Effect of continuous and pulsed blowing on the near- to mid-wake flowfield generated behind a simple model and a generic aircraft-type model

Eric COUSTOLS\textsuperscript{1}, Jean-Bernard DOR\textsuperscript{1}, Laurent JACQUIN\textsuperscript{2}, Pascal MOLTON\textsuperscript{2}, Frédéric MOENS\textsuperscript{3} and Guy PAILHAS\textsuperscript{1}

\textsuperscript{1}ONERA / DMAE – Toulouse - France
\textsuperscript{2}ONERA / DAFE – Chalais Meudon - France
\textsuperscript{3}ONERA / DAAP – Châtillon - France
Wake Vortex Research at ONERA

Context

- ONERA has been highly involved in Wake Vortex research, from complementary studies undertaken **mainly** in the framework of:
  - BRITE-EURAM 4th & 5th FP Projects [Eurowake (‘96→‘99), C-Wake (‘00→‘03)] and Technology Platforms [AWIATOR "Aircraft Wing with Advanced Technology OpeRation" (‘02→‘07)] and Thematic Networks [WakeNet (‘98→‘01) & WakeNet2-Europe (‘03→‘06)]
  - National programmes/activities:
    - ONERA Joint Research Project (‘97→‘04)
    - French DPAC programme (Civil aircraft applications) (‘00→‘05)

- Most of activities being part of the DLR/ONERA Collaborative Research Programme on aircraft wake vortices

Minimised Wake: Phase I (‘99→‘02) & Phase II (‘03→‘06)
Experimental Wake Vortex Research at ONERA

Main Objectives

- ONERA has thus defined a pluri-annual research programme which concentrates on experimental investigations dealing with:
  - characterisation of Wake Vortex formation, evolution (physics, dynamics) and decay, using either simple model or generic aircraft-type model (2/4-engine type) in the most appropriate ONERA testing facility (wind tunnel, water tank or catapult)
  - development of strategies for Wake Vortex control, minimisation

- This presentation will highlight the main results that have been recorded, for the last five years or so, regarding Wake Vortex control with special emphasis on active devices and control

- Results from ONERA Joint Research Project and DPAC studies
Wake Vortex Control

Two main strategies

- **Near-field**: to act at the source by:
  - increasing diffusion of vorticity or,
  - introducing turbulence in vortex cores,
  → vortex with larger core but less intense (weaker rolling moment for following a/c)

  * **Devices**: spoilers, wing-/flap-tip, fence...

- **Mid-/Far-field**: promote long-wave instability and trigger perturbations
  → obtain premature collapse of vortex by considering multiple-vortex system

  * **Passive concept**: Flap arrangement (D.F.S.) [cf. Moens et al.]

  * **Active devices**: Blowing, ...
Wake Vortex Stability and Control

Strategy

- **Search** for non-energetic mechanisms having strong potential to dissipate vortices → linear / co-operative instabilities
  - short wavelength (*Widnall*) → slight impact on mid-wake
  - large wavelength (*Crow*) can be considered and exploited for reducing wake vortex lifetime → **forcing** instabilities

- **Problem**: Ability of Crow instability to rapidly decrease potential danger of a 2-vortex system is not obvious because of low growth rate

- **Solutions**:
  - Exploit **more powerful** instabilities via span loading modifications (D.F.S.) [cf. Moens et al.]
  - Trigger instabilities via **blowing devices**
Wake Vortex Stability and Control

Outline of Blowing Strategy

- **First investigations** of the effect of continuous and pulsed blowing on the near- to mid-wake fields were made in the framework of the ONERA Joint Research Project:
  - Water tunnel tests (ONERA Toulouse)
  - Rather "simple" experimental set-up
  - Instrumentation: Hot-wire, LDA and PIV

- **Further investigations** devoted towards applications: the effect of continuous and pulsed blowing on the near- to ext'd near-wake fields (under DPAC fundings):
  - Wind tunnel tests (ONERA Fauga Mauzac)
  - Generic model of a Very Large Transport Aircraft (VLTA-type a/c)
  - Instrumentation: Hot-wire and 3D LDA

Developed by G. Pailhas (ONERA Joint Research Project Meeting, Feb. 11)
Experimental study at ONERA Toulouse Water Tunnel

Effect of continuous and pulsed blowing (Joint Research Project)
Experimental study at ONERA Toulouse Water Tunnel

Effect of continuous and pulsed blowing (Joint Research Project)

Instability of two wing tip counter-rotating vortices

(Hot-wire measurements)

x/b=33

instabilité de Widnall

instabilité de Crow
Experimental study at ONERA Toulouse Water Tunnel

Effect of continuous and pulsed blowing (Joint Research Project)

1 - injection dans l’axe des tourbillons
2 - injection perpendiculaire à l’axe des tourbillons

Without blowing

Continuous blowing

Pulsed blowing Fx=5.5Hz

x/b=27

WakeNet2-Europe - WG7 Workshop - Toulouse – 9-10 February 2005 - 9
Experimental study at ONERA Toulouse Water Tunnel

Effect of continuous and pulsed blowing (Joint Research Project)

Without blowing

With blowing

\( C_\mu = 2.5 \times 10^{-3} \)

\( f = 5.5 \text{Hz} \)
Experimental study at ONERA Toulouse Water Tunnel

Effect of continuous and pulsed blowing (Joint Research Project)

Without blowing

- $x/b=33$
- $x/b=40$

With blowing

- $C_\mu = 2.5 \times 10^{-3}$
- $f=5.5\text{Hz}$
- $-52\%$
- $-48\%$
- $-29\%$
- $-20\%$
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of continuous and pulsed blowing (DPAC fundings)

Generic Very Large Transport Aircraft-type Model (1:50 scale)

Model Geometry

- $b/2=0.8m - c\sim0.23m$
- slats, aileron, flaps, fairings, removable T.F.N., H.T.P.
- but no Winglet

Flow Conditions

- $U\sim50\text{ms}^{-1} - Rc\sim760,000 - C_L = 1.40$

Identification of vortex formation and roll-up using 3D LDA, with contributions from:
- wing tip, outboard/inboard tip flaps, TFN, fairings, wing/fuselage junction, HTP, ...
Experimental study at ONERA Fauga-Mauzac F2 W/T

*Effect of continuous blowing (DPAC fundings)*

Holes: 39 trous $\phi = 0,6\text{mm}$

Slots: 40x0,3mm$^2$

$\phi = 2$ et $3\text{mm}$

**Wing Tip Axial Jet**
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of continuous blowing (DPAC fundings)

"Open Flow Jet"

Flap Tip Axial Jet
Aileron Axial Jet
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of **continuous** blowing (DPAC fundings)
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of continuous blowing (DPAC fundings)

### Main characteristics of continuous blowing

<table>
<thead>
<tr>
<th>Type</th>
<th>Location</th>
<th>Geometry</th>
<th>$U_j$ (ms$^{-1}$)</th>
<th>Flow Rate (l / mn)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Axial Jet</strong></td>
<td>Wing Tip (WT Axial)</td>
<td>$\Phi_j = (2)-3$ mm</td>
<td>75 - 280</td>
<td>25 - 100</td>
</tr>
<tr>
<td></td>
<td>Flap Tip (FT Axial)</td>
<td>2mm</td>
<td>180 - 280</td>
<td>25 - 40</td>
</tr>
<tr>
<td></td>
<td>Aileron (AIL Axial)</td>
<td>2mm</td>
<td>280</td>
<td>40</td>
</tr>
<tr>
<td><strong>Slot/holes</strong></td>
<td>Wing Tip Slot Down (WT D-Slot)</td>
<td>$S_j=40 \times 0.3$ mm$^2$</td>
<td>195</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Wing Tip Slot (WT Slot)</td>
<td>- id -</td>
<td>195</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Wing Tip Discrete Slot Down (WT D-Slot Down)</td>
<td>$39$ trou$\Phi_j = 0.6$ mm</td>
<td>50 – 195</td>
<td>25 - 100</td>
</tr>
<tr>
<td></td>
<td>Wing Tip Discrete Slot (WT D-Slot)</td>
<td>- id -</td>
<td>195</td>
<td>100</td>
</tr>
<tr>
<td><strong>&quot;Open Jet Flow&quot;</strong></td>
<td>In the near-wake</td>
<td>$\Phi_j \sim 2$ mm</td>
<td>280</td>
<td>40</td>
</tr>
</tbody>
</table>

\[ C_{\mu_{\text{max.}}} = \sum_j \rho_j U_j^2 S_j / \rho_0 U_0^2 S_{\text{ref.}} \sim 1 \times 10^{-3} \]

$U_0 = 50$ ms$^{-1}$ – $C_L =$ 1.4 – $R_c$ $\sim$ 760000
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of continuous blowing (DPAC fundings)

Baseline

Axial Jet
($\phi=3\text{mm, 100l/mn}$)

Slot
(100l/mn)

Discrete Slot
(100l/mn)

→ Iso-countours of streamwise velocity at $X/b=1$
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of **continuous blowing** (DPAC fundings)

**Baseline**
- Axial Jet
  - ($\phi=3\text{mm}, 100\text{l/mn}$)
- Slot
  - (100 l/mn)
- Discrete Slot
  - (100 l/mn)

→ Iso-contours of streamwise vorticity at $X/b=1$
Experimental study at ONERA Fauga-Mauzac F2 W/T

*Effect of continuous blowing (DPAC fundings)*

### Baseline

- Axial Jet
  - *(d=3mm, 100l/mn)*

### Slot

- *(100l/mn)*

### Discrete Slot

- *(100l/mn)*

→ Iso-contours of turbulent kinetic energy at $X/b=1$
Experimental study at ONERA Fauga-Mauzac F2 W/T
Effect of \textit{continuous} blowing (DPAC fundings)

Wing Tip Vortex

Flap Tip vortex
Main conclusions from the effect of continuous blowing from mean and fluctuating quantities recorded at X/b=1

- Evidenced effect on lateral and vertical positions of the vortex generated at the wing tip, ∀ type of blowing at wing tip
- but effect more or less important with max. displacement (~10mm) less than the vortex core itself (max. displacement: axial Jet at Flap Tip and Wing Tip Slot/ Discrete Slot)

- Minor effect on the maximum level of axial vorticity component, even at large flow rates, while TKE was increased in vortex cores

Main results (at comparable blowing scetions & flow rates):

- Axial jet: a modest effect on tip vortex
- Lateral injection: more powerful than injection downwards
- Discrete holes: more active than slots
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of **pulsed** blowing (DPAC fundings)

- **Aim of pulsed blowing:** amplifying instabilities in the vortex wake roll-up phasis could anticipate their decay

- **Selection of blowing using discrete holes** was retained from former studies with continuous injection

- **Crow frequency close to 5 Hz**
  - 3D LDA and Hot-wire measurements at X/b=0.04, 1.0 & 2.25
  - 3 frequencies: 2.5Hz, 5 Hz & 10Hz
  - Spectral analysis: 100 blocks 2048 samples at Fe=2kHz & 10kHz
  - Same free-stream conditions as for the continuous blowing
  - $U_j \sim 48-100 \text{ ms}^{-1}$ and mean flow rate $\sim 0.28 \times 10^{-3}$
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of **pulsed** blowing (DPAC fundings)

Iso-contours of turbulent kinetic energy at X/b=0.04
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of **pulsed** blowing (DPAC fundings)

w/o blowing  with blowing

**Iso-countours of turbulent kinetic energy at X/b=0.04**

**Iso-countours of axial vorticity at X/b=0.04**
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of **pulsed** blowing (DPAC fundings)

Iso-contours of turbulent kinetic energy at $X/b=1$

**WakeNet2-Europe**

WakeNet2-Europe - WG7 Workshop - Toulouse – 9-10 February 2005 - 25
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of **pulsed** blowing (DPAC fundings)

- **w/o blowing**
- **with blowing**

### Iso-countours of Signal fluctuations

**X/b=1.0**

**X/b=2.25**
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of **pulsed** blowing (DPAC fundings)

**Iso-countours of Signal fluctuations at X/b=1**
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of **pulsed** blowing (DPAC fundings)

Iso-countours of Signal fluctuations at \(X/b=1\)
Experimental study at ONERA Fauga-Mauzac F2 W/T

Effect of **pulsed** blowing (DPAC fundings)

![Graphs showing frequency and power spectral density.](image)
Main conclusions from these studies

- **Active devices** (continuous & pulsed blowing) were considered to trigger instabilities for wake vortex control
- Several investigations were conducted in ONERA facilities (water tank and wind tunnel) for two different wake flow field topologies
- **Parametric study** was partially completed:
  - Different types: axial jets, injection thru slots or discrete holes
  - Several blowing velocities, flow rates with max. $C_\mu$: 2.5 $10^{-3}$/1.0 $10^{-3}$
- For simple counter-rotating topology, important decrease of vorticity recorded up to $\sim40b$, with continuous injection → Potentiality of pulsed frequency was evidenced too. Effect on circulation decay t.b.c
- For more complex initial wake topology (behind generic a/c type model) detailed scrutinisation in the ext'd near-wake field using hot-wire: effect on TKE, spectral density... Unsteadiness still present at X/b=2.25
- **Next steps**: remaining effect in mid-wake field from catapult tests, in combination with D.F.S. strategy? trigger instability (flow rate↑)?