

more rapid decay after reaching minimum (rebound) height

parameterization of P2P:

- onset of rapid decay $0.2 \, t_0$
- after reaching $z_{\text{min}}$
- decay rate adjusted to $\nu_2^* = 0.003$
onset time of rapid decay found in FAR-Wake

\[ z^* = 0.25 \]
\[ t^* = 0.12 \]
\[ Re_G = 32,000 \]

\[ \Rightarrow \text{real wake vortices: always sufficient disturbance level to cause fully turbulent vortex interaction} \]

increasing complexity

\[ 1.6 t_0 \geq \text{onset of rapid decay after reaching } z_{\text{min}} \geq 0.2 t_0 \]
decay rate $\nu_2^*$ in ground effect
from fitting with 2-phase decay model

effect of crosswind ?
effect of turbulence ?
previous trajectory model

- Image vortices at \( z = 1.5 \, b_0 \)
- GE vortices + images at \( z = 0.6 \, b_0 \)
- after rotation of 180 deg another pair of secondary vortices + images
- \( \Gamma^*_{s,\text{max}} = 0.4 \, w^* \)

asymmetric rebound in crosswind conditions

231 cases / 5210 obs.
black symbols: LES of Giovannini et al.
(UPS-IMFT, CENEARO, UCL)

adapted secondary vortex parameters

Lee-side vortex rebounds earlier
Luff-side secondary vortex is weaker
application examples

minor crosswind
⇒ symmetric rebound

$v^* \sim 0$
application examples

weak crosswind
⇒ asymmetric rebound

$v^* \approx 1$
wake generation below $b_0$ \( (z_{0,min} = 0.1 \, b_0) \)
application examples – exceptional WV rebound due to shear layers

(P2P results only shown as reference)

$$\frac{\partial v^*}{\partial z^*} = 1.8$$
application examples –
WV behaviour near obstacles

(P2P results only shown as reference)

\[ v^* = 1.5, \quad z_{\text{building}} = 9.7 \text{ m} \Rightarrow \Delta z^* = 0.2 \]
deterministic model performance – scoring

<table>
<thead>
<tr>
<th></th>
<th>RMS $\Delta \Gamma_{5-15} / \Gamma_0$</th>
<th>RMS $\Delta z / b_0$</th>
<th>RMS $\Delta y / b_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OGE model: median</td>
<td>0.145</td>
<td>0.199</td>
<td>0.462</td>
</tr>
<tr>
<td>90&lt;sup&gt;th&lt;/sup&gt; perc.</td>
<td>0.251</td>
<td>0.278</td>
<td>0.974</td>
</tr>
<tr>
<td>$v_2^* =0.003$: median</td>
<td>0.091</td>
<td>0.118</td>
<td>0.404</td>
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<td>0.224</td>
<td>0.860</td>
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40% 13% model improvement

110 approaches on 25R
correlation of lateral vortex drift and crosswind – CREDOS

- mean WV drift from 1st and last meas.
- safety corridor WVWS Frankfurt:
  \[ b_0/2 + 2 \cdot 15 \text{ m} + 30 \text{ m} \approx 84 \text{ m} \]

Minimum required crosswind for clearance of the flight path

\[ \text{a/c sep – time – } v_{\text{wv}} – v_{\text{cw}} \]

- 2 NM – 50 s – 1.7 m/s – 3.6 m/s
- 5 NM – 125 s – 0.67 m/s – 2.6 m/s

231 cases
Conclusions

• WakeFRA measurement data is of high quality
• no impact of buoyancy on decay
• weak impact of crosswind and turbulence on decay
• pronounced asymmetric rebound characteristics dependent on crosswind (weak crosswind \( \sim w_0 \) sufficient)
• shear layer (jet) above / obstacles increase rebound height \((z_{\text{max}} = 2.6 \ b_0)\)
• runway clearance for \( \text{cw} \geq 2.5 \ (3.3) \ \text{m/s for 5 (2) NM a/c separation} \)
• common normalization appropriate
• GE model improvement by 37% for \( \Gamma \), 40% for \( z \), 13% for \( y \)
• rapid decay OGE faster than IGE-decay
  \[
  \text{OGE: } 0.0037 \leq \nu_2^* \leq 0.02 \\
  \text{IGE: } 0.002 \leq \nu_2^* \leq 0.004
  \]
• for given EDR GE-decay slower than OGE (\( L_t \) smaller)
• GE evolution better predictable than OGE (\( y \) - 58%, \( z \) - 69%, \( \Gamma \) - 29%)
• fair GE predictions based on simply crosswind
Adjustment of P2P decay parameters

\[
\Gamma_{5-15}^* (t^*) = A - \exp \left( -\frac{R^*}{\nu_1^*(t^*-T_1^*)} \right) - \exp \left( -\frac{R^*}{\nu_2^*(t^*-T_2^*)} \right)
\]

**Diffusion**

**Rapid decay**

![Graph](image)