Airborne DWL investigations of wing tip vortices and their dissipation

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Simpson Weather Associates
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DoD funded study

1\textsuperscript{st} in a series of tests conducted at Yuma Proving Grounds, Arizona in April 2014

Partners:

- US Army ATEC at Yuma (host and co-ordination)
- US Air Force from McCord AFB (C-17)
- ONR CIRPAS (Twin Otter with TODWL)
- Draper Labs (Vortex Model)
- Simpson Weather Associates (TODWL operations, data processing and model validation)
Motivation

• C-17 Wing Tip Vortices generate tangential speeds of 100+ m/s.
• WTVs represent significant danger to paratroopers.
• Current spacing of trailing C-17’s is thought to be much greater than necessary. DoD not comfortable trusting models.
• Ground based DWLs have been used to investigate WTVs (LMCT, NASA, DLR, DoD…….)
• Airborne DWL offers significant flexibility in monitoring WTVs in a variety of aircraft configurations, atmospheric conditions and topographical regions.
Wing Tip Vortices
C-17 General Characteristics

Length: 174 feet (53.04 m)
Height at Tail: 55.1 feet (16.79 m)
Wing Span to Wingtips: 169.8 feet (51.74 m)
Maximum Payload: 164,900 lbs. (74,797 kg)
Range with Payload: 2,420 nautical miles
Cruise Speed: 0.74 – 0.77 Mach
Approach Speed: 130kts
Major considerations

• Differential speed between C-17 and Twin Otter. +10 kts of 130 kts.
• Scanner slew rate
• Six sampling modes
• What are the maximum tangential velocities expected?
• What are the time/space requirements for life cycle monitoring?
• Measurements of thermal stability and wind profiles between surface and 1000m
Vortex Model

- The flow field behind a lift-generating aircraft can be approximated by a pair of fully rolled up vortices a few wing spans behind the aircraft,
Vortex Model

• As the trailing wake rolls up, the vortices move inward from the wingtips and are eventually separated by an effective span, $b_{\text{eff}}$. For an elliptic loading,

$$b_{\text{eff}} = \frac{\pi b}{4}.$$ 

• The initial vortex strength is given by,

$$\Gamma_0 = \frac{kW}{\rho V_\infty b_{\text{eff}}} = \frac{4kW}{\pi \rho V_\infty b}.$$ 

• The vortex strength decays over time according to the empirically-derived vortex decay time $t_d$. $t_v$ is the current vortex age

$$\Gamma = \Gamma_0, \quad t_v \leq t_d$$

$$\Gamma = \Gamma_0 \frac{t_d}{t_v}, \quad t_v > t_d$$
Vortex Model

- The induced velocity is maximum at some distance from the vortex core.

- Induced velocity from Biot-Savart law with corrections to model zero velocity at vortex core
  - Velocity profile based on Kurylowich model

- Numerical model generates new vortex at each time step at each wing tip

\[ r_c = 36.2 \sqrt{\frac{vt_v}{\cos^2 \Lambda}} \]

\[ V_\theta = \frac{r}{2\pi r} \left[ 1 - e^{-1.26(r/r_c)^2} \right] \]
# Vortex Calculations – 1250 ft. AGL

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Distance from a/c (ft)</th>
<th>Altitude (ft)</th>
<th>Vortex Core Radius (ft)</th>
<th>Max Vtan (ft/s)</th>
<th>Radius (ft) with Vtan of 20 ft/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>1640 (0.5 km)</td>
<td>1216</td>
<td>1.39</td>
<td>391</td>
<td>37.99</td>
</tr>
<tr>
<td>15</td>
<td>3281 (1km)</td>
<td>1174</td>
<td>1.97</td>
<td>277</td>
<td>37.99</td>
</tr>
<tr>
<td>30</td>
<td>6561 (2km)</td>
<td>1088</td>
<td>2.78</td>
<td>195</td>
<td>37.99</td>
</tr>
<tr>
<td>60</td>
<td>13123 (4km)</td>
<td>918</td>
<td>3.93</td>
<td>138</td>
<td>37.98</td>
</tr>
<tr>
<td>90</td>
<td>19685 (6km)</td>
<td>780</td>
<td>4.81</td>
<td>76</td>
<td>25.41</td>
</tr>
<tr>
<td>120</td>
<td>26247 (8km)</td>
<td>682</td>
<td>5.56</td>
<td>49</td>
<td>19.06</td>
</tr>
<tr>
<td>150</td>
<td>32808 (10km)</td>
<td>606</td>
<td>6.22</td>
<td>35</td>
<td>15.24</td>
</tr>
<tr>
<td>180</td>
<td>39370 (12km)</td>
<td>546</td>
<td>6.81</td>
<td>27</td>
<td>12.53</td>
</tr>
<tr>
<td>210</td>
<td>45932 (14km)</td>
<td>494</td>
<td>7.36</td>
<td>21</td>
<td>9.64</td>
</tr>
<tr>
<td>240</td>
<td>52493 (16km)</td>
<td>450</td>
<td>7.86</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>270</td>
<td>59055 (18km)</td>
<td>411</td>
<td>8.34</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>65616 (20km)</td>
<td>377</td>
<td>8.79</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>

W = 400,000 lb, V = 130 knots, Altitude = 1250 ft, td = 60s
# TODWL Sampling Modes

<table>
<thead>
<tr>
<th>Mode Name</th>
<th>C - 17</th>
<th>T-Otter</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backslide</td>
<td>600’</td>
<td>3000’</td>
<td>Begin sampling with Twin Otter above and just forward of C -17; drift backwards while nadir raster scanning</td>
</tr>
<tr>
<td>Overtake</td>
<td>600’</td>
<td>3000’</td>
<td>Begin nadir raster sampling when TO is 1 -2 km behind C-17 and then overtake the C-17</td>
</tr>
<tr>
<td>Trailing</td>
<td>600’</td>
<td>1000’</td>
<td>Begin 3km behind C-17 and use dithered prospecting scan at – 6 degrees for 5 min.</td>
</tr>
<tr>
<td>Prospecting</td>
<td>600’</td>
<td>1000’</td>
<td>Begin 3km lateral to C-17 path and cross over DZ; do 180 and repeat going other direction.</td>
</tr>
<tr>
<td>DZ cross (GB)</td>
<td>600’</td>
<td>Zero’</td>
<td>Park the Twin Otter in a position to allow the lidar to scan the DZ from a side perspective to C-17 path.</td>
</tr>
<tr>
<td>DZ along (GB)</td>
<td>600’</td>
<td>Zero’</td>
<td>Park the Twin Otter in a position 3 -5 km “up approach” from the DZ to allow the lidar to scan the DZ along the C-17 path. C-17 would need to fly a J leg to avoid having vortexes hit the Twin Otter.</td>
</tr>
</tbody>
</table>
Aircraft positions and lidar cone of regard for “backslide” and “overtake” modes
Challenges

• Getting and keeping C-17 and Twin Otter aligned during 8km “runs” in cross winds and heavy turbulence
  – C-17 at 130 Kts with FL 550’ or 1250’ AGL
  – Twin Otter at 130 Kts with FL 3500’ - 5500’ AGL

• Keeping vortex pair within TODWL’s field of regard
  – Want a small field of regard to increase spatial and temporal resolution

• Sample features with spatial dimensions of a few 10’s of meters with a pulse length ~ 75m.

• Extract velocities in the presence of strong chirp returns from surface.
Summary

• The airborne DWL documentation of WTV life cycles has been successfully demonstrated. CIRPAS pilots deserve much credit for positioning the Twin Otter in prescribed locations relative to the C-17.

• The initial data sets (35 hours, >150 runs) cover extremely convective, neutral and nocturnal stable boundary layer conditions.

• SWA will work with Draper Labs to add statistical envelopes to its deterministic parametric model.

• This work may provide justification for the use of DWLs on C-17’s to directly detect WTVs.