An overview of European projects on Wake Vortices
(in connection to Working Group 7 activities
"Principles of Wake Vortex alleviation")

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Wake Vortex Research in Europe

Context

Europe has been highly involved in Wake Vortex research, from complementary studies undertaken in the framework of:

- BRITE-EURAM 4th, 5th & 6th FP Projects [Eurowake ('96→'99), WAVENC ('94→'97), C-Wake ('00→'03), S-Wake ('00→'03), Far-Wake ('05→'07)]; Technology Platforms [AWIATOR ('02→'07)]; Thematic Networks [WakeNet ('98→'01) & WakeNet2-Europe ('03→'06)]

- National programmes/activities:
  - ONERA Joint Research Project ('97→'04), DPAC programme (Civil aircraft applications) ('00→'05)
  - DLR Wirbelschlepppe Project ('00→'05)
  - DLR/ONERA Collaborative Research Programme on aircraft wake vortices Minimised Wake: Phases I ('99→'02) & II ('03→'06)
  - NLR – CERFACS – NATS activities; TsaGI too

- Industrial research (Airbus Industrie, 3E partners)
European wake vortex related programs

WakeNet
WakeNet 2-
Europe
WakeNet -
USA

S-WAKE
wake characterization

C-WAKE

M-FLAME
on board detection

WAVENC
encounter modeling

EUROWAKE
near field vortex

EUROWAKE

AWIATOR
minimizing by design

I-WAKE
on board detection

ATC-WAKE
ATM implementation

FAR-WAKE
Fundamental aspects

STILL ACTIVE
Wake Vortex Research in Europe

**Context**

-European partners have thus defined pluri-annual research programs which concentrate on complementary aspects:

- Characterisation of WV formation, evolution (physics, dynamics) & decay,
- Development of strategies for wake vortex control, minimisation
Wake Vortex Dynamics

Field description

Vortex field: generally split in **four regions**

- **Region I**: Near-wake field (few wing chord lengths)  
  Vortex formation
- **Region II**: Extended near-wake field (~10 b)  
  Vortex roll-up & merging
- **Region III**: Mid-wake field (≈ 80 b)  
  Vortex drift - instabilities appearance
- **Region IV**: Far-wake field (> 100 b)  
  Vortex collapse, disperse
  Development of instabilities

![Diagram showing regions of vortex field](image.png)

- Distance behind LTA aircraft: (150b ~ 4 n.m. separation)
Wake Vortex Dynamics

Field description in the mid-wake region from Catapulte

Model under the ramp at B20

B20 Catapult Facility
(ONERA Lille)
Wake Vortex Dynamics
Field description in the mid-wake region from Towing Tank

Model at TUDelft
Model at INSEAN

Movie provided by: CIRA
What do we know about Wake Vortex Alleviation?

State of the art (from "ToR" Terms of Reference of WG7)

- **Wake Vortex formation** and roll-up reasonably well understood though some **uncertainty** still present in the accurate prediction of the vortex strength for particular aircraft configuration.

- **Mechanisms for Wake Vortex alleviation** studied extensively in the near-/extended near-wake field but not so much in the mid- to far-wake field. Thus:
  - **effectiveness on decay phase** has to be **clarified** from ground-based facility tests (i.e. towing tank, catapult)
  - **effectiveness for full scale aircraft** has still to be **proven**
  - **validation** from CFD applications is **needed**

- **Problems of patents issues**
What do we know about Wake Vortex Alleviation?
Lessons learnt from European Projects & National Programmes

Alleviating wake vortices means:

**Near-field:** to promote small scale instabilities and increase diffusion of vorticity or to introduce turbulence in vortex cores to obtain thicker final vortices (larger cores but less intense \(\rightarrow\) smaller rolling momentum)

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

**Far-field:** to promote long-wave instabilities and trigger perturbations to obtain a premature wake collapse

- **Passive concept:** Multiple-vortex system (Flap arrangement)
- **Active devices:** Blowing, oscillating flaps, ailerons or spoilers
What do we know about Wake Vortex Alleviation?

Two main strategies

Near-field: \( \Gamma \) unchanged but lower rolling momentum expected (encounters with the vortices before \( T^* \) or with vortex pieces after \( T^* \))

Far-field: wake collapse due to long-wave instabilities

\[ T^* = T / t_0 \]
\[ t_0 = 2\pi b_0^2 / \Gamma_0 \]
\[ b_0 = s.b \]
\[ t^* = x^* C_L / 4\pi s^3 AR \]
What do we know about Instability in Wake Vortex?
Short- and long-wave instability

(by courtesy of
G. Pailhas – ONERA)

Short-wave:
(λ ~ O(a) ~ core radius ~ 5mm)

Long-wave:
(λ ~ O(b₀) ~ 30mm)

Widnall instability

Crow instability

instabilité de Crow
What do we know about Instability in Wake Vortex?
Short- and long-wave instability

(by courtesy of T. Leweke – IRPHE)
What do we know about Wake Vortex Alleviation?
Near-field control

short-wave instabilities (Widnall type) control the merging of co-rotating vortex systems

short wave (Widnall) ? Merger

(by courtesy of T. Leweke – IRPHE)
What do we know about Wake Vortex Alleviation?

Near-field control

short-wave instabilities (Widnall type) control merging of co-rotating vortex systems (e.g. wing tip / flap tip)

vortex merging can be controlled by devices, *if needed*

several ground tests were performed on this topic although some patents have been issued, limiting information, yet.
What do we know about Wake Vortex Alleviation?

Near-field control (Examples of devices)
What do we know about Wake Vortex Alleviation?

Near-field control works:

- Experiments in DNW-NWB showed:
  - a reduction of peak vorticity,
  - a reduction of max cross-flow,
  - an enlargement of vortex core, though some centres not well defined (turbulence generator)

Generally speaking:
- spread of vorticity but
- $\Gamma$ flap vortex remains unchanged

(by courtesy of E. Stumpf – DLR-Bs)
What do we know about Wake Vortex Alleviation?

Near-field control works

Non-dimensional axial vorticity peak $\xi$ of Outboard Flap Vortex (OFV) vs. $X/b$ for Reference & Device configurations

(by courtesy of C. Bellastrada – TU Munich)
What do we know about Wake Vortex Alleviation?

Near-field control ... may be hopeless ✰

Flap- & wing-tip devices by courtesy of Airbus France

X/b=1

X/b=5

without devices

with devices

E2-type a/c model (1:100 scale)

ONERA F2 W/T - $C_L=1.7$

vorticity - LDV /ONERA

EUROWAKE
What do we know about Wake Vortex Alleviation?
Near-field control ... is subtle ★

**PIV cross flow velocity at X/b=10**

- Basic, config 1
- Spoiler, config 2
- Spoiler, config 3

- Almost merged
- Not merged
- Fully merged

*SWIM model at DNW-LST W/T*

(by courtesy of A. de Bruin - NLR)
What do we know about Wake Vortex Alleviation?

Near-field control ... is subtle ☆ ☆

PIV cross flow velocity at $X/b=30$ (SWIM model at DNW-LLFT W/T)

(by courtesy of A. de Bruin - NLR)
What do we know about Wake Vortex Alleviation?
Near-field control ... using jets (cold dynamics)

Approach Idle (20,000 r.p.m.)

Reduction of vortex intensity

Power for Level Flight (40,000 r.p.m.)

5-Hole probe at $X/b=0.294$ & 1.322

Effect of Power Increase
(by courtesy of G. Elphick – Airbus-UK)
What do we know about Wake Vortex Alleviation?

Near-field control ... using jets *(cold dynamics)*

**Effect of Power Increase**

Euler computations (Tau-code):
- VLTA-type model
- ~6 Million grid (unstruct.)

- strong interaction of the outer flap vortex with the outer engine jet
- Engine jet wrapped around flap vortex and about to be trapped in vortex core region

(by courtesy of E. Stumpf)
What do we know about Wake Vortex Alleviation?

Near-field control ... to affect Far-field

(by courtesy of K. Huenecke, C. Huenecke & K. Schmidt – AI-D)
What do we know about Wake Vortex Alleviation?

**Far-field control**

**Idea:** to promote long-wave instabilities and to trigger perturbations to obtain a premature wake collapse

**Problem:**
- Large wavelength (*Crow*) can be considered and exploited for reducing wake vortex lifetime forcing instabilities
- Ability of *Crow* instability to rapidly decrease potential danger of a 2-vortex system is not obvious because of low growth rate

**Solutions:**
- Long-wave instabilities are very powerful if the number of vortex pairs is greater than one: multiple vortex system realised by wing span loading (DFS, spoilers) and enhanced by HTP loading, devices
- Trigger instabilities via blowing devices

ONERA Joint Project
DLR ONERA CRP
What do we know about Wake Vortex Alleviation?

Far-field control via Multiple-vortex system

Evidence from CFD of producing a counter-rotating vortex pair

can be used to detect "rapidly" the interesting cases

initial condition measured by DNW-NWB, enhanced and post-processed by UCL

roll-up calculation by UCL with vortex filament method indicating double vortex pair with counter-rotating vortices $x/b = 25$
What do we know about Wake Vortex Alleviation?

Far-field control via Multiple-vortex system

- When two pairs of counter-rotating vortices can be formed
  - strong interaction between the vortex pairs
  - leading to instabilities & a non-linear development (OMEGA-loops)
  - that destroy the vortices due to a strongly increased dissipation

Example of OMEGA-loops as calculated with 3-D (non-viscous) vortex method

\[ t_0 = 35.7 \text{ s} \quad \text{\tau}_0 = 0.95 \]

\[ t_0 = 35.7 \text{ s} \quad \text{\tau}_0 = 1.16 \]

Consistent with former exp. evidence in towing tank

(Savas, Durston et al.)

(by courtesy of G. Winckelmans – UCL)
What do we know about Wake Vortex Alleviation?

Far-field control via Multiple-vortex system

Experiments (3D LDV) showed:
- real potential for modifying wake evolution in extended near-wake field (effect on secondary flow)
- generation of 4-vortex system
What do we know about Wake Vortex Alleviation?

Far-field control via Multiple-vortex system

Trajectory measurements (tomoscopy, ONERA Catapulte B10)
What do we know about Wake Vortex Alleviation?

Far-field control via Multiple-vortex system

Trajectory measurements (tomoscopy, ONERA Catapulte B10)

Real strong potential of such wing loading modifications for altering vortex trajectories
What do we know about Wake Vortex Alleviation?

Far-field numerical control via Multiple-vortex system

testing different solutions (LES)

- Forced long-wave (Crow)
- Optimal

Vortices still remain strong
Greater Energy Drop

(by courtesy of
L. Jacquin – ONERA/DAFE and E. Stumpf – DLR)
What do we know about Wake Vortex Alleviation? 

Far-field numerical control via Multiple-vortex system

(by courtesy of E. Stumpf – DLR)
What do we know about Wake Vortex Alleviation?

Far-field control via HTP Loading

Model setup for generating a 4 wake vortices system

In memory of Heinrich...
What do we know about Wake Vortex Alleviation?

Far-field control via Multiple-vortex system

Flow visualisation of the wake flow fields

Left: the wake vortex pair of the principle airfoil.
The circulation (vortex core) keeps its intensity for more than 60 spans

Right: The two additional vortices added to interact with the main wake vortices which interact within 30 spans

(view from bottom of tank)
What do we know about Wake Vortex Alleviation?

Far-field control via Multiple-vortex system

Vortex peak velocity

Vortex core size

(by courtesy of Airbus-D)
Further Research on Wake Vortex Alleviation

What are the unsolved issues?

- **Testing facilities:**
  - To check if a selected near-wake field device really changes the vortex size/width and consequently the rolling momentum at the end of the diffusion regime.
  - To confirm that wake vortex break up observed in some facilities, resulting from "Optimised Wing Span Loading", are really attributed to long-wave instabilities and not to "installation- or end-effects".
  - To set-up the knowledge base for strategies of Wake Alleviation.
  - To answer the questions:
    - Is there any potential effect that we can expect from vortex interaction with jets in view of accelerating its decay?
    - Can turbulence be tuned out to enhance decay?
    - ends-effects, bursting, ....
  - ....
Further Research on Wake Vortex Alleviation

What are the unsolved issues?

- CFD tools:
  - To evaluate the potential of simplified simulations, e.g. vortex methods for defining strategy for Wake Vortex Alleviation
  - To evaluate the potential of actual CFD tools to capture the experimentally recorded vortex roll-up, formation and evolution phases, from input provided by data bases (generated in the framework of European programs)
  - To evaluate the sensitivity of vortex roll-up and merging to mesh resolution, longitudinal domain extent or initial perturbation
  - ....
Further Research on Wake Vortex Alleviation

What are the unsolved issues?

- **Aircraft applications:**
  - To confirm Wake Vortex alleviation with flight tests (with appropriate validated technique: ground or in-board Lidar?)
  - To evaluate the potential of long wave mechanism robustness to weather conditions
  - To evaluate the effect of atmospheric impact (cross-wind, thermal stratification, wind shear, turbulence, ground)
  - ...

Aircraft Wing with Advanced Technology Operation AWIATOR

Programme target is the proof of concept and in-flight validation of mature wing technologies for future transport aircraft application.

AWIATOR is a "Technology Platform" within the 5th Framework Programme of the EC

- Programme duration: 2002 – 2007
- Programme managed by Airbus D

23 partners from Europe (+Israel) plus several subcontractors participate:
Airbus D, F, UK, HQ; DLR, ONERA, NLR; EADS LG, M; Alenia, Sonaca, GKN, Sener, Spasa, IAI; CNRS, Cerfacs, Inasco, IST, UCL, NTUA, TUB, TUM
(Countries: De, Fr, UK, NL, It, Be, Es, Pt, Is)

(by courtesy of J. Koenig – Airbus-D, ECCOMAS 2004 Conference)
Task 1.1: Wake Vortex Devices (by courtesy of Jens Koenig, Airbus-D)

Objectives for Wake Vortex Research (T1.1)

- Gain **Knowledge**: How to measure aircraft’s wakes, how to rate aircrafts in the design stage
- Check Chance for **Manipulation**: To accelerate vortex decay by active or passive means: design, devices, configuration

**Strategy:**

- Calculations: Near & Far Field Flow
- Standard Ground Tests: Wind Tunnel
- Advanced Ground Tests: Water Tank, Catapult
- Flight Tests: Ground & In-Flight Meas‘ts

(by courtesy of J. Koenig – Airbus-D, ECCOMAS 2004 Conference)
FAR-Wake: FundamentAl Research on Aircraft Wake Phenomena

- Specific Targeted Research Project (STREP) – 6th FP Programme
- Starting date: 1 February 2005 (3 years)
- Participants: 10 universities, 6 research centers, Airbus
- Coordinator: Thomas Leweke

Objectives

- gain new knowledge about open issues of vortex dynamics relevant to aircraft wakes
- improve physical understanding

- short term:
  - more precise wake characterization methods (ground testing, CFD, flight tests)
  - more reliable wake prediction tools (ATM context)

- long term:
  - knowledge base for strategies of wake alleviation

(by courtesy of T. Leweke – IRPHE)
**Strategy:**

- study of **generic / simplified configurations**
- **multiple complementary approaches:**
  - theoretical analysis
  - experiments (mostly small-scale)
  - CFD
  - analysis of **existing data**
- emphasis on **physics**

**Work Package 1:** Vortex instabilities and decay
**Work Package 2:** Vortex interactions with jets and wakes
**Work Package 3:** Wake evolution near the ground
**Work Package 4:** Synthesis and Assessment

(by courtesy of T. Leweke – IRPHE)