STATUS OF ONERA RESEARCH ON WAKE VORTEX
IN THE FRAMEWORK OF NATIONAL ACTIVITIES
AND EUROPEAN COLLABORATION

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Abstract. This document provides a synthesis of recent experimental research studies conducted at ONERA, aiming at a better characterisation of aircraft wake vortex and its control. Thus, either generic, two-engine or four-engine transport aircraft-type models have been considered in existing complementary facilities from ONERA, being the most appropriate for scrutinizing different stages of wake evolution. Main results from several research programmes are discussed. They have been obtained both from National and European activities, although emphasis has been set on the 5th Framework Programme project “C-Wake: Wake Vortex Characterisation and Control”.

1 INTRODUCTION

Some concerns directly related to wake vortex issues have risen again in the past years in Europe, leading ONERA to set-up complementary research programmes aiming at, first of all a better characterisation of aircraft wake vortex, and secondly, its control. Thus, ONERA has been highly involved in current wake vortex research, dealing mainly with the aerodynamic aspects, through:

- national activities (French DPAC programme, ONERA Federative Research Project), and,
- EU-co funded projects and Technology Platform (4th and 5th Framework Programmes) such as Eurowake, C-Wake and AWIATOR.

All these activities are part of the DLR/ONERA "Minimised Wake" programme [1].

These research programmes concentrate on experimental investigations to measure and then to characterise the wake flow field generated both by aircraft-type models in experimental facilities (wind tunnel, water tank or catapult facilities) or by aircraft in real flight conditions. The last topic will not be covered in the present paper, recent work performed by ONERA with DLR and Airbus partners can be found in [2,3]. Several models have been considered, either generic, two-engine or four-engine types.

The different stages of the wake evolution (close to the model to far downstream) could be identified, taking into account the existing complementary experimental facilities at ONERA and their most appropriate measurement techniques:

- the F2 (research-type) and F1 (industrial-type) low speed wind tunnels (ONERA Centre of Fauga Mauzac) for scrutinising the near- and extended near-wake field, using essentially five hole probe, hot-wire and Laser Doppler Anemometry measurements;
- the free-flight research-type catapult facility (ONERA Centre of Lille) for focusing on the mid-/far-wake field, using complementary Laser tomoscopy, Particle Image Velocimetry and Lidar measurements.

In addition to such a characterisation being performed, means for minimising Wake Vortex intensity through either passive or active devices/concepts or adapted flap setting configurations will be evoked.

The present paper will highlight the mains results that have been recorded at ONERA for these last four years, with emphasising on characterisation of wake vortex evolution, and, on the development of strategies for wake vortex control, destruction or minimisation. All results, discussed hereafter, have been obtained in the framework of the C-Wake project and of DPAC funded studies, some of them taking benefit of studies initiated in the ONERA Federative Research Project [4].

2 MAIN OBJECTIVES OF THE EXPERIMENTAL INVESTIGATIONS

For an aircraft, with a mean aerodynamic chord length, \( c \), and a wing span, \( b \), it is usually proposed to split the vortex wake into four regions:
• The near-wake field, close to the wing trailing edge, typically of the order of several \( c \), but less than \( 0.1b \), is characterised by the formation of highly concentrated vortices downstream of discontinuities in the wing span loading (typically, at the wing surface discontinuities).

• The extended near-wake field, typically \( 0.1b < X/c < 10b \), is where the roll-up and merging of dominant vortices (mainly generated by the wing tips and outboard flaps) occur, leading gradually to 2 main counter-rotating vortices, one in each half-wake plane.

• The mid-wake field, at a maximum distance of about \( 100b \), is where the vortex system gradually drifts downwards due to mutual interaction of the vortices and where instabilities emerge.

• The far-wake and dispersion field at a distance greater than \( 100b \), is where developed instabilities result in strong interactions between these two vortices, leading to their dispersal.

The evolution of the wake field behind an aircraft is usually described by the longitudinal distance \( X \), normalised by the geometrical wing span, \( b \): \( X^\ast = X/b \) [5]. \( X=0 \) refers to the trailing edge of the wing tip, at a given value of the angle of attack or lift coefficient, \( C_L \). When plotting the circulation versus vortex lifetime, two phases can be identified (Figure 1): the diffusion regime and the decay. Thus, wake vortex evolution is very often plotted versus the dimensionless vortex lifetime \( t^\ast \): \( t^\ast = t/t_0 \), where \( t_0 = 2\pi b_0^2/\Gamma_0 \) [6]. Here, \( b_0 \) is the initial vortex spacing after roll-up: \( b_0 = s.b \) (\( s \), spanwise load factor, is equal to \( \pi/4 \) for an elliptically loaded wing) and \( \Gamma_0 \) the reference circulation. \( \Gamma_0 = C_L V b/(2s AR) \) is expressed in terms of lift coefficient \( C_L \), aircraft or model speed \( V \), wing span \( b \) and reference wing aspect ratio \( AR \) (=\( b^2/S_{ref} \)).

![Figure 1. Sketch of evolution of circulation versus vortex lifetime or distance (from [5]).](image)

Regarding wake vortex alleviation, two strategies have emerged from recent investigations:
- the low vorticity vortex (or "lvv"- type) approach which acts at the source by either increasing diffusion of vorticity in the extended near-wake field by every possible means or introducing turbulence in vortex cores. The idea is to produce vortices with larger cores and reduced vorticity level, leading to smaller rolling moment for following aircraft. That can be obtained through, for instance, passive devices: wing tip and flap tip devices or spoilers.
the quickly decaying vortex ("qdv"-type) approach, which aims at promoting long wave instabilities and triggering perturbations in order to obtain a premature collapse of the vortex system. That can be obtained by considering multiple-vortex system, generated from differential flap setting (passive way) or continuous/pulsed blowing (active system).

ONERA has essentially concentrated its activity on the second approach, in collaboration with DLR [1], investigating aircraft design modifications with retro-fittable concepts for low-vortex high lift configurations, thus being fully beneficial to aircraft industry.

An experimental study has been performed at ONERA Centre of Toulouse, in the framework of the Federative Research Project, in order to analyse the instabilities present in the core of two wing-tip counter-rotating vortices [7]. Two-point measurements were made through single and two-point hot-film probes allowing such investigation. From spectral analysis, two categories of instabilities, occurring simultaneously in a vortex pair, could be clearly identified: they are commonly referred to as Widnall ("short wavelength-type") and Crow instabilities ("long wavelength-type", with a wavelength of typically several vortex spacing: $\lambda_C \sim 8.25b_0$).

When dealing with wake vortex control, one has to look at non-energetic mechanisms having potential to dissipate vortices. The Widnall instabilities have a very slight impact on the mid-wake field, while long-wave instabilities could be used for decreasing vortex lifetime. However, the ability of a Crow-type instability to rapidly decrease the potential danger of a two-vortex system is not obvious because its growth rate, $\sigma_c$, is relatively low [$\sigma_c (2\pi b_0^2/\Gamma_0) \sim 0.8$]. A possible solution could be to exploit more powerful instabilities close to the aircraft wing, by generating multiple-vortex system in the near- or extended near-wake field, such that the wake vortex system is unstable. Thus, one can think at creating a new vortex in the inner part of the wing, the vorticity of which being either co- or contra-rotating with that of the outer part of the wing (wing tip and external flap tip). This may be achieved from wing span loading variation by modifying the flap settings and is usually referred to "Differential Flap Setting (D.F.S.)" concept. Another approach could be to destabilize the wake vortex field by triggering instabilities applying either continuous or pulsed blowing in the outer part of the wing. Moreover, such concepts could therefore be successfully combined with the D.F.S. approach.

Then, the approach that has been under consideration at ONERA has been to:
- conduct studies with active/passive devices and concepts in research-type testing facilities with the aim to select most promising ones with respect to wake alleviation purpose ($\S$3),
- investigate then the impact of such candidates, for wake vortex alleviation purpose, on the mid-wake field from catapult tests ($\S$4).

An overview of most of the results from the tests developed and conducted with respect to such an approach is provided in the following sections.
3 WAKE VORTEX CHARACTERISATION IN THE NEAR- AND EXTENDED NEAR-WAKE FIELD

Several test campaigns were defined and conducted for the last four years at the F2 low speed wind tunnel of ONERA Centre of Fauga-Mauzac, aiming at investigating the effect of wing tip devices, differential flap settings (cf. §3.1 and 3.2) and blowing (cf. §3.3) on the wake evolution. These tests were performed for low Reynolds number conditions, leading to chord Reynolds number of about 750,000. Following a request from industrial partners, a specific test campaign was then defined at the F1 wind tunnel of ONERA Centre of Fauga-Mauzac. Variations of stagnation pressure from 1 to 3.85 bars have then allowed to characterise the effect of chord Reynolds variations from 750,000 up to 2,850,000 on wake vortex formation and evolution behind a two-engine type model (cf. §3.4).

3.1 Characterisation of wake vortices generated behind a four-engine type model
(Tests at ONERA F2 wind tunnel – "VLTA-type" model)

The baseline configuration of a "VLTA"-type (Very Large Transport Aircraft) model (scale: 1/50, owner: ONERA), corresponding to a high-lift wing featuring a given “landing-type” approach for such an aircraft, was tested at the ONERA F2 wind tunnel. The half-model was equipped with removable Horizontal Tail Plane (H.T.P.) and Through Flow Nacelles (T.F.N.). An integrated winglet, defined for cruise conditions, was also mounted. The aerodynamic chord length of the model wing was $c=0.23m$; the half wing span $b/2$ about 0.8m. The model was mounted on a peniche of 20mm height which was fixed on a splitter flat plate (Figure 2).

![Figure 2 – Experimental set-up of the half "VLTA-type" model along the floor of the ONERA F2 wind tunnel. Zoom in the winglet vicinity. Oil-flow visualisations on the pressure and suction sides of the wing.](image-url)
Transition was tripped on the fuselage nose, on both sides of the H.T.P. and T.F.N. and on the pressure side of the wing; turbulent flow was assumed on the suction side, due to the presence of slats supports. Tests were conducted at ambient temperature, for two free-stream velocities: \(30 \text{ms}^{-1}\) and \(50 \text{ms}^{-1}\). The Reynolds number based upon \(c\), was slightly varying between 455,540 and 759,000. Because of low Reynolds number conditions, special care was brought to avoid any strong separation that should be prejudicial for future tests to be made at the free-flight catapult facility. Indeed, oil flow visualizations were made on both pressure and suction sides of the wing (Figure 2). On the lower part of the wing, the flow remained attached on the whole spanwise extent of the flap. However, some slight separation was clearly noticeable in the outboard part of the wing, in the aileron vicinity, this latter being set at \(2^\circ\). The separation extent was rather small, and should be attributed to geometric perturbation due to model scale and to the interaction between the wake issued from the small supports of the slats and the viscous layer that spreads over the wing. Neither tripping transition just behind these supports nor varying the free-stream velocity brought any favourable effect. However, such an observation led to perform the study of the effect of flap transition just behind these supports nor varying the free-stream velocity brought any favourable effect. However, such an observation led to perform the study of the effect of flap arrangement at a reasonable target value for the lift coefficient: \(C_L=1.4\), which is compatible with model free flight conditions at the catapult. A six-component balance therefore allowed adjusting the angle of attack to reach such a target lift coefficient.

For the baseline configuration, the wing being equipped with the winglet, wake surveys were made using 3D LDV and incense smoke as seeding. The iso-contours of the normalised axial vorticity \(\Omega(b/2)/U_\infty\) are plotted in Figure 3, for \(x/b=0.04\), \(1.0\) and \(2.25\). Grid refinement was adapted around vortex cores, leading to mesh step variations from 30mm to 5mm (small boxes). Very high level of vorticity were recorded close to the wing (\(x/b=0.04\)). Starting from the wing architecture, it was possible to identify the contributions from the different elements of the high-lift system (wing tip, external, middle and inner flaps), from the fuselage/wing junction as well as from T.F.N., fairings and supports. Moving downstream of the H.T.P. location (\(x/b=1.0\) & \(2.25\)), the wing wake spread and diffused. The vertical downwards motion of the wake, due to lift, was clearly noticeable as well as the roll-up process of the main vortices that subsisted: two co-rotating ones (wing tip & external flap) and one counter-rotating resulting from the H.T.P. plus wing/fuselage junction (Figure 3). The two co-rotating
vortices from the external part of the wing did not merge; PIV and tomoscopy from the catapult tests revealed that merging occurred at about 5 wing spans behind the model (cf. §4).

The effect of the winglet on the wake flow is compared from the iso-contours of the longitudinal component of the velocity and of the turbulent kinetic energy, $k$, (Figure 4). Rather high levels of $k$ have been recorded in the trailing vortex cores (7 to 8%), greater than those obtained in the wing wake. That corresponds to "vortex meandering" and has been formerly identified by several experimentalists [7,8,9,10,11]. At last, it should be concluded that the winglet did not have any influence on the maximum level of $k$, did not affect too much the streamlines pattern, but induced a 30% decrease in the maximum of vorticity for the wing tip vortex at identical mesh size.

![Figure 4 – Effect of winglet on iso-contours of turbulent kinetic energy and longitudinal velocity (Baseline configuration “VLTA-type” model - 3D LDV measurements – ONERA F2 W/T tests).](image)

### 3.2 Effect of differential flap setting on wake vortex evolution

*(Tests at ONERA F2 wind tunnel – "VLTA-type" model)*

**Flap arrangement**

Regarding the preceding "VLTA-type" half-model, the flap system was made of six parts, the inboard, middle and outboard flaps being divided in two sets. Flap arrangement was defined from 2D viscous computations on high lift sections combined with a 3D lifting surface method [12]. Several configurations were derived with the objective to select the two most promising ones for further mid-wake field investigation. The methodology used was based upon Betz theory, which states that vortices are created at the maximum of the absolute value of the derivative of the span load distribution $\Gamma(y)$, and that vortex strength is proportional to the area between two minima. These configurations were derived from the ideas to try to act on i) the stability of the vortex system by creating a strong vortex in the inner part of the wing, ii) the roll-up process by designing a flap splitting to have “serrated-type” load distributions.

With respect to the first idea and compared to the wing tip one, the inner vortex can be either counter-rotating (“VLTA-1 configuration”) or co-rotating (“VLTA-5 configuration”). Furthermore, the second idea was to generate multiple vortices in the wing wake; two other configurations (“VLTA-3” and “VLTA-4”) were then defined, the former generating four vortices while the latter five. These wing architectures are not directly retro-fittable, but the
aim of this study was to investigate extreme non-conventional span load concepts, in the framework of the C-Wake project. Depending on the findings, applications to existing aircraft might be done with more realistic constraints (cf. AWIATOR Technology Platform) or could be considered in the design process for new aircraft.

The following table provides the differential flap setting, compared to the baseline configuration for which the settings of each part was $\alpha$; "IN" refers to the flap not deployed and "NO" to the absence of the flap part.

<table>
<thead>
<tr>
<th>Flap parts</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLTA-1</td>
<td>NO</td>
<td>$\alpha+5^\circ$</td>
<td>$\alpha$</td>
<td>$\alpha$</td>
<td>$\alpha$</td>
<td>$\alpha$</td>
</tr>
<tr>
<td>VLTA-5</td>
<td>$\alpha+5^\circ$</td>
<td>$\alpha+5^\circ$</td>
<td>$\alpha$</td>
<td>$\alpha$</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>VLTA-3</td>
<td>$\alpha+5^\circ$</td>
<td>IN</td>
<td>$\alpha$</td>
<td>IN</td>
<td>$\alpha$</td>
<td>IN</td>
</tr>
<tr>
<td>VLTA-4</td>
<td>IN</td>
<td>$\alpha+5^\circ$</td>
<td>IN</td>
<td>$\alpha$</td>
<td>IN</td>
<td>$\alpha$</td>
</tr>
</tbody>
</table>

*Table 1 – Flap arrangement and flap settings for all D.F.S. configurations.*

The extended near-wake field was explored at $X/b=1$ using 3D LDV, with a mesh step of 15mm. It should be noted that almost all configurations (except “VLTA-5”) were tested without the H.T.P. to evaluate the effect of span loading variation without any interaction with the strong vortex coming out from the negative lift of the H.T.P.

The effect of flap setting and splitting on the normalised longitudinal component of the velocity is clearly noticeable on the wake itself (Figure 5), with more or less variations with
respect to the baseline configuration. Depending upon the configuration, new vorticity regions were then identified, with axial velocities less than the free-stream value (defects close to 15% were recorded). Derivations of the axial component of the vorticity revealed that configuration “VLTA-1” generated an intense counter-rotating vortex set at about 1/4 of half wing span, while for the “VLTA-5” configuration some co-rotating vortex was present in the median/inner part of the wing. On the other hand, configurations “VLTA-3 & /-4” produced less intense vortex regions compared to the main wing tip one, at the selected position with the appropriate vorticity either positive or negative.

Consequently, from such wake surveys performed at X/b=1, it was possible to validate the numerical methodology applied for defining span loading concept, and to capture and identify the effect on the secondary flow as well as on the vorticity distribution in the wake. The vortex generated at the wing tip remained nearly unchanged whatever the flap arrangement, because tests were made at comparable angles of attack of the model (cf. Table 2, §4), to reach a constant $C_L$ value (~1.4). These results clearly confirmed that the four pre-selected configurations, derived from modifications of the high lift system of the “VLTA-type” architecture wing, have real potential for modifying the wake evolution in the extended near-wake field. The interesting question that arises is: “what will be the behaviour of such a multiple-vortex system in the far-field?” Answer will be provided in §4. From the above-cited four configurations, the “VLTA-1” and “VLTA-5” configurations were then selected because of their strong effect on the extended near-wake field. Furthermore, theoretical studies performed by ONERA on the stability analysis of four vortex systems showed the potential of such “4-vortex” configurations to destabilise the wake vortex field [4,13].

3.3 Effect of continuous and pulsed blowing on wake vortex evolution
(Tests at ONERA F2 Wind Tunnel - "VLTA-type" model)

Using the same model as for former studies (cf. §3.1 & 3.2), ONERA investigated the effect of continuous and pulsed blowing on the extended near-wake field. For the baseline configuration and the same flow conditions ($C_L=1.4$, $U_\infty=50\,\text{ms}^{-1}$), several types of blowing were tested at the wing tip: axial, discrete holes or slots (Figure 6). It should be noted that blowing at the external flap tip or in the aileron vicinity was also tested. Blowing through discrete holes (WT D-Slot) or slots (WT Slot) could be performed either in the transverse direction (same terminology as before) or directed towards the bottom (WT D-Slot Down or WT Slot Down, respectively).

Considering the three types of blowing at the wing tip, different blowing velocities were considered from 75\,\text{ms}^{-1} up to 280\,\text{ms}^{-1}, leading to flow rates extrema: 25l/mn - 100l/mn; i.e. flow rate coefficient $C_\mu$ ($C_\mu=\Sigma \rho_j U_j^2 S_j/ \rho \infty U_\infty^2 S_{ref}$) of about $1 \times 10^3$. In the latter formula, index $j$ refers to the number of blowing device, the cross-section of which is $S_j$ and blowing velocity $U_j$, while index $\infty$ denotes the free-stream conditions and $S_{ref}$ the wing reference surface. Whatever type of blowing is concerned, an effect was evidenced on the lateral and vertical positions of the vortex generated by the wing tip. This effect is more or less important, with
maximum displacement of about 10mm, i.e. much less than the vortex core itself (in fact, the recorded greater displacement corresponded to that of the vortex from the external flap, with axial blowing at the flap tip). There was minor effect on the maximum value of the axial vorticity component, even at large flow rates, while turbulent kinetic energy was increased in the vortex core (Figure 7).

The main conclusions of these studies were that the axial jet had a modest effect on the tip vortex, and that the lateral injection was more powerful than injection directed downwards; furthermore, discrete holes appeared to be more active than slots, at comparable blowing sections and flow rates.

At last, some pulsed blowing was applied aiming at amplifying the unsteady behaviour of the flow in the mid-wake field. Blowing using discrete holes was retained from previous studies with continuous injection; the pulsed frequency corresponded to the typical long-wave instability of a simple two-vortex system (Crow) that would be generated behind this model.
At such flow conditions, this frequency is close to 5Hz. At the furthest available downstream station (X/b=2.25), hot-wire measurements allowed verifying that the unsteadiness was present in the wake flow (Figure 8). The next step will be to investigate the effect of such blowing devices, in combination with flap arrangement, on the mid-wake field, from tests to be made at the ONERA Catapult B20 facility.

Figure 8 – Effect of pulsed blowing (lateral discrete holes at the wing tip) on the spectral densities measured in vortex cores at X/b=1.0 and 2.25 (“VLTA-type” model – 3D LDV measurements - ONERA F2 WT tests).

3.3 Effect of Reynolds number variation on wake vortex topology and formation
(Tests at ONERA F1 Wind Tunnel - two-engine type model)

Tests of a two-engine-type aircraft configuration model (1:38 scale, b~1.18m, owner: Airbus-F) took place at the F1 wind tunnel of ONERA Centre of Fauga-Mauzac. The objective was to quantify the effect of Reynolds number effect on the wake vortices in a realistic aircraft landing configuration.

At a constant free-stream Mach number (M=0.2) the variation of the stagnation pressure from 1 bar to 3.85 bars allowed the Reynolds number (based on the mean aerodynamic chord length) to vary from 0.76 million to 2.85 millions. In order to minimize the interaction between the viscous flow developing over the wing and various possible elements, the model was equipped without any T.F.N., pylon and horizontal tail plane. The high-lift wing configuration comprised slats (24° setting), internal and external flaps (25°), internal and external tabs (14°), all speed aileron (10°) and external aileron (0°) (Figure 9b). Transition was tripped on the fuselage nose and on the vertical tail plane, but not on the wing.

The fuselage was hold through internal balance by a short Z-type tail sting which was connected to a vertical strut. Guy-wires were fixed on the vertical support to reduce its observed lateral variations at high pressure (Figure 9a).

In order to quantify wake vortex evolution, the downstream flow was measured, using five-hole probe (3mm diameter), at two longitudinal sections: X/b=0.5 & 3.5. To achieve such surveys, the model was set at two positions in the test section: the standard one in the middle...
(Figure 9a), which allows continuous angle of attack variations through a turntable; and some upstream one, where only fixed angles of attack at given values can be set.

Tests were performed at a constant $C_L$ value of 1.58, for these two model positions. Increasing the stagnation pressure corresponded to a lower angle of attack to reach the target $C_L$ value: 6.25° compared to 6.68° (cf. Figure 9d); part of this variation of the angle of attack of the model (0.23°), under aerodynamic load at high stagnation pressure, was attributed to model support deformation. However, to reach such target $C_L$ value, cross-checks with the balance at the upstream location in the test section did not reveal any discrepancy on either $\alpha$ or $C_L$, justifying similar loads effects or any pressure gradient in the test section.

An example of iso-contours of the longitudinal component of the velocity is provided at the forward wake survey (X/b=0.5) at Pi=1bar (Figure 9c). The contributions of the wing tip, flap tip and all speed aileron could then be clearly identified, as well as the wing/fuselage interaction, the fuselage wake and the model support. On this plot, two lines were drawn: “L1” going through the cores of the wing tip and external flap tip vortices, and line “L2” crossing the cores of vortices generated in the All Speed Aileron region (both outer and inner parts). Different components of the velocity or vorticity were derived along these two lines, allowing then comparing the effect of Reynolds number on wake flow topology (Figure 10).

At the forward station (X/b=0.5), the effect of Reynolds number variation has no major effect on the global flow topology in the external part of the wing (Figure 10a). One observed
a very small downwards variation of the wing tip vortex of about 0.006b/2, as well as 15% decrease on the maximum level of vorticity of the wing tip vortex due to a lower angle of attack of the model. Moreover, a more important displacement of the core of the flap tip vortex was estimated in both directions (0.018b/2). It could be attributed to the spanwise twist angle variation of the external part of the wing under loads, the maximum of which being at about 80% of the half wing span (input from Airbus-France). When computing the ratio between the core radius to the spacing between the wing and flap tip vortices, one ended up with values between 0.16 and 0.20, slightly dependent upon vortex and Reynolds number. However, these values are very close to that of the merging criterion (0.2) defined by Leweke and Williamson [14,15]. This justified that the merging of the wing tip and outer flap tip vortices has occurred at X/b=3.5, as expected from former tests with a similar wing geometry [10].

![Figure 10](image)

*Figure 10 – Wing and Flap tip - $\Omega_5$ dimensionless velocity at X/b=0.5 along line (L1) – b) ASA – $\Omega_5$ dimensionless vorticity at X/b=0.5 along line (L2) - c) $V_x$ dimensionless velocity at X/b=3.5 along a line crossing each vortex core (L3).*

When considering the vorticity distribution, at X/b=0.5, along the line “L2” (starting from the inner vortex), important differences were recorded for the inner vortex (higher vorticity and smaller core). They could be attributed to the existence of some separation extent on the All Speed Aileron, set at 10°, at low Reynolds number.

At last, at the furthest downstream station (X/b=3.5), two main vorticity pockets subsisted from the outer wing (wing tip and external flap tip) and inner wing (inner and outer ASA vortex and wing/fuselage interaction) but, unfortunately there is not enough information to understand the complete vortex roll-up. When plotting the axial velocity along a line crossing the cores of these two vorticity pockets, there is a slight effect on lateral positions of vortices, for comparable vorticity levels. Such differences could be due to the afore-mentioned wing deformation.

Thus, the Reynolds number increase (from 0.76 to 2.85 millions) did not reveal noticeable changes in the extended near-wake flow field, generated behind the two-engine type model.
4 WAKE VORTEX CHARACTERISATION IN THE MID-WAKE FIELD

An existing free-flight VLTA-type model (1:35 scale, owner Large Aircraft Division of Airbus), having high lift architecture identical to that of the half-model that was used for the extended near-wake field characterisation at F2 wind tunnel, was considered for investigations to be carried out at the ONERA B10 catapult facility. The set-up has allowed the observation of the different phases of the wake vortex evolution (from extended near- to mid-wake regions) without any wall or support interference. Indeed, once the full model is launched, it could fly freely in a 30m long, 9m wide and 10m high observation area [16,17]. The observation plane was a vertical plane, transverse to the flight path of the model, at about 10m downstream of the launching point.

The flights corresponded to steady glides at the target $C_L$ value: 1.4; taking into account the model weight, the flight velocity was about $23\text{ms}^{-1}$. For each model configuration (Baseline, “VLTA-1” and “VLTA-5” configurations), two to three shots were necessary for having a flight in trimmed conditions. The H.T.P. setting was generally deduced from either previous tests conducted at the B10 facility with that model or from polar curves provided by wind tunnel campaigns. Table 2 provides the information for the flight conditions. In-board information (accelerometers, gyrometers, pressure nose probe) completed with optical bases enabled to check the consistency of flight conditions.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>$\alpha (^\circ)$</th>
<th>$\alpha_{H.T.P.} (^\circ)$</th>
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<tr>
<td>VLTA-Basic</td>
<td>11.0</td>
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</tr>
<tr>
<td>VLTA-1</td>
<td>13.5</td>
<td>-14.75</td>
</tr>
<tr>
<td>VLTA-5</td>
<td>11.75</td>
<td>-4.0</td>
</tr>
</tbody>
</table>

Table 2 – Catapult tests: Angle of attack of the model and H.T.P. setting for the 3 high-lift wing configurations.

For each configuration, wake surveys were carried out using complementary techniques: trajectography or tomoscopy, PIV and Lidar measurements. Smoke visualisations with appropriate seeding allowed getting the vortex core trajectories as well as wake vortex evolutions, essentially for the main vortices which subsisted in the wake of the model, after
the roll-up process. Applying tomoscopy in that facility allowed checking the symmetry of the wake flow field, but pointing out however differences due to model imperfections.

As illustrated in Figure 12a for the baseline configuration, the repeatability of the shots was rather good. The lateral positions of the vortices are plotted as a function of the longitudinal distance, \( X \), normalised by the wing span \( b \) of the free-flight model. Due to tests process, there were always some small differences between two consecutive shots due to model launching conditions, which could induce some minor rolling effect in some cases. In order to take these issues into account, it was decided to perform wake vortex analysis in a vortex axis reference frame rather than in a ground based reference one. Indeed, longitudinal distance, distance between the two vortices, \( D \), and height from the ground of the centre of the two vortices, \( H \), should be more representative. The effect of configurations can be clearly noticeable in Figures 12b and 12c. In the first part of the flight, the wake vortex evolution for the “VLTA-1” flap arrangement did not provide too many changes. But, downstream of 15 wing spans, the main external vortices went slower towards the ground, which is in perfect agreement with the recorded increase in vortex spacing. On the other hand, considering “VLTA-5” configuration, a 4-vortex system subsisted till 20-25 wing spans, leading to closely spaced main vortices and thus steeper vortex descent. Depending upon model configuration (flap arrangement) wake surveys could be performed until a maximum distance varying between 25-30 to 60 wing spans, from which ground effects appeared. These latter were present at a height above the ground corresponding to \( H/b=1 \); indeed, there is a sudden spreading of the vortex trajectory in the lateral direction (Figure 12b, “VLTA-Basic” configuration, for instance).

Moreover, DLR and ONERA worked out together at the B10 facility, using Particle Image Velocimetry technique. That would allow measuring instantaneous velocity fields and getting a more detailed analysis of the secondary velocity field. A specific support was designed and built by DLR to hold 10 cameras (1280x1024 pixels resolution per camera). It allowed then covering a rather large observation area (1390mm x 920mm in the Y*Z plane, i.e. \( \sim120\% \ b/2 \times 80\% \ b/2 \)) and getting a very precise flow description with about 48500 vectors. Compared to former tests [18], improvement was brought to increase the field of view (FoV), though

![Figure 12 – Tomoscopy results: a) repetitivity of vortex separation for VLTA-Basic configuration, b) half of vortex spacing versus X/b – c) height of vortex versus X/b (ONERA B10 Catapult tests).]
keeping a high level of grid resolution (spatial mesh less < 5mm). The seeding was made from olive oil fog.

PIV measurements were performed by moving the cameras support (between two different shots and not during a shot) in order to try to catch, at a given vortex lifetime, the main dominant vortex system in the scrutinized window area.

The first PIV pictures were obtained very close behind the model: X/b~0.6 (Figure 13a) and X/b~3.6 (Figure 13b). It was then possible to make comparisons with the cross-flow velocity field measured the “VLTA-type” half model tested at the F2 wind tunnel (§3.1), in order to ensure that the “initial” conditions were the same for both facilities, whatever configuration was considered. This point is of course very important for checking consistency of the database that was generated from 0 to about 50 wing spans. Although results could not be provided at the same longitudinal station, due to image scanning, it should be noted a very good agreement regarding vortex topology, since vorticity issued from wing tip, external flap tip as well as gloomy parts could then be identified (Figures 13a/b versus Figure 3).

Unfortunately, no information regarding wing/fuselage turbulence or vorticity can be guessed; however, counter-rotating vortex could be guessed at the lower right corner of the PIV Field of View, coming from the H.T.P. by confrontation to the wind tunnel data (Figure 3).

However, from such type of PIV data, it was very hard to compute an estimate of the circulation for the three high-lift configurations. Indeed, different methods were developed by ONERA because of the identified following problems:

- vortices usually crossed the scrutinised window. Thus, evolution of \( \Gamma \) looked like a "bell curve", starting with low values of \( \Gamma \), reaching a maximum value and then decreasing,
- the vortex size might be larger than the measuring area, missing then some contributions,
- identification of vortex core would allow estimation of circulation from a single vortex through standard relationship \( \Gamma = 2\pi R V_{\theta}(R) \), according that the core is not located too close to the outer boundary of the PIV Field of View.

Comparisons between the different methods did not provide very consistent results. Such a conclusion justifies the needs for mobile PIV system as developed by Airbus-D for towing
tank investigations [19] in the framework of the C-Wake project. DLR and ONERA successfully applied it, in the framework of the AWIATOR Technology Platform, yet.

At last, ONERA proposed to apply Lidar measurement technique [2,3], in order to provide complementary information not only on the angular position of vortices and on the tangential velocity profiles, but also on the circulation distribution. The ground based Lidar was placed on the side of the observation area. Coherent Lidar operated by transmitting a laser beam and detecting the radiation back-scattered by small particles added in the catapult facility with smoke. The analysis of spectrum of Doppler shifts in the frequency of back-scattered radiation provided the line-of-sight velocity component. The beam scanning angle was 40°, and the scanning period 0.4s, corresponding approximately to about 3 wing spans. From Lidar measurements, one could get spectra of velocity profiles, angular cores trajectories, angular descent speed and circulation. However, the absolute positioning of the vortex core was not known but provided by tomoscopy, allowing then deriving tangential velocity profile as a function of the distance to the core centre, for different positions behind the model. Illustrations are provided at several longitudinal stations X/b in Figures 14a & b, for “VLTA-Basic” and “VLTA-5” configurations, respectively. With downstream distance, the maximum of tangential velocity decreased while the vortex core increased (Figure 14a). Such plots provided a rather detailed evolution of the velocity profiles and allowed pointing out the effect of flap arrangement (Figures 14b).

The velocity profiles exhibited a more “chaotic” behaviour, essentially due to the existence of multiple vortex system; this is clearly noticeable for “VLTA-5” configuration (Figure 14b). Depending upon the sign of vorticity of the inner vortex, a secondary velocity profile could be superimposed as a peak or a negative bump just after the maximum of tangential velocity. The interpretation in terms of vortex evolution or decay is then not as simple as for a standard two-vortex system.

From the Lidar velocity profiles, it was possible to estimate the circulation as a function of time from the relationship $\Gamma=2\pi RV_\theta(R)$ (valid for a single vortex, only). Because the Lidar set-up was on the side of the flights, the parts of the vortex lying between the main cores were mixed. Thus, circulation strength estimates were biased, but still were used for comparison purpose (Figure 14c). The outer parts of the velocity profiles between 2 vortex core diameters and a given value $r_{max}$ was used for the integration. The value of $r_{max}$ of b/2 was retained,
since for smaller values, circulation estimates were depending upon \( r_{max} \). At the time of the Lidar post-processing, the computation of the circulation strength by integrating between \( 1/12b \) and \( 1/4b \) was not yet of common practice [4]. Circulation was derived from the two main vortices (left- and right-hand side of the wake), justifying the recorded slight differences. However, taking into account the experimental uncertainties as well as the aforementioned difficulties for integrating the velocity profiles due to multiple-vortex system, it is hard to draw any quantitative conclusion on the influence of flap arrangement. At the first order, it can be stated that there was no clear vortex decay observed at the B10 facility for the three configurations tested. Moreover, the existence of ground effect at about 35 to 60 wing spans, depending upon the high-lift wing configuration, did not allow getting information about decay appearance.

5 CONCLUSIONS

This synthesis paper has dealt with experimental investigations carried out by ONERA in the wake vortex field, in the framework of National and European research programmes. Emphasis has been put, first of all, on a better characterisation of flow field developing behind modern transport aircraft models (either two- or four-engine type), and secondly on wake minimisation. All the testing campaigns were conducted in ONERA facilities, either research- or industrial type, using the most appropriate available instrumentation for scrutinising such wake flow field.

ONERA has concentrated a lot of efforts on the generation of four- or multiple-vortex system, compared to the standard two-counter rotating vortices that subsist far behind an aircraft, generating the long-wave Crow instability. The objective is to i) create a new intense vortex in the inner part of the wing, the vorticity of which having the same or the opposite sign of the one issued from the wing and the external flap tips, ii) promote long-wave instabilities, iii) trigger perturbations to obtain a premature collapse of vortex system. Such experimental investigations were formerly supported from theoretical approach.

Thus, from extensive studies in the near- and extended near-wake field at the ONERA F2 wind tunnel, two configurations were selected from specific flap arrangement, appropriate for wing loading variations. A rather powerful vortex in the inner part of the wing was generated, either co-rotating or counter-rotating with the ones generated at the outer part of the wing. The alteration on the wake vortex roll-up was rather well identified and promising, but was only possible down to couple of wing spans behind the model. Tests conducted later on at the ONERA free-flight catapult (B10) facility allowed to show up the real potential of such wing loading modifications for altering vortex trajectories, by creating either closer or wider resulting vortices in the mid-wake field, inducing larger or weaker descent speed. PIV and Lidar measurements, complementary to tomoscopy issues, allowed getting a more precise description of the secondary flow field, as well as of the velocity profiles and their subsequent modifications due to inboard or outboard wing loading. Unfortunately, because of ground effect alteration in this facility, investigations behind 50 wing spans was not possible, not allowing any hint about premature vortex decay. That issue should be overcome in the brand
new B20 catapult facility, that has been used in the framework of the AWIATOR Technology Platform, for quantifying the behaviour of wake vortex alleviation devices and concepts.

In parallel, ONERA has considered active devices, such as blowing, as a means to trigger instabilities for wake vortex control. Potential of continuous or pulsed blowing was shown in the extended near-wake field using a generic four-engine type aircraft model. Further testing campaigns should occur in the next months at the B20 facility, aiming at investigating the effect of blowing, in combination with flap arrangement, on the mid-wake field generated behind a free-flight four-engine type model.

At last, it should be pointed out that the recorded effects on the vortex trajectory from the catapult tests (confirmed too from towing tank investigations) are an evidence that the wake vortex evolution cannot be led by the aircraft weight only, in the definition of separation distances in airport vicinity. Thus, wing architecture and wing span loading should also be taken into account.

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