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Framework definition, wake characterisation and Synthesis planning for the FAR-Wake project

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A.C. de Bruin
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A.C. de Bruin

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Summary

Within the FAR-Wake project fundamental research is focussed on the precise role of wake vortex instabilities on wake decay (WP1), the effects of engine jets and fuselage wakes (WP2), and the influence of ground proximity on wake evolution, relevant to the airport environment (WP3). Experimental and numerical investigations as well as theoretical/analytical studies are planned and, where appropriate, this is complemented with existing knowledge and data from previous projects.

The work in the technical work packages is oriented to fundamental aspects of the wake generation and its evolution downstream. This research aims to assist with practical solutions in order to reduce the potential hazard for following aircraft and to enable reduced aircraft separation distances to be applied. Since wake alleviation, airport capacity and safety of aircraft operations are research priorities in the FP6 EC Work programme, synthesis and assessment of these aspects will be made in Work Package 4 of the FAR-Wake project.

The present report is the final deliverable D4.1 of Task 4.1 ‘Framework definition and wake characterisation’ and provides guidelines for the technical Work Packages in order to facilitate the final project Synthesis in Task 4.2 of the project. It provides a framework to be used during the analysis, recommendations for the experiments and calculations and recommendations for non-dimensional wake parameters to be explored during the analysis. This report also provides in some detail the data to be expected from the different work packages and partners and a planning of the partner contributions to the final synthesis report.
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<td>cross-section plane through the wake, area of integration, figure 2</td>
<td>m²</td>
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<tr>
<td>AR</td>
<td>wing aspect ratio AR=b²/S</td>
<td>-</td>
</tr>
<tr>
<td>b</td>
<td>wing span</td>
<td>m</td>
</tr>
<tr>
<td>C</td>
<td>integration contour along area A, see figure 2</td>
<td>-</td>
</tr>
<tr>
<td>CD,i</td>
<td>induced drag coefficient, defined in equation (2-15)</td>
<td>-</td>
</tr>
<tr>
<td>CEk</td>
<td>cross-flow kinetic energy coefficient per unit length, see equation (2-16)</td>
<td>-</td>
</tr>
<tr>
<td>CL</td>
<td>lift coefficient (= L/(1/2 ρU₂²S))</td>
<td>-</td>
</tr>
<tr>
<td>Di</td>
<td>induced drag</td>
<td>N</td>
</tr>
<tr>
<td>e</td>
<td>Oswald factor for the induced drag, see equation (2-15)</td>
<td>-</td>
</tr>
<tr>
<td>Ek</td>
<td>cross-flow kinetic energy (per unit length), see equations (2-11) and (2-12)</td>
<td>N</td>
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<tr>
<td>G</td>
<td>circulation ratio: G=Γ/Γ₀</td>
<td>-</td>
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<tr>
<td>G₅₁₅</td>
<td>circulation ratio: G₅₁₅=Γ₅₁₅/Γ₀</td>
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<tr>
<td>G⁺</td>
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<tr>
<td>r</td>
<td>distance from vortex core</td>
<td>m</td>
</tr>
<tr>
<td>rᵥ</td>
<td>viscous core radius, defined in figure 1</td>
<td>m</td>
</tr>
<tr>
<td>rₑ</td>
<td>vorticity core radius, defined in figure 1</td>
<td>m</td>
</tr>
<tr>
<td>Rp</td>
<td>dispersion radius, defined in equation (2-33)</td>
<td>m</td>
</tr>
<tr>
<td>Reₐ</td>
<td>Reynolds number based on circulation strength, defined in equation (2-32)</td>
<td>-</td>
</tr>
<tr>
<td>sb</td>
<td>distance between the vorticity centroids, defined in equation (2-6)</td>
<td>m</td>
</tr>
<tr>
<td>S</td>
<td>reference area for lift and drag coefficient (projected wing surface)</td>
<td>m²</td>
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<tr>
<td>t</td>
<td>wake evolution time (t= Δx/U)</td>
<td>s</td>
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<tr>
<td>t₀</td>
<td>time constant, based on initial wake properties, defined in equation (2-9)</td>
<td>-</td>
</tr>
<tr>
<td>t₀⁺</td>
<td>time constant, defined in equation (2-27)</td>
<td>-</td>
</tr>
<tr>
<td>U</td>
<td>true airspeed</td>
<td>m/s</td>
</tr>
<tr>
<td>Uj</td>
<td>axial flow or jet velocity, see equation (2-34)</td>
<td>m/s</td>
</tr>
<tr>
<td>v</td>
<td>horizontal cross-flow velocity in the wake</td>
<td>m/s</td>
</tr>
<tr>
<td>vₑ</td>
<td>horizontal cross-flow (w.r.t. vortex lines) in the ambient atmosphere</td>
<td>m/s</td>
</tr>
<tr>
<td>V₀</td>
<td>cross-flow velocity around a single vortex, see equation (3-10)</td>
<td>m/s</td>
</tr>
<tr>
<td>V⁺ᵣ</td>
<td>cross-flow velocity, tangential component defined in figure 2</td>
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</tr>
<tr>
<td>w</td>
<td>vertical cross-flow velocity in the wake</td>
<td>m/s</td>
</tr>
<tr>
<td>w₀</td>
<td>initial sink velocity of vorticity centroids (see equation (2-8))</td>
<td>m/s</td>
</tr>
<tr>
<td>w₀⁺</td>
<td>reference sink velocity of vorticity centroids (see equation 2-25)</td>
<td>m/s</td>
</tr>
<tr>
<td>x</td>
<td>axial position in the wake</td>
<td>m</td>
</tr>
<tr>
<td>y</td>
<td>lateral position with respect to the wake symmetry-plane</td>
<td>m</td>
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vertical position in the wake [m]

Greek symbols
\( \rho \) air (or water) density [-]
\( \nu \) kinematic viscosity \([m^2/s]\)
\( \omega \) vorticity, defined in equation (2-1) \([s^{-1}]\)
\( \psi \) cross-flow stream function, defined in equations (2-12) until (2-14) \([m^2/s]\)
\( \Gamma \) wake circulation strength, defined in equation (2-2) \([m^2/s]\)
\( \Gamma_y \) moment of vorticity, defined in equation (2-4) \([m^3/s]\)
\( \Gamma_{5-15} \) average circulation strength between 5 and 15 m from the vortex core (actually taken between 1/12b and 1/4b distance from the core) \([m^2/s]\)
\( \Gamma(r) \) circulation distribution based on \( w(y) \) profile, see equation (2-22) \([m^2/s]\)
\( \bar{\Gamma}_{5-15} \) re-defined average circulation based on \( w(y) \) profile, see equation (2-23) \([m^2/s]\)
\( \Phi \) decay parameter for the cross-flow kinetic energy, equation (2-18) [-]
\( \Phi^* \) decay parameter for the cross-flow kinetic energy, equation (2-30) [-]
\( \tau \) non-dimensional wake evolution time, defined in equation (2-10) [-]
\( \tau^* \) non-dimensional wake evolution time, defined in equation (2-31) [-]

sub-fixes
\( 0 \) initial wake condition
\( c \) vorticity centroid or vortex core
\( F \) full wake, including left- and right side of the wake
\( H \) wake half (either right or left from wake symmetry-plane \( y=0 \))
\( L \) left vortex
\( r \) at radius \( r \)
\( R \) right vortex

super-fixes
* mandatory wake characterisation parameter
+ outboard of the vortex pair
- inboard from the vortex pair
Abbreviations

AWIATOR Aircraft Wing Advanced Technology Operation
C-Wake Wake Vortex Control
DNS Direct Numerical Simulation
Eurowake Wake Vortex Formation of Transport Aircraft
LIDAR Light Detection And Ranging
LES Large Eddy Simulation
PIV Particle Image Velocimetry
RANS Reynolds Averaged Navier Stokes
S-Wake Assessment of Wake Vortex Safety
WAVENC Wake Vortex evolution and WAke Vortex ENCounter
1 Introduction

The aim of the FAR-Wake project [1] is to gain new knowledge on aircraft wake vortex phenomena, critical in the context of wake turbulence behind civil aircraft, but not sufficiently addressed or understood in previous studies. The research in FAR-Wake is focussed on the precise effect of vortex instabilities on wake decay (WP1), the effects of engine jets and fuselage wakes (WP2), and the influence of ground proximity on wake evolution, relevant for the airport environment (WP3). Experimental as well as theoretical/analytical studies are planned. Where appropriate this is complemented by using existing knowledge and data from previous projects.

In depth analysis of the results will be made in the different technical work packages but an assessment of the practical implications is to be made in WP4: Synthesis and assessment. This is to provide a solid knowledge base for future wake prediction and reduction strategies, relevant for increasing airport capacity and safety of air transport, one of the priorities of the EC work programme.

Within the FAR-Wake project 17 partners are participating, having different background and expertise. Some have already participated in previous European Research projects on aircraft wakes, but some are new in this field. It was therefore decided to provide a common framework at the beginning of the project. Task 4.1: ‘Framework definition and wake characterisation’ provides a recommended approach for analysing the results of experimental, numerical and theoretical work in order to enable the comparison of the different results and to facilitate the assessment of their practical implications in the final synthesis Task 4.2. The present report (project deliverable D4.1) provides recommendations for non-dimensional wake parameters to be explored during the analysis; the framework to be used during the analysis; an overview of planned experiments and calculations; recommendations for the planning of the work in the different Tasks. This report also provides in some detail the planning of the partner contributions to the final synthesis report.

In order to facilitate the comparison of individual results during the final reporting and synthesis process, section 2 of this report provides recommended nomenclature and scaling of wake parameters. An overview of planned experiments and numerical simulations and recommendations for the further planning of these activities are given in section 3. An overview and planning of partner contributions to Task 4.2, Final Synthesis and Assessment, is given in section 4.
2 Recommended nomenclature and scaling of wake parameters

In a project like FAR-Wake with 17 partners (some of which are new in the EC research projects on aircraft wakes) there is a clear need to adopt a common nomenclature for wake parameters and to identify proper wake characterisation parameters to be used. The need for having clear definitions arises because partners will be using different models and model scales during the experiments. Sub-scale experimental set-ups, with different fluid velocities, will be employed. Also for the numerical simulations and the theoretical studies a clear parameter definition framework is needed to be able to compare the results from different sources.

Based on the work in previous projects like Eurowake [2], WAVENC [3], C-Wake [4], S-Wake [5] and Awiator [6] a fairly “standard” nomenclature and wake characterisation procedure has evolved. A good introduction to the subject with some of the key parameter definitions is given in the WakeNet position paper [7] and in [8-9]. The wake parameter definitions and wake characterisation procedures described in this report are strongly recommended to be used during the FAR-Wake project in order to enable/facilitate direct comparison of results of different partners and to refer to previous work.

Within FAR-Wake the parameter definitions will mainly follow those applied during the Awiator project [10-11]. Some extra parameters are introduced however, because of WP2 where influence of wakes and thrust on wake development is to be considered.

Section 2.1 defines the main (dimensional) wake parameters. Section 2.2 introduces the non-dimensional parameters to be used during the analysis and reporting phase. Some additional useful parameters are introduced in section 2.3.

2.1 Definition of the main wake parameters

Wake vortices behind a body moving through a fluid, result as a natural consequence of the creation of lift. Within FAR-Wake work is primarily focussed on wakes behind stationary aircraft moving along straight lines. In the near wake (say up to one wingspan downstream) the wake topology can be quite complex (especially behind real aircraft geometries). Usually, due to vortex merging, short wavelength instabilities and/or complex interactions between the different vortices, the wake usually evolves into a single pair of vortices within 10 to 30 wingspans downstream (the extended near wake region). In the far wake region long wavelength instabilities can lead to a break-up and rapid decay of the vortex system. Ambient flow turbulence and atmospheric stability play an important role in the onset of instabilities and
thus in the decay of the vortex system. Suitable introductions to the properties of aircraft wakes and to vortex dynamics are given in [12-15].

Basic parameters for characterising the wake development will be based on global properties of the wake flow field. The evaluation of these parameters requires the availability of detailed and complete flow fields.

At some distance behind an aircraft (about one wing span), the flow field is to be considered as quasi two-dimensional (slow variations in x-direction) and with wake symmetry plane at y=0. In a plane x= constant there is a cross-flow velocity field and an associated vorticity field. During the so-called wake roll-up phase the distributed vorticity becomes more and more concentrated into fewer and stronger vortices. At some distance downstream (about 10 to 30 wing-spans) the vorticity field has usually re-organised itself in a single pair of concentrated (almost axi-symmetric) vortices, as depicted in figure 1. These vortices are of equal strength but have opposite sign.

In figure 1 three flow regions around the final rolled-up vortex core are distinguished. At the centre of each vortex there is a region where strong gradients in cross-flow velocity occur and where the vorticity $\omega$ is large. The maximum cross-flow velocity $V_{0,\text{max}}$ is reached at radius $r_c$. This is often called the ‘core radius’ but here the term ‘viscous core radius’ will be used.

Outside the viscous core region the vorticity is still non-zero, but beyond a certain distance, named the ‘vorticity core radius’ $r_v$, vorticity can be neglected. Due to laminar and turbulent viscous diffusion the vorticity cores will slowly grow\(^1\) until they touch at the wake symmetry plane. At that stage the positive and negative vorticity regions start to cancel each other and the total circulation will start to diminish. Note that generally, due to 3D effects and wake instabilities, the actual process is more complex.

The diffusive process is slow at full scale conditions, but can be quite noticeable during sub-scale testing. Vortex meandering may introduce an apparent diffusive effect in time-averaged flow fields (e.g. measured with pressure probes or averaged PIV flow-fields). Vortex merging depends on the distance between vortices and the size of the vortex cores. Since vortex core growth is relatively large at low Reynolds number, the merging will occur relatively early in sub-scale testing.

Basic parameters for the wake flow field are introduced below.

\(^1\) Note that the laminar/turbulent diffusion process will depend on the Reynolds number.
With \( w \) being the vertical and \( v \) being the horizontal cross-flow velocity component, the streamwise vorticity component \( \omega \) is defined as:

\[
\omega = \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}
\]  

(2-1)

The total circulation strength \( \Gamma \) is anti-symmetric with respect to the wake symmetry plane. For left- or right\(^2\) wake half (see figure 2) it is defined as:

\[
\Gamma = \iint_{\delta_H} \omega dA
\]  

(2-2)

It should be noted that the circulation \( \Gamma \) over a closed area \( A \) can also be obtained by integration of tangential velocities \( \tilde{V}_t \) along the outer contour \( C \) of that area:

\[
\Gamma = \oint_{C} \tilde{V}_tds = \iint_{A} \omega dA
\]  

(2-3)

It can be shown, e.g. [12-15], that under the assumption of quasi 2-D flow (non-viscous or viscous!) \( \Gamma \) remains essentially constant downstream up till the point where counter-signed vorticity touches or crosses the wake symmetry plane. This will, depending on weather conditions and the internal stability of the wake flow, usually occur at large distance downstream of the aircraft only.

The moment of vorticity \( \Gamma_y \), remains constant downstream [14-15] and is defined as:

\[
\Gamma_y = \iint_{\delta_H} \omega y dA
\]  

(2-4)

The vorticity centroid \( y_c \) follows from:

\[
y_c = \frac{\Gamma_y}{\Gamma}
\]  

(2-5)

Since \( \Gamma \) and \( \Gamma_y \) essentially remain constant, also \( y_c \) remains essentially constant downstream. Initial vorticity centroid position \( y_c \) depends on the span-wise loading. Parameter \( s \) is introduced as the non-dimensional lateral distance between the vorticity centroids:

\[
sb = 2y_c \quad \Rightarrow \quad s = 2y_c / b
\]  

(2-6)

\(^2\) For an unambiguous definition of “left-” and “right” wake half, we assume that the line of sight is along the flight direction (so: sight from the back).
The initial value, \( s_0 \), depends on the span-wise loading and for an elliptical loaded wing it is equal to \( \pi/4 = 0.785 \). It becomes larger for an outboard and smaller for an inboard loaded wing.

For an aircraft (model) flying stationary in air with density \( \rho \), at a true airspeed \( U \), along a straight trajectory and having a lift coefficient \( C_L \), the following relation applies for the initial circulation strength (see e.g. [7-9]):

\[
\Gamma_0 = \frac{C_L Ub}{2ARs_0}
\]  

(2-7)

The sub-fix 0 refers to the initial value at a short distance behind the aircraft. AR is the wing aspect ratio (AR= \( b^2/S \), where S is the reference area used in the definition of \( C_L \): e.g. the projected wing surface) and \( s_0 \) is the initial non-dimensional lateral distance between the vorticity centroids.

The initial sink speed of the vorticity centroids follows from Biot-Savart law as:

\[
w_0 = \frac{\Gamma_0}{2\pi s_0 b} = \frac{C_L U}{4\pi ARs_0^2}
\]  

(2-8)

It needs not be confused with the actual sink speeds of individual vortices observed at early wake life-times. It is the hypothetical sink speed for a fully rolled-up vortex pair having circulation strength \( \Gamma_0 \) and vortex spacing \( s_0 b \). With not much decay happening initially, the wake vortex pair sink speed \( w_0 \) given by equation (2-8) will approximately be observed after the wake roll-up phase\(^3\).

Motivated by dimensional analysis, a characteristic time constant \( t_0 \) is usually introduced (see [7], [10-11]). It is defined as the ratio between a length scale \( (s_0 b: \) the initial distance between the vortices) and a velocity scale \( (w_0: \) the initial sink speed \( w_0 \) of the vorticity centroids). So:

\[
t_0 = \frac{s_0 b}{w_0} = \frac{4\pi b ARs_0^3}{C_L U}
\]  

(2-9)

The characteristic time constant \( t_0 \) thus critically depends on the initial non-dimensional distance \( s_0 \) between the rolled-up vortices \( (t_0 \propto s_0^3) \) and is therefore very sensitive to the span loading.

For real and roughly similar aircraft (same AR and W/S), flying at roughly the same velocity \( U \), \( t_0 \) is proportional to wing span \( b \). Therefore wake vortices behind large aircraft tend to live longer than those behind small aircraft.

---

\(^3\) The roll-up phase length \( (x/b) \) depends on the span-loading distribution and is approximately inverse proportional to the total lift coefficient \( C_L \).
In sub-scale testing $U$ and $C_L$ can be chosen freely but this has a direct influence on the characteristic time $t_0$. Note that changing $C_L$ by changing the angle of attack, will only have a weak influence on span loading parameter $s_0$, whereas changing $C_L$ by model configuration changes will have a direct influence on span loading parameter $s_0$. The non-dimensional wake vortex life-time $\tau$ follows from:

$$
\tau = \frac{t}{t_0} = \frac{\Delta x}{b} \frac{1}{U t_0} = \frac{\Delta x}{b} \frac{1}{U} \frac{1}{s_0} = \frac{\Delta x}{b} \frac{1}{s_0^3} \frac{C_L}{4\pi AR} 
$$

(2-10)

Note that $t=0$ and $\Delta x=0$ refer to the moment of passage of the wing tip and to the location of the wing tip respectively. Note that $t=\Delta x/U$ has been used here. In wind tunnels the maximum non-dimensional life time that can be investigated is limited because of maximum $C_L$ and test section length. For tests in a water tank or catapult facility the maximum non-dimensional life time that can be reached is mainly influenced by the depth of the channel or the height of the test facility (though there might also be so-called end-effects caused by the start and stop of the model).

According to [14] the cross-flow kinetic energy (per unit wake length) follows from integration of cross-flow velocities over the cross-flow plane ($A_F$; see figure 2):

$$
E_k = \frac{1}{2} \rho \iint_{A_F} (v^2 + w^2) \, dA
$$

(2-11)

This expression needs to be integrated up to very large distances from the vortices, where experimental data are usually not available. It is possible [14] to use an alternative expression that involves the vorticity $\omega$ and the crossflow stream function $\psi$:

$$
E_k = \frac{1}{2} \rho \iint_{A_F} \omega \psi \, dA
$$

(2-12)

In this case the integration can be confined to the area with non-zero vorticity. The relation between the stream function and the cross-flow velocity components is:

$$
\begin{align*}
 v &= +\psi_z \\
 w &= -\psi_y 
\end{align*}
$$

(2-13)

Stream function $\psi$ is obtained as the solution of a Poisson equation with Neumann boundary conditions dictated by the velocity components along the boundary of domain $A_F$ (Eq. (2-13)):

$$
\Delta \psi = -\omega
$$

(2-14)
Total kinetic energy of a single axi-symmetric vortex, with \(1/r\) velocity behaviour at large distance from the vortex core (e.g. Lamb-Oseen or Burnham-Hallock model), is infinite and diverging at a rate of \(\ln(r)\) when distance of integration \(r \to \infty\). However, for a vortex pair the cross-flow kinetic energy is finite (see [14] and [16]).

The work per time unit, done to balance the induced drag \(D_i\), is equal to \(U_D\) and equals the cross-flow kinetic energy shed to the wake. Therefore, immediately behind the aircraft the cross-flow kinetic energy per unit length \(E_{k,0}\) is equal to \(D_i\). The induced drag coefficient \(C_{D,i}\) is related to the lift coefficient and the span-wise wing loading:

\[
C_{D,i} = \frac{C_L^2}{\pi AR e}
\]  
(2-15)

The so-called Oswald factor \(e\) depends, like \(s_0\), on the span-wise loading. Then the following relations apply for the kinetic energy coefficient:

\[
C_{E_k} = \frac{E_k}{\frac{1}{2} \rho U^2 S} \quad \text{and} \quad C_{E_{k,0}} = C_{D,i}
\]  
(2-16)

The cross-flow kinetic energy decreases downstream due to viscous dissipation.

For monitoring wake decay in a given experiment, the non-dimensional wake vortex strength \(G\) and the ‘cross-flow kinetic energy ratio’ are appropriate parameters. These are defined as:

\[
G = \Gamma / \Gamma_0
\]  
(2-17)

and:

\[
\Phi = E_k / E_{k,0} = E_k / D_i = C_{E_k} / C_{D,i}
\]  
(2-18)

By definition, \(G\) and \(\Phi\) are equal to 1 shortly behind the aircraft (model). Further downstream \(G\) will remain constant up to the point where vorticity cancellation starts at the wake symmetry plane\(^4\) but cross-flow kinetic energy-ratio \(\Phi\) will decrease right from the beginning due to viscous dissipation effects.

The shape of the circulation profile \(\Gamma(r)\) (or rather the non-dimensional value \(G(r)\)) can be determined through evaluation of equation (2-3) in or around a circular area \(A_r\) with radius \(r\) around the vortex centre (e.g. the vorticity centroid or a peak-vorticity location):

\(^4\) When vorticity cores with opposite sign touch each other at the wake symmetry-plane.
\[ \Gamma(r) = \iint \omega dA = \int_0^r 2\pi \omega r dr \]  

(2-19)

Corresponding mean (circumferential averaged) velocity profile (with \(0 < r < (s_b/2)\)) follows as:

\[ V_\theta(r) = \frac{\Gamma(r)}{2\pi r} \]  

(2-20)

Peak velocity defines the size of the viscous core \(r_c\). Plotting the profiles in log-log scaling (see e.g. [17]) reveals vortex core structure and (for rolled-up vortices) gives an impression of the size of the vorticity core (where profile starts to display \(1/r\) behaviour).

For analysing the wake vortex strengths from LIDAR measurements it has become a standard practice (see [7-8] and [17]) to evaluate the average circulation strength between 5 and 15 m from the vortex core:

\[ \Gamma_{z=15} = \frac{1}{10} \int_{-5}^{15} \Gamma(r) dr \]

This definition is however not independent of aircraft wing span and is therefore not suited for sub-scale testing. The following modified definition has been proposed (see e.g. [10-11]):

\[ \Gamma_{z=15} = \frac{6}{b} \int_{y_L}^{y_R} \Gamma(r) dr \]  

(2-21)

For LIDAR measurements \(\Gamma(r)\) has to be evaluated from vertical velocity profile \(w(y)\) along a horizontal line through the vortex pair. With lateral position of left and right vortex core denoted as \(y_L\) and \(y_R\), four portions of the velocity profile can be distinguished:

\(w^+_r, w^-_r, w^+_L\) and \(w^-_L\), super script + denotes the outboard and superscript − denotes the inboard portion of the left or right profile. Average circulation strength \(\bar{\Gamma}(r)\) is defined by:

\[ \bar{\Gamma}(r) = 2\pi r \left[ w^+_r(y - y_r) - w^-_r(y_R - y) + w^+_L(y - y_L) - w^-_L(y_L - y) \right]/4 \]  

(2-22)

From which follows:

\[ \bar{\Gamma}_{z=15} = \frac{6}{b} \int_{y_L}^{y_R} \bar{\Gamma}(r) dr \]  

(2-23)
2.2 Non-dimensional scaling of key wake parameters

Since experiments and calculations will be performed under different conditions (e.g. different model scales, different velocities, different lift coefficient $C_L$) it becomes necessary to define suitable non-dimensional scaling of key parameters in order to enable a comparison of the different results and to assess the implications for full scale conditions. Suitably scaled parameters will be denoted with a super-fix $\ast$. 

Instead of using dimensional co-ordinates $(x, y, z)$ and $r$ (distance to a vortex core), positions are to be referenced to wing span $b$, either by using $x/b$ or $x^\ast$ notation. Velocities are referenced to undisturbed flow velocity $U$ and denoted as, e.g. $v/U$ or $v^\ast$. Vorticity should preferably be presented non-dimensional, so: $\omega^\ast = \omega b/U$. It should be noted that cross-flow velocity and vorticity depend on $C_L$. So these parameters are useful to display the measured flow fields of a certain experiment, but not yet suitable to characterise the main wake properties. 

Wake characterisation is to be based on the overall properties of the wake flow, such as decay of circulation strength $\Gamma$ and cross-flow kinetic energy $E_k$ as function of time. Non-dimensional parameters as function of non-dimensional time were introduced in equations (2-17), (2-18) and (2-10). These are adequate for analysing the results of a given experiment, but not suited to compare results from different experiments, because differences in initial conditions (due to different span-loading, so different values for $s_0$ and $e$) are masked with this kind of scaling. 

To allow an absolute comparison of different aircraft configurations it is more suited to refrain from scaling with parameters $s_0$ and $e$, but use ‘ideal’ (and fixed) values for these parameters instead. Hence, it is proposed to use reference values that are based on an elliptic loaded reference wing (with $e = 1$ and $s = \pi/4$), having the same wing span, wing aspect ratio and lift. The thus derived parameters are denoted with a super-fix $\ast$. The reference circulation strength follows from equation (2-7) with $s_0 = \pi/4b$: 

$$\Gamma_0^\ast = \frac{2 C_L U b}{\pi A R}$$  \hspace{1cm} (2-24) 

The reference sink speed follows from equation (2-8) with $s_0 = \pi/4b$: 

$$w_0^\ast = \frac{4 C_L U}{\pi^3 A R}$$ \hspace{1cm} (2-25) 

The reference cross-flow kinetic energy follows from equation (2-15) with $e=1$: 

$$E_k^\ast = \frac{U^4}{4 \pi^2 A R^3}$$
\[ C_{\infty,0}^* = C_{D,i}^* = \frac{C_L^2}{\pi AR} \]  

The reference time constant \( t_0^* \) follows from equation (2-9) with \( s_0 = \pi/4 \):

\[ t_0^* = \frac{\pi^4 b AR}{16 C_L U} \]  

Then the recommended non-dimensional wake characterisation parameters become:

\[ G^* = \frac{\Gamma}{\Gamma_0^*} \]  

\[ \bar{G}_{s=15} = \frac{\Gamma_{s=15}}{\Gamma_0^*} \]  

\[ \Phi^* = \frac{C_{\infty}}{C_{\infty,0}^*} = \frac{C_{\infty}}{C_{D,i}} \]  

and non-dimensional time becomes:

\[ \tau^* = \frac{t}{t_0^*} = \frac{t \frac{16 C_L U}{\pi^4 b AR}}{b \frac{16 C_L}{\pi^4 AR}} \]  

The presented equations are based on global properties of the wake and therefore apply to all stages of wake roll-up and decay, including the case that there are still multiple vortices in the wake. However, for their proper evaluation, detailed flow field data from CFD or experiments are needed.

In addition to these parameters the Reynolds number effect can be based on the circulation strength, using the following definition:

\[ \text{Re}_r = \frac{\Gamma}{v} \]  

2.3 Some additional parameters

In addition to these global wake characterisation parameters it can be useful to analyse the wake vortex dispersion radius \( \bar{r} \) (or \( \bar{r}/b \)) from:

\[ \bar{r}^2 = \frac{1}{\Gamma} \int \int \left[ (y - y_c)^2 + (z - z_c)^2 \right] \rho dA \]  

Here \( y_c \) and \( z_c \) denote the positions of the vorticity centroid. One can show (see [14]) that for a purely 2D wake evolution the dispersion radius can only increase by viscous diffusion.
It should be noted that evaluation of the dispersion radius is very sensitive to vorticity patches located far from the vortex centre (either true vorticity or experimental scatter). However, integration to a variable radius \( r \) around the vortex centre may yield valuable information on the vortex structure.

In Work Package 2 of FAR-Wake specific effects of wakes and cold and hot jets will be investigated experimentally as well as by CFD calculations. A large variety of test conditions is planned. Parametric CFD studies are only planned for the jet/vortex interaction. Some useful non-dimensional parameters for jet vortex interaction are defined in [18] and application is found in [19]. A suitable parameter to characterise the coupling between azimuthal and axial velocity components for the case of a single jet interacting with a vortex is:

\[
R = \frac{\rho_v U_j(U_j - U)A_j}{\rho_0 \Gamma_0^2} \quad \text{or:} \quad R = \frac{\int \int \rho_v U_j(U_j - U) dA}{\rho_0 \Gamma_0^2} \quad (2-34)
\]

With \( U_j > U \), this parameter is positive for jets. In [19] it is argued that for typical aircraft jets this parameter is order 0.1. The same parameter can however also be used to characterise the strength of wakes. In that case \( R \) becomes negative. For the case of a real aircraft geometry with simulated jets it may be more suitable to adapted non-dimensional equations (2-34) with \( \Gamma_0^* \) instead of \( \Gamma_0 \), leading to parameter \( R^* \).

For simulated vortices with axial flow profile it is possible to define an inverse swirl parameter as:

\[
R_\theta = \frac{(U_j - U)_{\max}}{V_{\theta,\max}} \quad (2-35)
\]

When modelling a vortex with axial flow, the shape of the axial flow profile is usually taken equal to the vorticity profile (a so-called Batchelor or “q”-vortex). If not, it needs to be specified.

For heated jets the key parameter for the stability of the system is the exit density ratio \( S_p = \rho_j/\rho_o \) between the jet flow and the ambient air. Indeed, as shown in [20], the jet becomes absolutely unstable for \( S_p < 0.72 \).
3 Planned experiments, numerical simulations and theoretical work.

Within FAR-Wake the work has been organised in three main work packages (WP1: Vortex instabilities and decay; WP2: Vortex interactions with jets and wakes; WP3: Wake evolution near the ground). Experimental, theoretical and CFD work is planned for each of these topics. WP and Task managers will have to assure proper balancing and coherence between the contributions of the experimental, theoretical and CFD work.

The Far-Wake project therefore starts with the preparation of status overview deliverables (D1.0, D2.0 and D3.0) of the three technical Work Packages. These documents [22-24] provide an overview of previous work done on the subjects and also give a summary of open items to be further investigated. These are important reference documents for the definition of the work in FAR-Wake. Reference [21] provides some additional background information on wake instability mechanisms.

Within Far-Wake different wake phenomena and parameter ranges will be investigated. These investigations are fundamental in nature, but not of pure academic interest. In view of the objectives of the project the parameter ranges investigated should (if possible) include those occurring on realistic civil aircraft applications.

In order to facilitate the planning, the coherence and the relevance of the work for practical applications to real aircraft wakes, as part of the synthesis task of FAR-Wake, a questionnaire is distributed amongst the partners early in the project. The purpose is:

- to give in Excel sheet INFO an overview of partner contributions in experimental (EXP), numerical (CFD) and theoretical (THE) work in the FAR-Wake project;
- to give detailed information on planned experimental work in the different sub-Tasks in EXP Excel sheet(s);
- to give detailed information on planned CFD work in the different sub-Tasks in CFD Excel sheet(s);
- to give detailed information on planned theoretical work in the different sub-Tasks in THE Excel sheet(s);
- to assist with optimum focusing of the research programme;
- to present an overview of the partner capabilities and plans;
- to enable an optimum co-operation between partners by exchanging information on calculation capabilities and experimental set-ups at an early stage;
- to allow definition of parameter ranges of practical interest.

The complete set of questionnaire inputs for Work Packages 1, 2 and Task 3.1 is given in Appendices A, B and C.
Table 1 gives an overview of partner participation in experimental, CFD and theoretical work in the different Subtasks. Table 2 gives the main points of contact.

Based on the given inputs from the partners, the following remarks are made for the different sub-tasks.

3.1 WP1: Vortex instabilities and decay

3.1.1 Waves on vortices

Subtask 1.1.1: Vortex meandering

The three partners involved in this subtask will employ different methods to analyse the viscous instabilities of vortices leading to vortex meandering. For the Batchelor vortex type, IRPHE and UPS-IMFT will employ asymptotic theory for the viscous centre modes in the limit of large Reynolds numbers and UMA will apply a spatial stability method for analysing the viscous instabilities in more detail. IRPHE also wants to look to the viscous instabilities of other profile shapes. Background turbulence is not a factor in these studies: the vortex meandering is entirely attributed to the internal instabilities in and around the vortex core.

It is strongly recommended that IRPHE and UMA have a close co-operation in order to enable a comparison of their results, e.g. by selecting the same Batchelor type profiles.

A completely distinct perspective to the meandering problem is also taken by UPS-IMFT, where non-linear transient amplification as a response to background turbulence is studied. An optimum perturbation and stochastic forcing analysis method will be used to study the problem.

The following points are suggested for consideration at an early stage:

- close co-operation between IRPHE, UPS-IMFT and UMA in selecting the same Batchelor type profiles in order to enable a comparison of the results;
- Explore the vortex meandering from typical low-Reynolds subscale test range (Re_r = 10^4 to 10^5) up to full scale flight Reynolds numbers (Re_r = 4x10^6);
- define suitable cases for UPS-IMFT (same profiles and Reynolds numbers) in order to allow a comparison with the other results;
- think about the possibility (based on the theoretical results) to distinguish between internally (instability) or externally (flow turbulence) of experimentally observed meandering characteristics;
- decide on experimental reference data to compare with the theoretical results.
The following points need consideration in the final synthesis of the results (D111):

- provide explanations for the vortex meandering phenomenon;
- assess relative importance for sub-scale and full scale conditions;
- assess effects of vortex meandering on mean wake properties in the far wake (is it possible to “design” wakes that are more susceptible to meandering type instabilities);
- recommend further experimental and/or theoretical work.

**Subtask 1.1.2: End effects and vortex bursting**

The work in this sub-task involves five partners performing experimental, theoretical and computational work on the subject of end-effects and vortex bursting. A brief summary of the work is given here (details are given in Appendix A).

- **IRPHE** will use asymptotic theory (in the limit of large axial wave numbers) to analyse the structure of short wavelength travelling inviscid modes along Lamb and Batchelor type of vortices. This is accompanied by experimental work in a water tank using an impulsively rotated flat plat wing model. Travelling modes are created by end-effects and/or deformation of the wing tip. Vortex field will be measured with a 2D PIV method and will also be visualised.

- **CERFACS** will study solitary wave propagation (end-effects) and collision of two propagating waves (vortex bursting) using 3D DNS method (NTMIX3D) for a Lamb-Oseen type vortex. Axisymmetric and helicoidal modes (Kelvin modes, m=0 and m=1) will be simulated.

A very similar study with 3D DNS method (FLUDILES) is planned by **ONERA**.

- **UCL** will employ a 3D LES method (VIC-FMM) where perturbations are introduced differently than in the other methods: i.e. by circulation variations due to wing acceleration and deceleration. Their results will be compared with existing experimental results on start and stop phenomena measured at UCL.

- **UPS-IMFT** will employ a technique based on the reconstruction of given initial conditions on the basis of temporal eigenmodes. For given initial conditions the pre-computed eigenmodes are combined to compute the temporal evolution. The method is restricted to the linear regime.

The following suggestions for close co-operation between the partners are made:

- **IRPHE** will focus on comparison of its theoretical results with water-tank experiments;
- The stability analysis work of **UPS-IMFT** needs to be closely correlated (e.g. choosing the same profiles) with the theoretical work planned at **IRPHE**;
- The numerical work planned by **ONERA** and **CERFACS** is quite similar and a common test case i suggested (e.g. one related to ONERA B20 conditions) in order to compare the results at an early stage and then define detailed complementary work;
- **UCL** generates the travelling waves in a different way than **ONERA** and **CERFACS** and it would be interesting to see what kind of Kelvin modes are developing in their simulation. If
possible, the growth rate of the different Kelvin modes should be determined and compared with stability theory and numerical results from ONERA and CERFACS. For the final synthesis it would be good:

- to have a clear view on the influence of start and stop modes on perturbation structure and growth;
- to give a recommendation on the best start and stop procedures for tests in water tank and catapult facility, such as to minimise the disturbing effect of travelling modes;
- to clarify the effect of Reynolds number on travelling modes;
- to investigate whether a vortex bursting mechanism can be employed on actual aircraft by some sort of active control.

3.1.2 Instabilities of vortex systems

Subtask 1.2.1: Short wavelength instabilities

As shown in Appendix A and in Table 1, a variety of theoretical, numerical and experimental work is planned by four partners.

IRPHE will perform stability analysis of short wavelength instabilities, only valid for sufficiently large Reynolds number. A range of axial velocity ratios will be considered: the inverse swirl parameter $R_s$ (equation (2-35)) will range from 0 to 0.5 and the influence of the other vortex is simulated with an external strain field. Numerical simulations for co- and counter-rotating vortices will also be made with a 3D temporal DNS code in order to validate the theoretical model and to determine the effect of axial flow on vortex merging. The maximum Reynolds number in the simulations is in the order of $Re_\Gamma=20000$. Finally the work is accompanied by experimental work in a wind tunnel (80% part-span flap configuration, $Re_\Gamma=100000$) and water tunnel (two straight wings with NACA0012 profiles facing each other, $Re_\Gamma=10000$). Hotwire and flow visualisation techniques are used in wind tunnel and 2C- (and possibly 3C-) PIV and visualisation techniques are used in the water tunnel.

CERFACS will apply its spatial DNS method NTMIIX3D to analyse short wavelength instabilities in co- and counter rotating vortex configurations. Exact simulation configurations are still to be specified.

UPM will focus on the BiGlobal eigenvalue problem (EVP) for a dipole vortex configuration including the effect of axial flow. A similar problem has been investigated in the past, but without axial flow. An accurate quasi-steady basic state of the flow (periodic in axial and inhomogeneous in other directions) is needed to perform the global eigenvalue analysis. The basic state will be computed with a 2D DNS method. Accurate eigenvalue spectrum is expected up to $Re_\Gamma=10000$.

TUE uses an experimental test setup with two constant chord (but twisted) profiles facing each other at relatively small distance, in order to create two counter-rotating vortices ($Re_\Gamma \approx 10000$)
with small core radii. Measurements with 2C-PIV and flow visualisation will be made up to about 60 vortex spacing downstream. The main purpose of these tests is to investigate the effect of various imposed flow turbulence (created with an actively controlled upstream grid) on wake development. The work will be accompanied by LES simulations for a single and for interacting vortices with various levels of free-stream turbulence.

The following suggestions are given to the planning of the work:

- The complementary experimental and CFD (LES and DNS) work of TUE is focussed on the effect of ambient (external) turbulence. This work does not necessary to be closely matched with that of the other partners. In the CFD simulations one of the key issues for investigation could be what kind of instability modes are most amplified, depending on the imposed turbulence structure, length scales and amplitudes and to compare the results with the experiments.
- The CFD work of CERFACS (spatial DNS) needs to be tailored to the numerical (temporal DNS) and experimental work of IRPHE in order to have maximum benefit of both activities.
- The basic state for the flows investigated by UPM should be chosen in close agreement with the work of IRPHE in order to allow some comparison of results.

For the synthesis of the results some of the CFD work should be aimed to extend the Reynolds range beyond that of the experiments by TUE and IRPHE and the ambient turbulence in the TUE tests should be quantified in terms of eddy dissipation rate and/or turbulent kinetic energy in order to allow a comparison with turbulence levels observed in real atmospheric flows. This would allow a comparison with available real atmospheric measurements and CFD results on wake vortex decay. A spectral analysis of the generated turbulence (including the length scales) is needed for proper initialisation of the CFD simulations and to support the analysis of the experimental data.

It should also be noted that the flow turbulence investigations have a possible link with Subtask 1.1.1: vortex meandering due to ambient flow turbulence.

**Subtask 1.2.2: Medium and long wavelength instabilities**

There are six partners contributing to this activity (details are given in Appendix A and in table 1). The experimental and CFD work on the effect of flow turbulence of TUE, described under Task 1.2.1, also applies for this Subtask. The main difference is here that flow excitation and analysis is more focussed on the larger length scales.

The experimental work of DLR (both DLR Braunschweig and DLR-Göttingen are involved here) concentrates on the effect of differential flap and horizontal tail settings on medium and long wavelength instabilities. DLR-Göttingen will test the generic type F13 model (wing span...
0.3m, see figure D.5) in the HSVA water tank using 3C-PIV and flow visualisation technique. The model configurations selected will be chosen such as to give most promising (fast growing instabilities) according to theory, while yet being of practical relevance. Additional experiments in the Göttingen water channel are planned by DLR-Braunschweig with the same model, but with oscillating flaps. Numerical simulations for the same model will be made by DLR with RANS and LES using the DLR-TAU code. ONERA\(^5\) will extend these simulations into the far-wake using a temporal LES simulation with the same code. The same model (and a four times larger model) will also be tested in the wind tunnel of TUM-FLM where emphasis is on flow turbulence measurements (using hot-wire probe and optionally also 3C-PIV and flow visualisation) in the wake of the F13 model.

UPE is offering temporal stability analysis for wake flow fields, test cases will be decided in close collaboration with ONERA.

UCL performs three CFD activities. In the first activity (UCL activity 2) a vortex filament method is used to investigate different 4-vortex systems with relevant \(b_2/b_1\) and \(\Gamma_2/\Gamma_1\) ratios in order to identify the most promising configurations for efficient wake decay. These are then further investigated using 3D temporal LES (UCL activity 3) and initial phases are also computed with spatial LES (UCL activity 4) in order to compare with the temporal results.

The following recommendations are given for this Subtask:

- **UCL** investigations (UCL activity 2) should include vortex spacing conditions achievable with DLR model F13 in order to define most promising test conditions for DLR and TUM-FLM.
- Definition of a common CFD testcase for DLR, ONERA and UCL, in agreement with F13 tests, is recommended.
- CFD simulations by ONERA and UCL can possibly be initiated with F13 experimental data.
- UCL (UCL activity 2) investigations could however also take into account other (more promising) 4-vortex systems.
- Temporal and spatial simulations for the F13 model should be analysed for flow turbulence aspects and this is to be compared with the FLM-TUM experimental results.
- The temporal stability analysis by UPM should be made for temporal ONERA and/or temporal UCL CFD conditions in order to allow a comparison of results.

In order that the results are of practical relevance at least part of the configurations should be practical realisable in terms of flap span and/or circulations strength ratios. Perhaps one could

\(^{5}\) In original DoW ONERA had planned spatial simulations. The now planned work deviates from original DoW and it is still being discussed whether this is appropriate.
limit the work of DLR and ONERA to practically realisable configurations (to be discussed) and UCL could make an extension to really most optimum configurations (which can not be realised easily in practice).

3.2 WP 2: Vortex interactions with jets and wakes
An overview of the partner participation is given in table 1 and in Appendix C.

3.2.1 Vortex interactions with jets

Subtask 2.1.1: Cold engine jets
In total 7 partners participate in this Subtask (see Appendix B and table 1 for the details). A good planning of the activities is therefore necessary.

NLR will investigate measured flow fields for an A340 half-model configuration as tested by Airbus-UK in the framework of C-Wake. The usage of the data is subject to a non-disclosure agreement with Airbus. Four different model configurations have been tested at two different lift coefficients and with Through Flow Nacelles (TFN) as well as three Turbo Power Simulator (TPS) settings. Near wake flow fields measured with 5-hole probe are available at x/b=0.3 and 1.3. A qualitative and quantitative assessment of the influence of power setting on near wake topology and development will be made. The quantitative assessment uses NLR’s standard wake analysis method WAKE and will focus on the wake topology and decay of cross-flow kinetic energy.

The remainder of the partners in this task deal with generic model configurations.

TUD will perform water tank tests with 3C-PIV, using the simple SWIM model geometry (as previously tested by NLR and ONERA in C-Wake project) with 2/3 span flap. A new underwater model will be constructed with a wingspan of 0.6m. Cold jets of 30mm diameter (5% wing span) will be added with Uj up to 1.7U (U< 5m/s). Jet positions, orientations and swirl can be altered. Since the model geometry is relatively simple it is an ideal test-case for CFD simulations (as e.g. demonstrated during the C-Wake project). Test set-up is shown in figures D.2-4.

ONERA is planning parametric temporal DNS simulations with the FLUDILES code for cold jet/single vortex interactions. Vortex core diameter, jet location, diameter and strength will be varied. Identical configurations will also be used for hot-jet simulations in Subtask 2.1.2.
**CERFACS** also performs parametric CFD simulations, but with LES using the NTMIX3D code. Simulations planned are similar as those planned by ONERA, but at higher Reynolds number and in addition also the effect of jet inclination will be simulated.

**UCL** is planning LES simulations with the 3D temporal VIC-FMM code. The initial vorticity field will be taken from near field measurements (provided by Airbus-D) and the initial turbulent jet will be provided by LES simulations from CERFACS.

**UBA** will perform extensive jet/vortex interaction studies in a series of experiments in an open jet (x/b<0.6), closed circuit wind tunnel (x/b<1.2) and in water tunnel (x/b<=2.5) using 2C-PIV and LDA technique. Test set-ups are shown in figures D.7-12. The experiments focus on the near wake. Both mean flow (2C-PIV) as well as flow turbulence (LDA) will be measured. In the last year of the project UBA will also investigate experimentally the effect of pulsed jets.

In summary, the parameter range of configurations that could be of practical interest (jet positions, orientation, strength and swirl) is very large. Clearly, with so much partners in this Subtask, there is a need to decide on specific tasks for the different partners to avoid unnecessary duplication of work. All experimental work (except that of TUD) concentrates on the near wake where influence of jet/vortex merging/interaction is strongest.

The CFD work by ONERA, CERFACS and UCL should be planned in close agreement with each other and with the experiments made by UBA and TUD.

The following points are left for the attention of the Subtask manager and partners:

- Planning of a coherent experimental and CFD research (e.g. validation of CFD).
- Sufficient and intelligent coverage of the parameter space, including the conditions (jet diameter and velocities) for realistic low and high-pass turbofans during take-off and landing.
- UBA will test pulsed jets in the 3rd year of the project, but no partner seems yet to have planned accompanying CFD simulations on pulsed jet/vortex interaction, which could be interesting to influence early wake break-up. Perhaps this can be simulated in temporal CFD simulations, e.g. by UCL?
- The potential of using co- or counter rotating jet-swirl could be systematically investigated in parametric studies.

A question of practical concern in the experiments is that the intrusion of a jet blowing device in the neighbourhood of the wing interacts with the wing flow and therefore influences the span-loading and/or near wake vortex topology. It is therefore not really possible to separate the effects of the wing and of the jet and this complicates parametric experimental studies.
Parametric CFD simulations with a prescribed jet superimposed on a given wake topology are however possible.

The research questions are: entrainment mechanism of jet turbulence in the vortex core, vortex stability in the presence of a jet, influence of jet intensity, swirl and pulsation. Questions for the synthesis of the results are:

- Is it feasible to initiate CFD simulations for the far-wake region from experimental data in the near wake?
- To what extend do (realistic) jets influence the far-wake characteristics?
- To what extend can jet-swirl or pulsation influence wake decay?

**Subtask 2.1.2: Hot engine jets/compressibility effects**

Three partners are planning experimental and/or CFD work on hot-jets, details are given in table 1 and appendix B.

A detailed experimental data set for flow properties in isolated vertical hot jets (various density ratios) is available at **CUT** (see figure D.1 for the test set-up). The data set includes axial mean flow and fluctuating velocity as well as spectra of axial flow velocity component. The jet velocity in the experiments is however rather low ($U_j < 20$ m/s), so Ma number effects are expected to be small. This data set can and has been used as reference to numerical simulations by **CUT** of isolated hot jets. **CUT** will also perform numerical simulations of hot jets in the presence of a vortex using LES code SAILOR. Temperature ratio will be between 1 and 2 and distance to vortex core and vortex strength will be varied in the simulations.

**ONERA**\(^6\) will perform hot jet/vortex interaction experiments in F2 wind tunnel using LDA and hot-wires, up to $x/b=3$.

CFD simulations at low (DNS by **ONERA**) and high (LES by **CERFACS**) Reynolds number are extensions of the work on cold jets in Subtask 2.1.1.

The following points need to be considered by the Subtask manager and involved partners:

- All planned work seems to concentrate on (nearly) uniform temperature jets. However, jets from modern high by-pass engines have a hot core jet surrounded by an (almost) cold jet. Perhaps some work could be focussed on realistic jets.

\(^6\) Note: this work replaces the work on stability analysis of hot jet in presence of a vortex as proposed in the original DoW.
• Experimental work by ONERA on effect of hot jets could benefit from the experimental data available from CUT (comparison of results).
• CFD studies of ONERA, CERFACS and CUT should be planned in close agreement with each other and with the planned experiments.
• Advantage should be taken from measured hot jet properties by CUT to initialise the calculations.
• Parameter ranges to be considered, should include realistic temperature (profile) conditions in jets of medium and high bypass engines at take-off and landing.
• Jet thrust should be realistic in relation to wing lift.
• When comparing with cold jet results, comparison should preferably be made at the same thrust (not the same jet velocity).

For the final synthesis of the results the hot-jet versus cold-jet vortex interference effects and in particular the impact in the far wake should be assessed. The presence of the jet will influence the axial velocity pattern in and around the vortex core after merging of the vortex and the jet. Therefore, the findings of Subtask 1.2.1 on the stability of vortices with axial flow should also be taken into account.

3.2.2 Vortex interactions with wakes

Subtask 2.2.1: Effect of fuselage on vortex wake
At high angle of attack, such as in landing or take-off condition, the wake of the fuselage will carry substantial streamwise vorticity confined in the turbulent wake close to the wake symmetry plane. The downstream evolution of this wake is important for several reasons:
• The streamwise vorticity patches at either side of the wake plane are close and may therefore initiate a substantial convection velocity to the fuselage wake, such that it may escape from the remaining vorticity field shed by the wing.
• Also, the presence of a turbulent wake flow may cause a rapid diffusion of the vorticity and/or vorticity exchange across the wake symmetry plane resulting in decay of total bound circulation.
• These effects may alter the mean properties of the far wake (e.g. altering the circulation strength) or influence the growth of long wavelength Crow instabilities.

Three partners are participating in this Subtask (see table 1 and appendix B). Existing experimental data (Eurowake, C-Wake and Awiator) will be analysed by Airbus and DLR and numerical simulations will be performed by DLR and CENAERO for the TAK geometry as tested by TUM. ACAD model of the TAK geometry needs to be created as part of the sub-Task (this required a modification of the original DoW).
DLR will perform RANS simulations for the TAK-model in high lift configuration to investigate the effect of the fuselage wake on the wake vortex system. With the RANS method only mean flow conditions can be computed, results are compared with available experimental data for the same geometry. Calculations are made for half model (+ peniche) at tunnel Reynolds number (half model experimental data available from FLM-TUM, see also figure D.6), and for full model at tunnel and flight Reynolds number.

CENAERO will perform additional CFD calculations for the same TAK-geometry also using RANS. Calculations will be made in successive steps: fuselage alone, fuselage + wings, fuselage + wings + tail planes. Results will be compared with experimental data for the same model (from FLM-TUM) and with calculation results of DLR.

The following points should be addressed for the synthesis:
- From the survey of existing wake data:
  - What happens with the streamwise vorticity and circulation shed by the fuselage when moving downstream in the (turbulent) fuselage wake?
  - Does the fuselage wake escape, or does it quickly decay downstream and what is the remaining effective wing root circulation?
- Comparison of RANS results from DLR and CENAERO.
- Comparison of RANS simulation results in the near symmetry plane region with available experimental data (e.g. for TAK model measurements by FLM-TUM).
- Assessment of numerical dissipation in the RANS simulations for the fuselage wake.

Remark: all CFD work on this subject is entirely focussed on the TAK model geometry. This is a bit risky. First of all there are only half-model measurement data available, which have obvious limitations in proper symmetry plane conditions, especially at further downstream positions in the wake, where the half-wake will strongly interact with the boundary layers at the tunnel wall. Also it is not clear what can be concluded from the CFD results if no parametric investigation is made.

Subtask 2.2.2: Wakes generated by wing elements
This Subtask considers the effect of wing-mounted drag increasing devices on wake formation, roll-up, instabilities and decay. Four partners are involved (see table 1 and Appendix B).

With a 0.8 part-span flap model with straight wing (also used in Subtask 1.2.1) IRPHE will perform measurements in a wind tunnel. Cylindrical devices (diameter up to 5% chord and length up to 40% chord) will be attached to the wing at various positions with respect to the flap.
tip and wing tip positions. Hotwire measurements will be made between $x/b=0.5$ and $3.5$ in order to assess the effects of the cylindrical devices on wake structure and stability.

**TUM-FLM** will perform wind tunnel experiments with the TAK half-model up to $x/b=5$ downstream, using hot-wire traverses and 3C-PIV (optionally). Reynolds stresses and turbulence spectral densities will be determined. Focus is particularly on the influence of the wake of a detailed landing gear.

**CENEARO** originally planned RANS and/or LES simulations with a generic wing geometry (straight wing) with simplified landing gear geometry (cylinder). The location and size of the simulated landing gear would be varied. However, this work has now been skipped, according to an amendment of contract.

**UCL** will perform 3D temporal LES simulations with the VIC-FMM method, focussing on wake roll-up as influenced by the finite thickness of the wing boundary layers. Initial flow conditions will be generated from an elliptically loaded wing, to which a boundary layer type momentum deficit will be added. *Note: the simulated effect of various boundary layer thicknesses basically relates to an idealised simulation of Reynolds effects. Perhaps it could be considered to (also) investigate the effect vorticity layer thickness on wake roll-up for 4-vortex wakes, where the thickness of the boundary and vorticity layer will probably have an effect on wake merging and vortex structure after merging.*

The following recommendations are given for the synthesis of the results:

- **Effect of cylindrical device (experiments by IRPHE):**
  - Effect on wake stability, depending on position and size of the device.
  - Wake characteristics for a simulated landing gear and qualitative comparison with the TUM-FLM experimental data for a realistic landing gear.

- **Effect of realistic landing gear (experiment by TUM-FLM):**
  - Influence on wake topology.
  - Influence on broadband turbulence level.
  - Influence on narrow-band frequency turbulence spectrum.
  - Qualitative assessment of possible influence on wake instabilities.

- **Effect of wing-mounted elements (through-flow nacelles, winglets: experiments by TUM-FLM):**
  - Same recommendations as for the realistic landing gear.

- **Influence of boundary layer thickness (numerical simulations by UCL).**
3.3 WP 3: Wake evolution near the ground
An overview of the partner participation is given in Table 1 and in Appendix C.

3.3.1 Task 3.1: Dynamics and decay in idealized conditions

Subtask 3.1.1: Longitudinal uniform wakes
The development of long-wavelength instabilities in two- and four-vortex systems created near the ground is investigated by IRPHE, UCL, CENAERO, IST and UPS-IMFT.

IRPHE will perform experiments on the dynamics and 3D instabilities of vortex pairs near the ground. A counter rotating vortex pair is created in a water tank by the impulsive rotation of two slender flat plates along their long axis. The Reynolds number $Re_\Gamma$ is between 1000 and 10000. The ratio between core size and separation distance is about 0.1 to 0.25 (at least two times larger than for usual aircraft vortices) and their initial height above ground is between 2 and 5 vortex separation distances. Vortices will be visualised (both light sheet and full volume visualisation) and measured with 2C-PIV.

UCL (UCL activity 7) considers wakes that are created close to the ground in NGE or IGE conditions where aircraft span-loading is influenced by the presence of the ground. Parametric simulations are being made varying the span-loading, the initial height and the Reynolds number. Span loading is obtained using a modified “lifting line” method, this is subsequently followed by 2D wake roll-up studies with a DNS/RANS code (VIC-FMM method). The outcomes of this parametric study will provide realistic initial vorticity fields for vortices created close to the ground and show the main influences on wake evolution for wakes created near the ground.

UCL (UCL activity 8) uses a non-viscous vortex filament method to simulate intrinsic 3D instabilities in two- and four vortex systems close to the ground. Instabilities will be triggered by small random deformation of filament node co-ordinates. Simulations will yield the most unstable wavelength and corresponding growth rate.

CENAERO will perform 3D LES simulations on the development of 3D instabilities in two- and four-vortex systems near ground. These simulations especially focus on the physical mechanisms due to head- and cross- wind conditions and ground roughness effects.

UPS-IMFT will also perform LES simulations on the development of long wavelength instabilities in two- and four- vortex systems near the ground, including the effects of head and/or crosswinds in atmospheric (near-ground) boundary layer.

IST will perform numerical simulations with 2D- DNS method. The uncertainty in the dynamics of two-vortex systems near the ground in crosswind conditions, with- and without buoyancy effects, using a polynomial chaos expansion method is considered.
Recommendations for the work share between partners:

- The experimental work of IRPHE might be complemented with CFD work by UCL and/or UPS-IMFT.
- The span-loading evaluations by UCL can be used for wake initialisation of studies planned in Subtask 3.1.2. Results from the UCL 2D wake evaluations in Subtask 3.1.1 can later be compared with the 3D spatial evaluations in Subtask 3.1.2.
- A systematic parametric study of crosswind effects should be planned and the complementarities between the LES simulations by UCL and UPS-IMT need to be guaranteed.
- The work by IST using polynomial chaos expansion methods should be properly interrelated with the other activities in this task.
- Proper planning of test case parameter ranges and relation with Subtask 3.1.2 needed.

The following recommendations are given for the synthesis of the results:

- Systematic approach to the problem should enable to assess the influence of Reynolds number, vortex core size, wake creation altitude, non-viscous instabilities and the effect of crosswind on asymmetric wake development and bouncing.

Subtask 3.1.2: Spatially evolving wakes

Experiments with a simple towed model in a water towing tank, creating a two-vortex system at constant altitude above ground and complementary CFD work with 3D LES is planned by UCL (UCL activity 8). The purpose is to characterise the most unstable wavelength and corresponding growth rates in the presence of the ground. In the experiments 2D visualisations will be made with laser induced fluorescence LIF and 3D visualisations with Black Light method.

**Airbus-D** will analyse existing data from experiments in towing tank (C-Wake and Awiator) for ground effects.

**DLR** will perform stereo PIV experiments in the water towing tank in Gottingen in order to investigate the spatial evolution of a two- and four- vortex system near or in ground effect (NGE and IGE). The considered test conditions will be selected according to existing experimental data (for same model) without ground effects.

Observations and recommendations for the synthesis of the work:

- In order to allow a proper assessment of the 3D effects, the experimental results should be compared with Subtask 3.1.1, which requires the selection of similar test conditions in both tasks.
A proper matching of UCL and DLR experiments is needed.

In real flight conditions the near ground flight trajectory is non-steady because of the acceleration and rotation phase (departure) or the deceleration and flare motion phase (landing). This seems not to be taken into account in planned experiments nor in CFD. Consequences of this omission are not clear.

Combined effect of spatially evolving wake in crosswind conditions is not considered.

The validity of the results can (and should) also be assessed against the field test data that are being analysed in Task 3.2.

3.3.2 Task 3.2: Dynamics and decay in real conditions

If the new EU proposal CREDOS (Crosswind-Reduced Separations for Departure Operations) is accepted, a strong impact of this Task on the activities in CREDOS is anticipated. Also it might perhaps be possible to share some new field test data between the two projects.

There are only two partners (DLR and NLR) involved in the analysis of existing data. NGE and IGE wake vortex data will be selected from existing databases such as Memphis, AVOSS, DFS wind-line data for Frankfurt, C-Wake and/or Awiator. The selected data will be analysed in detail in order to assess the effect of cross-wind, ambient turbulence, etc. on wake vortex motion and decay.

The following remarks and recommendations are given for the synthesis of this Subtask:

- Quality of the selected data should be assured.
- Statistical analysis of the results needs to be made.
- The results have to be used for the validation and improvement of the wake vortex prediction tools P2P and P-VFS in Task 3.3.
- Cross checking with the results from Task 3.1 is recommended.

3.3.3 Task 3.3: Assessment and real-time modelling

In this Task DLR and UCL make an assessment of the outcomes of Tasks 3.1 and 3.2. The implications for wake vortex modelling with P2P and P-VFS method are considered in order to improve the modelling.
4 Planning of partner contributions to the final synthesis and assessment

The purpose of the final synthesis and assessment Task 4.2 is two-fold:

- To synthesize and summarise the technical results of all Tasks.
- To evaluate the relevance and implications for real aircraft wake transport and decay.

Instead of a final assessment at the end of the project, intermediate synthesis reports will be issued by NLR in collaboration with the WP and Task managers, within 2 month’s after each Annual Review.

Though NLR takes the lead for the issue of the synthesis reports, inputs for Work Packages 1 to 3 are to be written by the Task managers, based on the outcomes of the technical work in their Tasks.

In order to facilitate the Synthesis task the following roles are defined for the different actors:

All partners:

- Take account of the preferred parameter definitions as defined in the present report (for a proper exchange of results between various Subtasks).
- Timely prepare the technical reports and contractual deliverables and send them for review to your Task and Workpackage manager.
- If possible, indicate if your results can have an exploitable effect for wake vortex transport and decay in the context of increased safety for following aircraft in a real operational environment. Can the studied phenomenon be applied.

Task and Subtask managers:

- Try to harmonise the work of the partners in your Subtask at an early stage in order to assure maximum output of your Subtask to the project.
- Critically review the technical reports and contractual deliverables of your partners. Apart from the technical content, also check whether consequences for real aircraft operation are sufficiently addressed in final conclusions.
- Forward the completed Technical reports and Deliverables to the Synthesis Task core team (Airbus and NLR).
- Clearly address the expected consequences for real aircraft wakes in the annual review reports.
- Provide specific information to the annually updated Synthesis report (see Task 4.2).

NLR and Airbus (main partners in Synthesis Task):

- Take the initiative to prepare the annual updated Synthesis report (NLR).
- Critically follow the main outcomes of the technical work as presented in the Technical reports and deliverables and inform Subtask manager on any possible improvements in the reporting and/or remaining work that could improve the exploitation of the results.
5 References


22. T. Leweke: Previous work and present knowledge on vortex instabilities and decay, FAR-Wake deliverable D1.0, July 2005.
24. L. Dufresne, G. Winckelmans: Previous work and present knowledge on wake vortices near the ground, FAR-Wake deliverable D3.0, July 2005.
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**Table 1**: Overview of partner participation in the different Subtasks

- **Bold** = missing (but only minor contribution from A-D expected)
- **nr** number of questionnaire sheets for this topic
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<tr>
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<td>Ramon Fernandez-Feria</td>
<td>+34 952130262</td>
<td><a href="mailto:ramen.fernandez@uma.es">ramen.fernandez@uma.es</a></td>
<td>UMA</td>
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<td>E.T.S. Ingenieros Industriales</td>
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<td>28033 Madrid, Spain</td>
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<tr>
<td>UPM</td>
<td>Vassilis THEOFILES</td>
<td>+34 915832301</td>
<td><a href="mailto:vassilis@theofiles.upm.es">vassilis@theofiles.upm.es</a></td>
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<td>Universidad Politecnica de Madrid</td>
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<td>Plaza Cardenal Cisneros, 2</td>
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<td></td>
<td>28046 Madrid, Spain</td>
</tr>
<tr>
<td>UPS-MNFT</td>
<td>Pierre Branchler</td>
<td>+33 56 126 333</td>
<td><a href="mailto:branchler@mnf.fr">branchler@mnf.fr</a></td>
<td>Université Paul Sabatier</td>
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<tr>
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<td></td>
<td></td>
<td>Institut de Mécanique des Fluides de Toulouse</td>
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<td></td>
<td>Avenue du Président Camille Soula</td>
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<td>Lisbon Portugal</td>
</tr>
</tbody>
</table>
Fig. 1 Definition of the viscous and the vorticity vortex core radii, for a rolled up wake where vorticity is concentrated in two counter rotating (approximately axi-symmetric) vortices.

Fig. 2 Definition of integration areas for analysing the distributed wake vorticity.
Appendix A  Overview of work, parameter ranges and planning for WP1:  
Vortex instabilities and decay

<table>
<thead>
<tr>
<th>Subtask number:</th>
<th>111</th>
<th>Partner:</th>
<th>IRPHE</th>
</tr>
</thead>
</table>

**Description of the activity:**

- Studies of vortex meandering as a viscous instability of the vortex:
- Temporal stability of axisymmetric vortices with axial flow: asymptotic analysis
- of the viscous centre modes in the limit of large Reynolds numbers
- frequency and spatial structure of the mode as a function of the vortex characteristics
- application to the Batchelor vortex and comparisons with the numerical computations done by ONERA (Fabre & Jacquin, 2004)
- extension to other vortex profiles in order to provide with predictions of stability characteristics in the case of realistic aircraft vortices

**Description of the theoretical method(s) used**

- Use asymptotic analysis in the limit of large Reynolds numbers.
- The results are obtained for any vortex with axial flow.
- We expect a general formula for the temporal growth rate and an expression for the unstable modes as functions of vortex profile characteristics, the Reynolds number, the axial wavenumber, the azimuthal wavenumber.

**Planning (specify month number m1-m36 with respect to kick-off):**

- first results available: 
- final results available: 
- all analysis finished/reported: $m_{18}$

| related DoW deliverable numbers | TR1.1.1-1 |

**References**

**FAR-Wake questionnaire for theoretical (THE) activities**

*Subtask number:* 111  
*Partner:* UMA

**Description of the activity:**

We will analyze the instabilities of some vortices modelling aircraft trailing vortices through a spatial stability analysis. The main task will be to characterize these instabilities (values of the frequency, the azimuthal wave number, the Reynolds number, and the swirl parameter at which they occur), with special emphasis in the viscous modes and in the onset of absolute instabilities for the large swirl numbers occurring in actual aircraft vortices. In particular, we will consider the spatial stability of Batchelor’s vortex, and look for viscous unstable modes for large q(>1.5) and large Reynolds number.

**Description of the theoretical method(s) used**

The nonlinear eigenvalue problem resulting from the spatial stability analysis will be solved using a staggered Chebyshev spectral collocation technique together with the linear companion matrix method. Although most of the results will be obtained using the near-parallel flow approximation, some cases of interest taking into account non-parallel effects will also be considered. Numerical accuracy will be very demanding as the Reynolds number and the swirl parameter increase, but we expect to reach the highest values of interest for aircraft trailing vortices.

**Planning (specify month number m1-m36 with respect to kick-off):**

- first results available: m6
- final results available: m18
- all analysis finished/reported: m21

**Related DoW deliverable numbers** D1.1.1

**References**


**FAR-Wake questionnaire for theoretical (THE) activities**

**Subtask number:** 111  
**Partner:** IMFT-UPS

**Description of the activity:**
This activity aims at reconsidering the recurrent phenomenon of vortex meandering in the light of two recent results:

1. Trailing vortices have been shown to sustain unexpected long-wave viscous instabilities for arbitrarily small axial flows that could be related to vortex meandering (1): the objective is then to derive general analytical predictions for these so-called centre modes (joint activity with IRPHE).
2. A study has recently revealed that a simple vortex model could exhibit non-trivial transient behaviours resulting in intense short-time amplification of specific components of the free-stream fluctuations, whose similarity with vortex meandering appears worthy of further investigation (2). Both approaches will focus on large-scale bending waves in the limit of large Reynolds numbers and small axial flows, first in the case of the Batchelor vortex and then with an extension to more realistic profiles.

The expected results should eventually help to discriminate between two explanations: vortex meandering as an intrinsic instability mechanism or an intrinsic response to ambient fluctuations.

**Description of the theoretical method(s) used**

- Viscous instability:
  - Use asymptotic analysis in the limit of large Reynolds numbers
  - Relate predicted instability results to the main characteristics of the base flow profile

- Transient growth:
  - Extension of the optimal perturbation formulation to vortices with axial flow
  - Implementation of a stochastic forcing approach for vortex flows (3)
  - Both methods are based on numerical resolution of the linearized Navier-Stokes equations via a Chebyshev spectral collocation technique.

**Planning** (specify month number m1-m36 with respect to kick-off):

- First results available: m12
- Final results available: m18
- All analysis finished/reported: m18

**Related DoW deliverable numbers:** D1.1.1

**References**


---

**FAR-Wake questionnaire for theoretical (THE) activities**

**Subtask number:** 112  
**Partner:** IRPHE

**Description of the activity:**
Characterisation of perturbation waves propagating on simple models of vortices:

- Linear and nonlinear stability analysis
- Dispersion relation
- Spatial structure

**Description of the theoretical method(s) used**

- Use asymptotic analysis in the limit of large axial wavenumber.
- Theoretical predictions are compared to numerics for Lamb and Batchelor vortices.
- Expected results are a simple expression for the dispersion relation and the structure of the waves. The results are inviscid and for short waves. They are expected to provide poor results for long waves.

**Planning** (specify month number m1-m36 with respect to kick-off):

- First results available: m3
- Final results available: m8
- All analysis finished/reported: m8

**Related DoW deliverable numbers:** TR1.1.2-1

**References**

Main references of previous work, using same theoretical method
### FAR-Wake questionnaire for EXPerimental activities

**Subtask number:** 112  
**Partner:** IRPHE

**Short description of the activity:**  
Characterisation of perturbation waves propagating on simple models of vortices: experiments in water tank

#### existing EXP data?

- (Y)

#### Source of existing data  
Confid. Restrictions: N

#### experimental parameter range (expected):  
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Type of facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>test medium</td>
<td>water</td>
<td>windtunnel</td>
</tr>
<tr>
<td>average kinematic viscosity</td>
<td>1.00E-06 [m²/s]</td>
<td>watertunnel</td>
</tr>
<tr>
<td>maximum test velocity</td>
<td>NA [m/s]</td>
<td>water tank</td>
</tr>
<tr>
<td>simulated wingspan</td>
<td>NA [m]</td>
<td>field trials (real aircraft)</td>
</tr>
<tr>
<td>simulated wingchord</td>
<td>NA [m]</td>
<td>T(z) profile (deg K) measured?</td>
</tr>
<tr>
<td>typical lift coefficient (CL)</td>
<td>NA [-]</td>
<td>flow turbulence level in facility</td>
</tr>
<tr>
<td>x/b range (downstream)</td>
<td>NA [-]</td>
<td>cross-section dims. of facility [fb] (50cm)^2</td>
</tr>
</tbody>
</table>

#### Topic specific information

The flow considered is a single Gaussian (Oseen-) vortex without axial flow. The characteristics are: Re $\Gamma \approx 1000-15000$; core radius: $\sim 10$ mm; vortex length: 1 m.

The perturbation waves are excited by a deformation of the edge of the wing or by end effects. Phase and group velocities of the perturbation are measured.

#### Measurements:

- pressure probe (traverses): N  
- hotwire: N
- PIV (2C): Y  
- LDA: N
- PIV (3C): N  
- LIDAR: N
- Flow visualisation: Y  
- Model forces: N

#### expected grid resolution (Dy,Dz): (1,1) [mm]

#### Planning (specify month number m1-m36 with respect to kick-off):

- model available: m1  
- first analysis reported: m8
- first tests completed: m3  
- all analysis finished/reported: m8
- final tests completed: m8  
- related DoW deliverable numbers TR1.1.2-1

#### Further details of model and test set-up

The flow is generated by a rectangular flat plate with sharpened edge, size 10 cm x 1.3 m, impulsively rotated in water along its long edge. The vorticity is measured by PIV at mid-height.

The group/phase velocity of the perturbations are measured by dye visualisations on side views.

The angular frequency of the perturbation is measured by comparing the position of the vortex centers in two cross-cut sections, separated by half a wavelength.

#### References

A similar set-up was used in the following studies

**FAR-Wake questionnaire for CFD activities**

**Subtask:** 112  
**Partner:** CERFACS

**Short description of the activity:**  
Simulations of waves propagation along vortices. Solitary wave propagation (End-Effects) and collision of two waves propagating in opposite direction (vortex Bursting) will be studied.

**Purpose of the CFD study**  
- parametric study  
- validation against EXP

**Description of CFD method and its limitations**

- **CFD-code name:** NTMIX3D  
- **CFD method(s):** DNS  
  - if other, specify: 3D
- **Boundary conditions:** Non-reflecting, Symmetric  
- **Discret. schemes:**  
  - 6th order Compact scheme for space discretization  
  - 3rd order Rung Kutta method for the time integration
- **Turbulence models:**
- **gridding strategy:** stretched
- **max number gridcells:** 120*120*321
- **gridcells in core:** 5<n<13
- **grid studies planned:** Y (limited)
  - if not
  - **initialisation method:** other
  - **if other, then specify:** Lamb-Oseen vortex model

**simulated parameter range**

- **max Reynolds ($\Gamma/\nu$):**
- **x/b range:**
- **Tau* range:** $t \sim 7 t_{\text{eddy}}$ ($t_{\text{eddy}} = 2 \pi rc/\nu \theta_{\text{max}}$)

**flow turbulence**

**Topic specific information**

The axisymmetric and helicoidal (mode of Kelvin waves, $m=0$ and $m=1$ respectively) perturbation will be simulated. The influence of perturbation amplitude will be also studied.

**Further details**

H. Moet et al., "Wave propagation in vortices and vortex bursting", Phys. Fluids 17, may 2005

**Planning (specify month number (m1-m36) with respect to kick-off):**

- first CFD results reported: $m8 / m18$
- all CFD results reported: $m33$
- related DoW deliverable numbers D1.1.2

**References**

H. Moet et al., "Wave propagation in vortices and vortex bursting", Phys. Fluids 17, may 2005
### FAR-Wake questionnaire for CFD activities

**Subtask:** 112  
**Partner:** UCL  
**Activity:** 1

**Short description of the activity:**

End effects and vortex bursting  
Numerical simulations (space developing) of perturbation waves, generated by an accelerated and/or decelerated wing, propagating on simple vortex models.

**Purpose of the CFD study**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parametric study</td>
<td>N</td>
<td>Y validation against EXP</td>
</tr>
<tr>
<td>CFD-code name:</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>CFD method(s):</td>
<td>LES</td>
<td></td>
</tr>
<tr>
<td>Calculation method:</td>
<td>3D spatial</td>
<td></td>
</tr>
<tr>
<td>Boundary conditions:</td>
<td>Unbounded domain</td>
<td></td>
</tr>
<tr>
<td>Discret. schemes:</td>
<td>Parallel Vortex In-Cell and fast multipole methods (VIC-FMM)</td>
<td></td>
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<tr>
<td>Turbulence models:</td>
<td>Modified Smagorinsky (WALE), hyper-viscosity</td>
<td></td>
</tr>
<tr>
<td>Gridding strategy:</td>
<td>Uniform VIC grid, particles redistribution on uniform grid</td>
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</tr>
<tr>
<td>Max number gridcells:</td>
<td>20 to 80 millions of VIC grid points</td>
<td></td>
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<tr>
<td>Gridcells in core:</td>
<td>6-8 / diameter (targeted but depends of roll-up process)</td>
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<tr>
<td>Grid studies planned:</td>
<td>Y</td>
<td></td>
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**Initialisation method**

<table>
<thead>
<tr>
<th>Method</th>
<th>Other</th>
<th>cf. details</th>
</tr>
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<tbody>
<tr>
<td>Initial core sizes</td>
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<td>cf. details</td>
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</table>

**Axial flow profile**

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<th>Value</th>
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<tr>
<td>NA</td>
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</table>

**Simulated parameter range**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>x/b range:</td>
<td>~50 Max.</td>
<td></td>
</tr>
<tr>
<td>Tau* range:</td>
<td></td>
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<tr>
<td>Flow turbulence:</td>
<td>No</td>
<td></td>
</tr>
</tbody>
</table>

**Topic specific information**

Analysis and assessment of wave propagation phenomena associated with circulation variations due to wing acceleration or deceleration in take-off and landing situations.

**Further details**

Wing modelled using unsteady lifting line method with a time-varying total circulation to mimic accelerations or decelerations. Simulations will be initiated from the wing model being at rest. According to the LES model used and the thickness of the initial vortex sheet, effective core size $r_c$ may vary (targeted values of $r_c/b$ to be in the range 0.05 to 0.1). Comparisons to be made with our experimental results obtained in the UCL towing tank in 2004.

**Planning (specify month number (m1-m36) with respect to kick-off):**

<table>
<thead>
<tr>
<th>Event</th>
<th>Value</th>
<th>Related DoW deliverable numbers</th>
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<tbody>
<tr>
<td>First CFD results</td>
<td>m24</td>
<td>D1.1.2</td>
</tr>
<tr>
<td>All CFD results reported</td>
<td>m33</td>
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</tbody>
</table>

**References**

- Desentans, O. & Gigantelli, S. 2004 Instabilities of wake vortices with fast deceleration: investigation in a towing tank, Graduation thesis for Mechanical Engineer degree, Université catholique de Louvain (UCL), Louvain-la-Neuve, Belgium
FAR-Wake questionnaire for CFD activities

Subtask: 112 partner: ONERA/DAFE/DMAE

Short description of the activity:
Analysis and assessment of wave propagation phenomena:
Simulations (DNS) of wake vortex submitted to several perturbations (pinch effect).

Purpose of the CFD study
parametric study Y validation against EXP N

Description of CFD method and its limitations

CFD-code name: FLUDILES
CFD method(s): DNS
if other, specify:
calc. method: 3D temporal
Boundary conditions: Non-reflecting, Periodic
Discret. schemes: 6th order compact scheme for space discretization
3rd order Runge-Kutta method for time integration

Turbulence models:

gridding strategy: uniform or stretched
max number gridcells: 201 x 201 x 151
gridcells in core n > 6
grid studies planned: Y
if not
initialisation method other (theoretical)
if other, then specify Lamb-Oseen vortex model

simulated parameter range
max Reynolds (Γ/ν):
x/b range:
Tau* range: 10
flow turbulence

Topic specific information
Sbt 1.1.2: parameters to be varied are perturbation amplitude and type (m=0, m=1, m=2)
These studies are relevant to the phenomena occurring at the B20 catapult of ONERA Lille: end effects and vortex bursting.

Further details
The launching effect of B20 is modelled by a pinched perturbation in the DNS initialization.
The CFD method will be validated in linear regime by comparison with theoretical studies.
Finally, the method will be applied to nonlinear perturbations.

Planning (specify month number (m1-m36) with respect to kick-off):
first CFD results reported: m18
all CFD results reported: m33 related DoW deliverable numbers D1.1.2

References
P. Coton, A. Dolfi-Bouteyre & E. Coustols, Report of ONERA B20 Catapult Tests (Equilibrium conditions, Laser tomoscopy and Lidar measurements), AWIATOR Deliverable 1.1.2-16,

E. Coustols, Summary of Subtask 1.1.2 Experimental Data Base, AWIATOR Deliverable 1.1.2-24

D. Fabre, Instabilité et instationnariatés dans les tourbillons: application aux sillage d'avions.
Thèse de doctorat, Université Paris VI, France, 2002 (PhD report)
### Subtask number: 112  
**Partner:** IMFT-UPS  

**Description of the activity:**  
The main objective of this activity is to investigate the spatio-temporal properties of various models of vortices via the characterisation of the propagation of perturbation waves on a vortex (joint activity with IRPHE).  
This analysis is carried out by performing a reconstruction of the linear response of the vortex to localised initial perturbations.

**Description of the theoretical method(s) used**  
The technique is based on the reconstruction of a given initial condition on the basis of the temporal eigenmodes. These eigenmodes are precomputed numerically for different kinds of vorticity profiles (Batchelor vortex, then more realistic vortices) with a Chebyshev pseudo-spectral method.  
Once the initial condition is defined, its temporal evolution is then directly obtained at a very low computational cost by combining the predicted development of the eigenmodes involved.  
This method is a priori restricted to the linear regime.

**Planning (specify month number m1-m36 with respect to kick-off):**  
first results available: m9  
final results available: m9  
all analysis finished/reported: m9  
related DoW deliverable numbers D1.1.2

**References**  

---

### Subtask number: 121  
**Partner:** IRPHE  

**Description of the activity:**  
Determination of short-wavelength instability characteristics of two-vortex systems; analysis of the effects of axial flow

**Description of the theoretical method(s) used**  
Assume a vortex in an external strain field.  
Instability characteristics are computed by considering resonant Kelvin modes of the underlying vortex.  
Coupling coefficients are computed numerically using the method described in Moore & Saffman, 1975, and Eloy & Le Dizès, 2001.  
Limited to weakly deformed vortices and large Reynolds numbers. Rankine and Batchelor vortices are both considered.  
Axial parameter (ratio max velocity by maximum azimuthal velocity) is varied from 0 to 0.5.

**Planning (specify month number m1-m36 with respect to kick-off):**  
first results available: m4  
final results available: m4  
all analysis finished/reported: m4  
related DoW deliverable numbers TR1.2.1-2

**References**  
main references of previous work, using same theoretical method  
Moore & Saffman, *The instability of a straight vortex filament in a strain field,*  
Eloy, C. and Le Dizès, S., *Stability of the Rankine vortex in a multipolar strain field,*  
**FAR-Wake questionnaire for CFD activities**

**Subtask:** 121  
**Partner:** IRPHE  

**Short description of the activity:**  
*Numerical simulations on co-rotating and counter-rotating vortex configurations: temporal DNS*  
*Two objectives: validate the theoretical model (activity 4) of the short-wavelength instability with axial flow, determine the effect of axial flow on merging.*  

**Purpose of the CFD study**  
parametric study  
validation against THEORY  
Y

**Description of CFD method and its limitations**  

<table>
<thead>
<tr>
<th>CFD-code name:</th>
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</thead>
<tbody>
<tr>
<td>DNS + linear DNS</td>
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<table>
<thead>
<tr>
<th>calc. method:</th>
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<tbody>
<tr>
<td>3D Temporal</td>
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<table>
<thead>
<tr>
<th>Boundary conditions:</th>
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<tbody>
<tr>
<td>Periodic downstream/upstream</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Discret. schemes:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral elements (Australian code)</td>
</tr>
<tr>
<td>Periodic spectral (IRPHE code)</td>
</tr>
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<table>
<thead>
<tr>
<th>Turbulence models:</th>
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</thead>
<tbody>
<tr>
<td>N</td>
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</table>

<table>
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<tr>
<th>gridding strategy:</th>
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</thead>
<tbody>
<tr>
<td>Cartesian (IRPHE Code)</td>
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<table>
<thead>
<tr>
<th>max number gridcells:</th>
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<tbody>
<tr>
<td>512<em>512</em>kz (kz=from 1 to ?) (IRPHE code)</td>
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</table>

<table>
<thead>
<tr>
<th>gridcells in core</th>
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<tbody>
<tr>
<td>At least 400 (IRPHE code)</td>
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<th>grid studies planned:</th>
</tr>
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<tbody>
<tr>
<td>Y</td>
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</table>

<table>
<thead>
<tr>
<th>if not initialisation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP/other 2D temporal DNS, then 3D with white noise perturbation</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>initial core sizes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-0.2 times the vortex separation distance</td>
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<table>
<thead>
<tr>
<th>axial flow profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>same as axial vorticity profile</td>
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<table>
<thead>
<tr>
<th>inverse Swirl number</th>
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<tbody>
<tr>
<td>0-0.5</td>
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**Simulated parameter range**  

<table>
<thead>
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<th>max Reynolds (Γ/ν):</th>
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</thead>
<tbody>
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<td>20000</td>
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</table>

<table>
<thead>
<tr>
<th>x/b range:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tau* range:</td>
</tr>
<tr>
<td>flow turbulence</td>
</tr>
</tbody>
</table>

**Topic specific information**  
The flows considered are laminar vortex pairs.  
Initially, counter-rotating vortices will be simulated, since theory is available for this case.  

**Further details**  
tbc  

**Planning (specify month number (m1-m36) with respect to kick-off):**  
first CFD results reported: m4  
all CFD results reported: m6  
related DoW deliverable numbers TR1.2.1-3  

**References**
**FAR-Wake questionnaire for EXPerimental activities**

**Subtask number:** 121  
**Partner:** IRPHE

**Short description of the activity:**  
Experiments on co-rotating and counter-rotating vortex configurations: wind tunnel and water channel

**Existing EXP data?** (Y)  
**Source of existing data** Airbus contract  
**Confid. Restrictions** Y

**Experimental parameter range (expected):**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average kinematic viscosity</td>
<td>1.50E-05 [m2/s]</td>
<td>windtunnel</td>
</tr>
<tr>
<td>Maximum test velocity</td>
<td>60 [m/s]</td>
<td>water towing tank</td>
</tr>
<tr>
<td>Simulated wingspan</td>
<td>~0.8 [m]</td>
<td>field trials (real aircraft)</td>
</tr>
<tr>
<td>Simulated wingchord</td>
<td>0.2 [m]</td>
<td>T(z) profile (deg K) measured?</td>
</tr>
<tr>
<td>Typical lift coefficient</td>
<td>[-]</td>
<td>flow turbulence level in facility</td>
</tr>
<tr>
<td>x/b range (downstream)</td>
<td>4 [-]</td>
<td>cross-section dims. of facility [b]</td>
</tr>
</tbody>
</table>

**Topic specific information**

The flow considered is a pair of co- or counter-rotating vortices with axial flow, generated by a flapped wing. The characteristics are:

- \( Re \Gamma \approx 100000 \)
- Axial velocity defect: \( \sim 20-40\% \)
- Core radius / separation distance: \( \sim 10\ mm / 75\ mm \) \( \sim 0.1-0.15 \)
- "realistic" two-scale velocity profiles

**Measurements:**

- Pressure probe (traverses): N  
- PIV (2C): N  
- PIV (3C): N  
- Flow visualisation: Y  
- Expected grid resolution (Dy,Dz): (1-2,1-2) [mm]

**Planning (specify month number m1-m36 with respect to kick-off):**

- Model available: m4  
- First tests completed: m5  
- Final tests completed: m8  
- First analysis reported: m9  
- All analysis finished/reported: m21

**Further details of model and test set-up**

The flow is generated by a symmetric rectangular NACA0018 wing profile (half-model) of chord 20 cm and (half-)span 40 cm (=b/2), equipped with a symmetric flap over 32 cm. 3-component hot-wire measurements of the velocity profiles can be made between \( x/b = 0.5 \) and \( x/b = 3.5 \) (between 5 and 35 vortex spacings) downstream of the trailing edge. Details on a previous version of the set-up can be found in the following report (in French):

- C. Roy: "Caractérisation des vortex co-rotatifs générés par une maquette d’aile d’avion", Project report, DEA (Master) de Mécanique, Université Pierre et Marie Curie, Paris VI (2004)

**References**

Related previous work:

**FAR-Wake questionnaire for EXPerimental activities**

**Subtask number:** 121  
**Partner:** IRPHE

**Short description of the activity:**  
Experiments on co-rotating and counter-rotating vortex configurations: wind tunnel and water channel

**existing EXP data?** (Y)  
**Source of existing data** Airbus contract  
**Confid. Restrictions** Y

<table>
<thead>
<tr>
<th>experimental parameter range (expected)</th>
<th>type of facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>test medium: water</td>
<td>windtunnel</td>
</tr>
<tr>
<td>average kinematic viscosity: 1.00E-06 [m2/s]</td>
<td>watertunnel</td>
</tr>
<tr>
<td>maximum test velocity: 0.5 [m/s]</td>
<td>water towing tank</td>
</tr>
<tr>
<td>simulated wingspan: ~0.4 [m]</td>
<td>field trials (real aircraft)</td>
</tr>
<tr>
<td>simulated wingchord: 0.1 [m]</td>
<td>T(z) profile (deg K) measured? N</td>
</tr>
<tr>
<td>typical lift coefficient (CL): [-]</td>
<td>flow turbulence level in facility &lt;1%</td>
</tr>
<tr>
<td>x/b range (downstream): 4 [-]</td>
<td>cross-section dims. of facility [fb] ~2</td>
</tr>
</tbody>
</table>

**Topic specific information**

*The flow is similar to the one described on the left, except for the Reynolds number. Re Γ ~ 10000*

**Measurements:**

- pressure probe (traverses): N  
- hotwire: N  
- PIV (2C): Y  
- LDA: N  
- PIV (3C): (Y)  
- LIDAR: N  
- Flow visualisation: Y  
- Model forces: N  
- expected grid resolution (Dy,Dz): (1,1) [mm]

**Planning (specify month number m1-m36 with respect to kick-off):**

- model available: m4  
- first tests completed: m5  
- first analysis reported: m9  
- all analysis finished/reported: m21  
- final tests completed: m8  
- related DoW deliverable numbers TR1.2.1-4

**Further details of model and test set-up**

*The flow is generated by two NACA0012 symmetric rectangular wing profiles facing each other, of chord 10 cm and span 20 cm. Visualisation and PIV measurements can be made up to 35 vortex spacings downstream.*

**References**

**FAR-Wake questionnaire for CFD activities**

**Subtask:** 121  
**Partner:** CERFACS

**Short description of the activity:**
Analyze of short-wavelength (elliptic) instabilities in co- and counter-rotating vortex configurations by spatial DNS simulations.

**Purpose of the CFD study**
- Parametric study: N  
- Validation against EXP: Y

**Description of CFD method and its limitations**
- **CFD-code name:** NTMIX3D  
- **CFD method(s):** DNS  
- **Calculation method:** 3D  
- **Boundary conditions:** Symmetric, Non-reflecting  
- **Discretization schemes:** 6th order Compact scheme for space discretization, 3rd order Rung Kutta method for the time integration

**Turbulence models:**
- **Gridding strategy:** stretched  
- **Max number gridcells:** to be determined  
- **Gridcells in core:** n>11  
- **Grid studies planned:** N  
- **If not:**  
- **Initiation method:** to be determined  
- **If other, then specify:**  

**Simulated parameter range**
- **Max Reynolds (\(\Gamma/\nu\)):** to be determined  
- **x/b range:** to be determined  
- **\(\tau^*\) range:** to be determined  

**Flow turbulence**

**Topic specific information**

**Further details**

**Planning (specify month number (m1-m36) with respect to kick-off):**
- First CFD results reported: m27  
- All CFD results reported: m30  
- Related DoW deliverable numbers: D1.2.1

**References**
**FAR-Wake** questionnaire for theoretical (THE) activities  
**Subtask number:** 121  
**Partner:** UPM  
**Description of the activity:**  
It is planned to analyze the instability of one model-component of a trailing-vortex system at the interface between near- and far-field, prior to the formation of the four- (or two-) vortex systems. It is planned to focus on a dipole configuration addressed in the past, extending it to include an axial flow component.  
**Description of the theoretical method(s) used**  
The incompressible BiGlobal eigenvalue problem (EVP) will be solved (Jacquin, et al. 2003; Hein & Theofilis 2004). Key assumption is that the basic state is quasi-steady, inhomogeneous in two- and periodic in the third spatial direction. Central to a successful analysis is the provision of an accurate basic state. This will be obtained by two-dimensional DNS (Theofilis 2004). Accurate eigenspectrum results may be expected at Reynolds numbers up to $O(10^4)$.  
**Planning (specify month number m1-m36 with respect to kick-off):**  
First results available: $m6$ (DNS), $m24$ (EVP), $m36$ (analysis)  
final results available: $m36$  
all analysis finished/reported: $m36$  
related DoW deliverable numbers TR121-1  
**References**  
Theofilis, V. 2004 Direct numerical simulations of the roll-up process of a trailing-vortex system, using experimentally using experimentally obtained data at realistic Reynolds numbers, AWIATOR Report TR 1.1.1-6, DLR IB 224-2002-C-12
FAR-Wake questionnaire for experimental activities

Subtask number: 1.2.1 & 1.2.2  partner: TUE

Short description of the activity:
Simulations of a simple system of two counter rotating vortices in a windtunnel with variable external turbulence

existing EXP data?  N
Source of existing data  N.A.
Confid. Restrictions  N

experimental parameter range (expected):

test medium:  air
average kinematic viscosity:  15x10**-6 [m2/s]  watertunnel  N
maximum test velocity:  15 [m/s]  water towing tank  N
simulated wingspan:  0.1 [m]  field trials (real aircraft)  N
simulated wingchord:  0.075 [m]  T(z) profile (deg K) measured?  n.a.
typical lift coefficient (CL):  1 [-]  flow turbulence level in facility  variable
tax range (downstream):  60 [-]  cross-section dims. of facility [ft]  hence relative to span of .1 m

Topic specific information
- two twisted 'half models' with a rectangular planform will be mounted on opposite tunnelwalls (.1 m distance between the wing tips).
- turbulence will be generated using an active grid system

Measurements:
pressure probe (traverses):  N  hotwire:  Y
PIV (2C):  Y  LDA:  N
PIV (3C):  N  LIDAR:  N
Flow visualisation:  Y  Model forces:  N
expected grid resolution (Dy,Dz):  (2.5 ,2.5 ) [mm]

Planning (specify month number m1-m36 with respect to kick-off):
model available:  aug-05  first analysis reported:  Feb 2006
first tests completed:  Feb 2006  all analysis finished/reported:  Feb 2007
final tests completed:  Feb 2007  related DoW deliverable numbers

Further details of model and test set-up  TR 1.2.1-5 & TR 1.2.2-3
NB the hotwire probe will only be used to characterise the generated turbulence

References
The effect of external turbulence on the decay of (simulated) aircraft trailing vortices - a project description
FAR-Wake questionnaire for CFD activities

Subtask: 1.2.1 & 1.2.2 partner: TUE

Short description of the activity:
Large-eddy simulation of the evolution of a single vortex and of two or more interacting vortices will be conducted in a three-dimensional turbulent flow. This study is aimed at understanding the decay of vortices and the dependence of this decay on the level of external turbulence as will also be studied experimentally in the TU/e windtunnel (expected \( \tau^* \) max of about 3). Different subgrid models will be included in order to establish the robustness of the predictions. Moreover, the development in different time-regimes will be quantified for symmetric as well as asymmetric vortex pairs.

Purpose of the CFD study

parametric study
- to support the experimental investigation in providing additional and more detailed flow information for similar conditions (as close as possible) as obtained in the experiment.

validation against EXP
- EXP and CFD initial and boundary conditions will be as closely matched as possible to allow also a direct comparison.

Description of CFD method and its limitations

CFD-code name: woodflow

CFD method(s): DNS and LES
if other, specify: on explicit time-stepping and higher order finite volume discretization

calc. method: on explicit time-stepping and higher order finite volume discretization

Boundary conditions: Periodic boundary conditions

Discret. schemes: higher order finite volume discretization

Turbulence models: various sub-grid models

gridding strategy: not relevant

max number gridcells: order 500*3 to 1000*3

gridcells in core: order 100 across

grid studies planned: Y

if not initialisation method: analytical approximation of experimental results

if other, then specify initial core sizes: follows from experiment

axial flow profile: will be represented analytically (Batchelors similarity solution)

inverse Swirl number: follows from experiment

simulated parameter range

max Reynolds (\( \Gamma/\nu \)): 40000

x/b range: 60

\( \tau^* \) range: 2.5

flow turbulence: hopefully non-dimensional eddy dissipation rate up till 1

Topic specific information

Further details

still to be determined how the external turbulence will be imposed

Planning (specify month number (m1-m36) with respect to kick-off):

first CFD results reported: Feb 2006

all CFD results reported: Feb 2007 related DoW deliverable numbers

References

FAR-Wake questionnaire for theoretical (THE) activities

Sub-task number: 1.2.1 & 1.2.2  partner: TUE

Description of the activity:
Various analytical methods will be used to support the analysis of the experiment and the initialisation of the CFD calculations.

Description of the theoretical method(s) used
From lit available:
- Parametric fits for cross wise velocity profiles
- Similarity solutions for the axial and cross flow velocities

Planning (specify month number m1-m36 with respect to kick-off):
first results available: Feb 2006
final results available: Feb 2007
all analysis finished/reported: Feb 2007 related DoW deliverable numbers TR 1.2.1-5 & TR 1.2.2-3

References
well known literature
**FAR-Wake questionnaire for EXPerimental activities**

**Subtask number:** 122  
**partner:** DLR

**Short description of the activity:**
In the "Wasserschleppkanal Goettingen" some experiments with the oscillating flap setting concept should be realized to find out if the stimulation of the inherent Crow-instabilities with oscillating flaps leads to an early decay of the wake vortex in the farfield.

The maximum test velocity in the water is 2 m/s, the oscillation frequency of the flaps should be in the range of 0.5 Hz.

The 3-flap-F13-model is an advancement of the F13-model without flaps which was developed by Heinrich Vollmers at DLR Goettingen.

Later on the water towing tank experiments are to be completed with an in-flight test on DLR-ATTAS. Here the DLC-flaps as well as the ailerons should be moved with the 0.5 Hz frequency to initiate the Crow-instability. This in-flight test will be carried out in spring of 2006. As soon as further information about this experiment is available I will give a short report about it.

Experiments in a water towing tank

**Source of existing data**

<table>
<thead>
<tr>
<th>experimental parameter range (expected)</th>
<th>test medium</th>
<th>average kinematic viscosity</th>
<th>maximum test velocity</th>
<th>simulated wingspan</th>
<th>simulated wingchord</th>
<th>typical lift coefficient (CL)</th>
<th>x/b range (downstream)</th>
<th>type of facility</th>
<th>Confid. Restrictions</th>
<th>Y/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>test medium: water</td>
<td></td>
<td>m2/s</td>
<td>m/s</td>
<td>m</td>
<td>m</td>
<td></td>
<td>[m]</td>
<td>watertunnel</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>simulated wingspan: 0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>field trials (real aircraft)</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>simulated wingchord: 0.05</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>T(z) profile (deg K) measured?</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>typical lift coefficient (CL): [-]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>flow turbulence level in facility</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>x/b range (downstream): [-]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cross-section dims. of facility [b]</td>
<td>N</td>
<td></td>
</tr>
</tbody>
</table>

**Topic specific information**

**Measurements:**
- pressure probe (traverses): N
- PIV (2C): N
- PIV (3C): Y
- Flow visualisation: Y
- expected grid resolution (Dy,Dz): ( , ) [mm]

**Planning (specify month number m1-m36 with respect to kick-off):**
- model available: m8
- first tests completed: m11
- final tests completed: currently unknown

**Further details of model and test set-up**

As soon as available I will send some pictures and sketches of the model with a short description.

**References**

main references of previous work, using same test set-up or techniques
**FAR-Wake questionnaire for ExPerimental activities**

<table>
<thead>
<tr>
<th>Subtask number:</th>
<th>122</th>
<th>partner:</th>
<th>DLR-G</th>
</tr>
</thead>
</table>

**Short description of the activity:**
Validation experiment with 4-vortex wake in HSVA existing EXP data? N

**Source of existing data**

<table>
<thead>
<tr>
<th>experimental parameter range (expected)</th>
<th>type of facility</th>
<th>Confid. Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>test medium: water</td>
<td>windtunnel</td>
<td>N</td>
</tr>
<tr>
<td>average kinematic viscosity: 1.2e-6 [m2/s]</td>
<td>watertunnel</td>
<td>N</td>
</tr>
<tr>
<td>maximum test velocity: 3.6 [m/s]</td>
<td>water towing tank</td>
<td>Y</td>
</tr>
<tr>
<td>simulated wingspan: 0.3 [m]</td>
<td>field trials (real aircraft)</td>
<td>N</td>
</tr>
<tr>
<td>simulated wingchord: 0.05 [m]</td>
<td>T(z) profile (deg K) measured?</td>
<td>Y</td>
</tr>
<tr>
<td>typical lift coefficient (CL): 1.1 [-]</td>
<td>flow turbulence level in facility</td>
<td></td>
</tr>
<tr>
<td>x/b range (downstream): 0 - ca.200 [-]</td>
<td>cross-section dim of facility [b]</td>
<td>h=10,w=16</td>
</tr>
</tbody>
</table>

**Topic specific information**

The aim of these measurements is to provide velocity data in planes perpendicular to the flight path of the model. The utilized model (F13) is able to generate a 2 or 4 vortex system. A broad range of vortex spacing b1/b2 and strength Gamma1/Gamma2 are achieved by exchangeable horizontal tip wings. For the investigations of the instabilities of a 4-vortex system the ranges b1/b2 = 0.3 to 0.4 and Gamma1/Gamma2 = -0.3 to -0.6 are recommended. The towing tank dimensions in relation to the model size ensure that flow is unaffected by end- and wall-effects.

**Measurements:**

<table>
<thead>
<tr>
<th>pressure probe (traverses):</th>
<th>N</th>
<th>hotwire:</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIV (2C):</td>
<td>N</td>
<td>LDA:</td>
<td>N</td>
</tr>
<tr>
<td>PIV (3C):</td>
<td>Y</td>
<td>LIDAR:</td>
<td>N</td>
</tr>
<tr>
<td>Flow visualisation:</td>
<td>Y</td>
<td>Model forces:</td>
<td>Y</td>
</tr>
<tr>
<td>expected grid resolution (Dy,Dz):</td>
<td>(3-6, 3-5) [mm]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Planning (specify month number m1-m36 with respect to kick-off):**

<table>
<thead>
<tr>
<th>model available:</th>
<th>m19</th>
<th>first analysis reported:</th>
</tr>
</thead>
<tbody>
<tr>
<td>first tests completed:</td>
<td>all analysis finished/reported:</td>
<td>m21</td>
</tr>
<tr>
<td>final tests completed:</td>
<td>m19</td>
<td>related DoW deliverable numbers</td>
</tr>
</tbody>
</table>

**Further details of model and test set-up**

Instantaneous velocity data is obtained by means of Stereo-PIV, which allows to determine axial velocity profiles and, particularly in the case of large towing tanks, the correct vorticity component perpendicular to the measurement plane. The spatial resolution in the axial direction is given by the current model speed and the maximum possible recording frequency of 5 Hz.

**References**

### FAR-Wake questionnaire for CFD activities

**Subtask:** 122  
**Partner:** DLR

**Short description of the activity:**  
Numerical calculations on 3-flap-F13-model

<table>
<thead>
<tr>
<th>Purpose of the CFD study</th>
<th>parametric study</th>
<th>validation against EXP</th>
<th>Y</th>
</tr>
</thead>
</table>

**Description of CFD method and its limitations**

**CFD-code name:** DLR TAU-Code, LES solver  
**CFD method(s):** RANS, LES  
**calc. method:** 2D, 3D

**Boundary conditions:** inflow, outflow, farfield, symmetry

**Discret. schemes:** currently unknown

**Turbulence models:** k-omega-model

**gridding strategy:** non-structured, stretched

**max number gridcells:** 20M

**gridcells in core:** currently unknown

**grid studies planned:** planned

**initialisation method:** other

**LO and BH initial core sizes:** currently unknown

**axial flow profile:** currently unknown

**inverse Swirl number:** currently unknown

**simulated parameter range**

max Reynolds \((Re)\): 100000  
\(x/b\) range: currently unknown  
\(Tau^*\) range: currently unknown  
flow turbulence: currently unknown

**Topic specific information**

**Further details**

**Planning (specify month number (m1-m36) with respect to kick-off):**

first CFD results reported: currently unknown  
all CFD results reported: m30  
related DoW deliverable numbers D1.0

**References**

main references of previous related CFD work by your institute

FAR-Wake questionnaire for theoretical (THE) activities
Subtask number: 122 partner: ONERA/DAFE

Description of the activity:
Stability analyses of dipolar vortices with axial flow:
Longwave instabilities, Mediumwave instabilities in the presence of axial flow

Description of the theoretical method(s) used
1/ 2D DNS to obtain basic flowfields characterized by the Reynolds number,
the aspect ratio a/b and the Swirl number
2/ 3D stability analysis thanks to a normal mode analysis

This work replaces the work on statial instabilities of 4 vortex systems

Planning (specify month number m1-m36 with respect to kick-off):
first results available: m21
final results available: m33
all analysis finished/reported: m33

References

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FAR-Wake questionnaire for CFD activities
Subtask: 122 partner: DLR-ONERA/DAFE

Short description of the activity:
Temporal CFD studies of 4-vortex systems (in co-operation with DLR)

Purpose of the CFD study
parametric study Y validation against EXP N

Description of CFD method and its limitations
CFD-code name: TAU
CFD method(s): LES
if other, specify:
calc. method: 3D temporal
Boundary conditions:
Discret. schemes:
Turbulence models:
gridding strategy:
max number gridcells:
gridcells in core
grid studies planned: N
if not
initialisation method
if other, then specify
simulated parameter range
max Reynolds (Γ/ν): 
x/b range: 
Tau* range:
flow turbulence

Topic specific information
See DLR 1.2.2-1 task

Further details
Planning (specify month number (m1-m36) with respect to kick-off):
first CFD results reported: m21
all CFD results reported: m33
related DoW deliverable numbers D1.2.2

References
**FAR-Wake questionnaire for theoretical (THE) activities**

**Subtask number:** 122  
**Partner:** UPM

**Description of the activity:**  
Identification of secondary BiGlobal linear instability mechanisms in a (anti-) symmetric two-vortex system analysed in other Far-Wake tasks

**Description of the theoretical method(s) used**  
The incompressible secondary BiGlobal eigenvalue problem (EVP) will be solved using Floquet methods (Abdessemed et al. 2005). 
Key assumption is that the basic state is a time-periodic flow, inhomogeneous in two- and periodic in the third spatial direction. Such flow results from amplification of the primary instability identified in subtask 1.3.1. 
There exists an ambiguity in defining the amplitude at which the primary eigenmode may be superimposed upon the DNS-calculated basic state; amplitude such that linearization holds. Accurate eigenspectrum results have been obtained in different flows at Reynolds numbers up to O(1e3).

**Planning (specify month number m1-m36 with respect to kick-off):**  
first results available: m24 (validation), m36 (analysis)  
final results available: m36  
all analysis finished/reported: m36  
related DoW deliverable numbers TR122-4

**References**  
**FAR-Wake questionnaire for CFD activities**

<table>
<thead>
<tr>
<th>Subtask:</th>
<th>122</th>
<th>partner: UCL</th>
<th>Activity 2</th>
</tr>
</thead>
</table>

**Short description of the activity:**
Medium- and long-wavelength instabilities
Numerical simulations (time developing) of four-vortex systems, in order to identify most promising configuration for efficient wake decay.

**Purpose of the CFD study**
parametric study: Y  validation against EXP: N

**Description of CFD method and its limitations**
- CFD-code name: NA
- CFD method(s): Euler / inviscid vorticity equation
- if other, specify:
- calc. method: 3D temporal
- Boundary conditions: Unbounded conditions with periodicity in filament’s direction
- Discret. schemes: Lagrangian vortex filament method
- Turbulence models: None
- gridding strategy: Uniform initial distribution of nodes along each filament
- max number gridcells: Maximum number of nodes ~2000 (about 500 / filament)
- gridcells in core: 1 filament to represent each vortex tube
- grid studies planned: No
- If not:
  - initialisation method: Analytical condition on ratio between node separation and vortex core size
  - if other, then specify:
  - initial core sizes: rc/b ~ 0.05
  - axial flow profile: NA
- inverse Swirl number: NA

**Simulated parameter range**
- max Reynolds ($\Gamma/\nu$): Inviscid simulations
- x/b range: NA
- Tau* range: ~ 1 up to reconnection time (cf. details)
- flow turbulence: No

**Topic specific information**
Relevant ranges of b2/b1 and of Gamma2/Gamma1 will be considered for both counter- and co-rotating four-vortex system (tbd with others partners).
Longitudinal periodicity length to be set at one equivalent Crow long wavelength for uniform WV systems. For helical WV systems, to be set at one equivalent orbital motion.

**Further details**
Unsteadiness of base flow (four-vortex orbital motion) modelled by helical initial condition.
Linear and non-linear evolution up to vortex reconnection.
Instabilities are triggered by adding a random displacement (of small amplitude) perturbation on the initial vortex position.
Unstable modes characterised by spectral analysis (e.g., wavelength, growth, etc.).
The simulation is carried out up to reconnection time; thus it depends on time of growth and saturation of the instabilities.

**Planning (specify month number (m1-m36) with respect to kick-off):**
- first CFD results reported: m12
- all CFD results reported: m33
- related DoW deliverable numbers D1.2.2

**References**
**FAR-Wake** questionnaire for CFD activities

<table>
<thead>
<tr>
<th>Subtask:</th>
<th>122</th>
</tr>
</thead>
<tbody>
<tr>
<td>partner:</td>
<td>UCL</td>
</tr>
<tr>
<td>Activity:</td>
<td>3</td>
</tr>
</tbody>
</table>

**Short description of the activity:**

*Medium- and long-wavelength instabilities*

Numerical simulations (time developing) of most promising four-vortex systems cases identified in Activity 2 to assess medium- and long-term wake decay behaviour.

**Purpose of the CFD study**

*parametric study* $N$

$N$

**Description of CFD method and its limitations**

<table>
<thead>
<tr>
<th>CFD-code name</th>
<th>NA</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD method(s)</td>
<td>LES / DNS</td>
</tr>
<tr>
<td>if other, specify</td>
<td></td>
</tr>
<tr>
<td>calc. method</td>
<td>3D temporal</td>
</tr>
<tr>
<td>Boundary conditions</td>
<td>Unbounded boundary conditions + longitudinal periodicity (VIC-FMM)</td>
</tr>
<tr>
<td>Discret. schemes</td>
<td>Parallel Vortex In-Cell and fast multipole methods (VIC-FMM)</td>
</tr>
<tr>
<td>Turbulence models</td>
<td>Various (e.g.: hyper-viscosity, modified Smagorinsky (WALE), etc.)</td>
</tr>
<tr>
<td>gridding strategy</td>
<td>Uniform (both codes)</td>
</tr>
<tr>
<td>max number gridcells</td>
<td>20 to 80 millions of VIC grid points</td>
</tr>
<tr>
<td>gridcells in core</td>
<td>6-8 / diameter (targeted but depends of roll-up process)</td>
</tr>
<tr>
<td>grid studies planned</td>
<td>Yes together with spectral assessment of convergence and comparisons between spectral and VIC-FMM results</td>
</tr>
<tr>
<td>if not initialisation method</td>
<td>Other</td>
</tr>
<tr>
<td>if other, then specify</td>
<td>Analytical WV configurations (VM2 and/or low-order algebraic core function)</td>
</tr>
<tr>
<td>initial core sizes</td>
<td>NA</td>
</tr>
<tr>
<td>axial flow profile</td>
<td>NA</td>
</tr>
<tr>
<td>inverse Swirl number</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Simulated parameter range**

<table>
<thead>
<tr>
<th>max Reynolds ($\Gamma/\nu$):</th>
<th>DNS $10^3 - 10^4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LES $10^5 - 10^7$</td>
<td></td>
</tr>
<tr>
<td>x/b range:</td>
<td>NA</td>
</tr>
<tr>
<td>$\tau^*$ range:</td>
<td>Max. of about $10$</td>
</tr>
</tbody>
</table>

**Flow turbulence**

No

**Topic specific information**

Parametric configuration to be determined by vortex filament simulations.

Extension of vortex filament results (see Activity 2) to intermediate (reconnection) and long term (decay) behaviour.

Longitudinal periodicity length to be set at one equivalent Crow long wavelength for uniform WV

**Further details**

Characterization of decay in terms of energy and vortex parameters (circulation, etc.).

**Planning**

(specify month number (m1-m36) with respect to kick-off):

first CFD results reported: $m12$

all CFD results reported: $m33$

related DoW deliverable numbers D1.2.2

**References**


**FAR-Wake questionnaire for CFD activities**

**Subtask:** 122  
**partner:** UCL  
**Activity 4**

**Short description of the activity:**

Medium- and long-wavelength instabilities  
Numerical simulations (space developing) of four-vortex systems, in order to identify most promising configuration for efficient wake decay.

**Purpose of the CFD study**

Parametric study  
Validation against EXP

**Description of CFD method and its limitations**

- **CFD-code name:** NA  
- **CFD method(s):** LES  
- **calc. method:** 3D spatial  
- **Boundary conditions:** Unbounded boundary conditions + generic inflow condition + zero normal gradient outflow  
- **Discret. schemes:** Parallel Vortex In-Cell and fast multipole methods (VIC-FMM)  
- **Turbulence models:** Various (e.g.: hyper-viscosity, modified Smagorinsky (WALE), etc.)  
- **gridding strategy:** Uniform  
- **max number gridcells:** 20 to 80 millions of VIC grid points  
- **gridcells in core:** 6-8 / diameter  
- **grid studies planned:** Y  
- **initialisation method:** Other  
- **initial core sizes:** $r_c/b \sim 0.05$  
- **axial flow profile:** NA  
- **inverse Swirl number:** NA  
- **simulated parameter range**  
- **max Reynolds ($\Gamma/\nu$):** $10^6 - 10^7$  
- **x/b range:**  
- **Tau* range:**  
- **flow turbulence**

**Topic specific information**

Comparisons with temporal simulations (cf. Activity 3) of similar configurations.

**Further details**

Possibility limited to the early stage dynamics of instabilities (linear and non-linear) as one cannot afford a long enough x/b.

**Planning (specify month number (m1-m36) with respect to kick-off):**

- first CFD results reported: $m12$  
- all CFD results reported: $m33$  

**related DoW deliverable numbers D1.2.2**

**References**


Cocle, R., Simulation of high Reynolds number flows using an efficient combination of vortex-in-cell and fast multipole methods. PhD thesis (in preparation), Université catholique de Louvain (UCL), Louvain-la-Neuve, Belgium
### FAR-Wake questionnaire for EXPERimental activities

**Subtask number:** 122  
**Partner:** TUM-FLM

#### Short description of the activity:
Analysis of mean, turbulent and spectral density distributions of velocity components applying hotwire anemometry supplemented by two-point correlations within existing EXP data?  

<table>
<thead>
<tr>
<th>Source of existing data</th>
<th>Confid. Restrictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>none</td>
<td>N</td>
</tr>
</tbody>
</table>

#### Experimental parameter range (expected):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test medium</td>
<td>air</td>
</tr>
<tr>
<td>Average kinematic viscosity</td>
<td>$17 \times 10^{-6}$ [m/s]</td>
</tr>
<tr>
<td>Maximum test velocity</td>
<td>25.0 [m/s]</td>
</tr>
<tr>
<td>Simulated wingspan</td>
<td>(0.3), 1.2 [m]</td>
</tr>
<tr>
<td>Simulated wingchord (mac)</td>
<td>[-]</td>
</tr>
<tr>
<td>Typical lift coefficient (CL)</td>
<td>[-]</td>
</tr>
<tr>
<td>X/b range (downstream)</td>
<td>(60), 16 [-]</td>
</tr>
</tbody>
</table>

#### Topic specific information

Measurements are conducted in TUM-FLM wind tunnel facility C (test section length: 21 m; cross section of test section: 1.8 m x 2.7 m)  
Tests are performed using miniature cross- and triple-wire probes and PIV.  
Data acquisition parameters are as follows: sampling rate of 3000 Hz (ea. channel), sample block of 19200 values (ea. survey point), low-pass filter freq. of 820 Hz, digital resolution of 16 bit  

**Measurements:**
- Pressure probe (traverses): N
- PIV (2C): N
- PIV (3C): Y (optional)
- Flow visualisation: Y (optional)
- Expected grid resolution (Dy,Dz): (15, 10) [mm]

**Planning (specify month number m1-m36 with respect to kick-off):**
- Model available: m18
- First analysis reported: m27
- First tests completed: m23
- All analysis finished/reported: m33
- Final tests completed: m30
- Related DoW deliverable numbers: D 1.2.2

**Further details of model and test set-up**
- Model configuration: t.b.d.
- X/b stations: 1 ... 16 / (60)
- Normalized spatial resolution: $Dy/b$: 0.005, $Dz/b$: 0.005
- Recording mean flow field velocity components $u$, $v$, and $w$ and flow field velocity fluctuations $u''u'$, $v''v'$, $w''w'$, $u'v'$, $u'w'$, and $v'w'$ (Reynolds stresses), statistics and spectral densities.

#### References

Appendix B  Overview of work, parameter ranges and planning for WP2: Vortex interactions with jets and wakes

**FAR-Wake questionnaire for EXPerimental activities**

<table>
<thead>
<tr>
<th>Subtask number:</th>
<th>211</th>
</tr>
</thead>
<tbody>
<tr>
<td>partner:</td>
<td>NLR</td>
</tr>
</tbody>
</table>

**Short description of the activity:**

Analysis of existing wake fields with simulated jets of various strength

- **existing EXP data?**: Y
- **Source of existing data**: C-Wake
- **Confid. Restrictions**: Y

**experimental parameter range (expected):**

- **type of facility:**
  - air
  - windtunnel
  - watertunnel
  - wind tunnel
  - field trials (real aircraft)

- **average kinematic viscosity**: 1.4 * 10^-5 [m^2/s]
- **maximum test velocity**: 68 [m/s]
- **simulated wingspan**: 4.02 [m]
- **simulated wingchord**: 0.505 [m]
- **typical lift coefficient (CL)**: 1.4, 1.76

**experimental parameter range (expected):**

- **x/b range (downstream)**: 0.3, 1.3

**topic specific information**

Four different model configurations have been tested with TFN and with 3 TPS power settings: (10, 20 and 30000 rpm). The two measured wake locations x/b=0.3 and 1.3 will be analysed with the WAKE method from NLR. This yields cross-flow kinetic energy and lift (including estimate for wing load at first station). Data available for two lift coefficients.

Detailed analysis in order to find the effect of TPS on wake evolution and cross-flow kinetic energy decay in near wake.

**measurements:**

- pressure probe (traverses): Y/N
- hotwire: N
- PIV (2C): N
- LDA: N
- PIV (3C): N
- LIDAR: N
- Flow visualisation: N
- expected grid resolution (Dy,Dz): (40, 40) [mm]

**planning (specify month number m1-m36 with respect to kick-off):**

- model available: first analysis reported: m12
- first tests completed: all analysis finished/reported: m12
- final tests completed: 2002 related DoW deliverable numbers D211_1

**Further details of model and test set-up**

Half model tests in Filton low-speed windtunnel, including force balance measurements

**References**

- For the specific tests in C-Wake several C-Wake publications exist (+ confidential reports from Airbus-UK)
- For the WAKE method several reports exist, one is on an application to wake with jets:
**FAR-Wake** questionnaire for EXPERimental activities

Subtask number: 211  
partner: TUD

Short description of the activity:
3-component PIV measurements behind a generic wing model equipped with cold jets. The effect of the jets including their relative position with respect to a strong flap end vortex will be investigated in the near to mid field range.

**existing EXP data?**  
N

**Source of existing data**  
Confid. Restrictions  
N

**experimental parameter range (expected):**  
**type of facility:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected Value</th>
<th>Facility Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test medium</td>
<td>water</td>
<td>wind tunnel</td>
</tr>
<tr>
<td>Average kinematic viscosity</td>
<td>1.14E-06 [m2/s]</td>
<td>water tunnel</td>
</tr>
<tr>
<td>Maximum test velocity</td>
<td>5 [m/s]</td>
<td>water towing tank</td>
</tr>
<tr>
<td>Simulated wingspan</td>
<td>0.6 [m]</td>
<td>field trials (real aircraft)</td>
</tr>
<tr>
<td>Simulated wingchord</td>
<td>0.075 [m]</td>
<td>T(z) profile (deg K) measured?</td>
</tr>
<tr>
<td>Typical lift coefficient (CL)</td>
<td>1.0 &amp; 1.5 [-]</td>
<td>Flow turbulence level in facility 0.10%</td>
</tr>
<tr>
<td>X/b range (downstream)</td>
<td>150 [-]</td>
<td>Cross-section dims. of facility [lb] 4.22m x2.50mx142m (= w x d x l)</td>
</tr>
</tbody>
</table>

**Topic specific information**
3-component PIV measurements, Data rate=3.33 Hz

**Simulated jets:** jet diameter=30mm, velocity=1.7V0, temperature range=cold(15degC), positions, jet direction, swirl, etc.

Positions: left of Vortex, Right of Vortex, In line with vortex. Also changes in Jet direction and the application of anti-swirl is anticipated.

**Multi-vortex systems:** spacing b1/b2=2/3, strengths Gamma1/Gamma2=TBD

**Measurements:**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Expected Value</th>
<th>Facility Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure probe (traverses)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>PIV (2C)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>PIV (3C)</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Flow visualisation</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Expected grid resolution (Dy,Dz)</td>
<td>(1.7,1.7) [mm]</td>
<td></td>
</tr>
</tbody>
</table>

**Planning (specify month number m1-m36 with respect to kick-off):**

<table>
<thead>
<tr>
<th>Planning Step</th>
<th>Month Number</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model available</td>
<td>m8</td>
<td>First analysis reported: m11</td>
</tr>
<tr>
<td>First tests completed</td>
<td>m10</td>
<td>All analysis finished/reported: m14</td>
</tr>
<tr>
<td>Final tests completed</td>
<td>m12</td>
<td>Related DoW deliverable numbers</td>
</tr>
</tbody>
</table>

**Further details of model and test set-up**
See separate figures

**References**

1) L.L.M. Veldhuis, F. Scarano, C. van Wijk: "Vortex wake investigation of an AirBus A340 model using PIV in a Towing Tank  
C-WAKE Report PR 1.1.3-TUD, 29-10-2001

2) F. Scarano, C. van Wijk, L.L.M. Veldhuis: "Traversing field of view and AR-PIV for mid-field vortex wake investigation in a towing tank.  
Experiments in Fluids 33 (2002) 950-961
### FAR-Wake questionnaire for CFD activities

<table>
<thead>
<tr>
<th>Subtask:</th>
<th>211</th>
<th>Partner: ONERA/DMPH</th>
</tr>
</thead>
</table>

**Short description of the activity:**
Simulations (DNS) of cold jet/single vortex interactions at low Reynolds numbers. Identical configurations will be used to simulate hot turbulent jet/vortex interactions (Sbt 2.1.2).

**Purpose of the CFD study**
- Parametric study: Y
- Validation against EXP: Y

**Description of CFD method and its limitations**
- **CFD-code name:** FLUDILES
- **CFD method(s):** DNS
- **Calc. method:** 3D
- **Boundary conditions:** Symmetric, Non-reflecting, Periodic
- **Discret. schemes:** 6th order Compact scheme for the discretisation in space, 3rd order Runge Kutta method for the time integration
- **Turbulence models:**
- **Gridding strategy:** stretched or uniform
- **Max number gridcells:** $327^3$ (estimation)
- **Grid cells in core:** $n=10$
- **Grid studies planned:** Y
- **Initialisation method:** other (Lamb-Oseen vortex model)

**Simulated parameter range**
- **Max Reynolds (Γ/ν):** 5000
- **x/b range:**
- **τ*: range:** $t \sim 210 \, t_v \, (t_v = 2 \, r_c/v_{max})$

**Flow turbulence**

**Topic specific information**
- Sbt 2.1.1: Parameters to be varied are: vortex core diameters, jet locations

**Further details**

**Planning (specify month number (m1-m36) with respect to kick-off):**
- First CFD results reported: m12
- All CFD results reported: m15
- Related DoW deliverable numbers: D2.1.1-2

**References**
**FAR-Wake questionnaire for CFD activities**

<table>
<thead>
<tr>
<th><strong>Subtask:</strong></th>
<th>211</th>
<th><strong>partner:</strong></th>
<th>UCL</th>
<th><strong>Activity 5</strong></th>
</tr>
</thead>
</table>

**Short description of the activity:**
Cold engine jets
Numerical simulations (time developing) of wake vortex roll-up and dynamics/decay in presence of a turbulent jet.

**Purpose of the CFD study**
- parametric study: **Y**
- validation against EXP: **N**

**Description of CFD method and its limitations**

| CFD-code name: | NA |
| CFD method(s): | LES |
| if other, specify: | 3D temporal |

**Boundary conditions:**
- Unbounded boundary conditions + longitudinal periodicity (VIC-FMM)
- Fully periodic boundary conditions (parallel spectral code)

**Discret. schemes:**
- Parallel Vortex In-Cell and fast multipole methods (VIC-FMM)
- Parallel spectral code: Fourier expansions of velocity field.

**Turbulence models:**
- Various (e.g.: hyper-viscosity, modified Smagorinsky (WALE), etc.)

**gridding strategy:**
- Uniform (both VIC-FMM and parallel spectral code)
- Parallel Vortex In-Cell and fast multipole methods (VIC-FMM)

**max number gridcells:**
- 20 to 80 millions of VIC grid points

**gridcells in core:**
- 6-8 / diameter (targeted but depends of roll-up process)

**grid studies planned:**
- Yes

**initialisation method:**
- Other
- See detail below

**initial core sizes:**
- NA

**axial flow profile:**
- Generic axial jet flow and turbulent jet from LES (provided by CERFACS)

**Inverse Swirl number:**
- Tbd

**simulated parameter range**
- max Reynolds ($\Gamma / \nu$): According to experiment measurements
- x/b range: NA
- Tau* range: Max. of about 10
- flow turbulence: NA

**Topic specific information**
Further coordination with the involved partners is still required to determine parameters to be

**Further details**
Initial turbulent jet results of LES provided by CERFACS (parameters tbd)
Initial configuration of wake vortex:
- vorticity field corresponding to analytical span loading
- vorticity field from experimental near field measurements (provided by Airbus-D)

**Planning (specify month number (m1-m36) with respect to kick-off):**
- first CFD results reported: m33
- all CFD results reported: m36
- related DoW deliverable numbers D2.1.1-3

**References**


**FAR-Wake** questionnaire for CFD activities

<table>
<thead>
<tr>
<th>Subtask:</th>
<th>211</th>
</tr>
</thead>
<tbody>
<tr>
<td>partner:</td>
<td>CERFACS</td>
</tr>
</tbody>
</table>

**Short description of the activity:**
Simulations (LES) of cold jet/single vortex interactions at high Reynolds numbers. Then, a promising configuration for rapid wake decay using a turbulent jet superposed on a measured vortex wake flow will be simulated by temporal LES simulation. Identical configurations will be used to simulate hot turbulent jet/vortex interactions (Sbt 2.1.2).

**Purpose of the CFD study**
- parametric study: **Y**
- validation against EXP: **Y**

**Description of CFD method and its limitations**
- CFD-code name: **NTMIX3D**
- CFD method(s): **LES**
- if other, specify calc. method: **3D**
- Boundary conditions: **Symmetric, Non-reflecting, Periodic**
- Discret. schemes: 6th order Compact scheme for the discretisation in space
  - 3rd order Rung Kutta method for the time integration
- Turbulence models: **LES model : Filtered Structure Function**
- gridding strategy: stretched or uniform
- max number gridcells: 301*301*61 (estimation)
- gridcells in core: n>10
- grid studies planned: **Y**
- if not initialisation method: other
  - if other, then specify: **Lamb-Oseen vortex model**

**simulated parameter range**
- max Reynolds (Γ/ν):
- x/b range:
- Tau* range: \( t \sim 16t_{\text{eddy}} ( t_{\text{eddy}} = 2 \pi rc/\nu_{\text{max}} ) \)

**Topic specific information**
Sbt 2.1.1: Parameters to be varied are: vortex and jet intensities/diameters, jet location/inclination

**Further details**

**Planning (specify month number (m1-m36) with respect to kick-off):**
- first CFD results reported: m12 / m18
- all CFD results reported: m30
  - related DoW deliverable numbers: D2.1.2 m36
    - D2.1.1-3

**References**
**FAR-Wake questionnaire for EXPerimental activities**

<table>
<thead>
<tr>
<th>Subtask number:</th>
<th>211</th>
<th>partner:</th>
<th>UBA</th>
<th>Y1_1</th>
</tr>
</thead>
</table>

**Short description of the activity:**
Tests of the interaction of a cold jet with a single vortex. All the measurements will be for the very near wake.

<table>
<thead>
<tr>
<th>existing EXP data?</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source of existing data</td>
<td>Confid. Restrictions</td>
</tr>
<tr>
<td>experimental parameter range (expected):</td>
<td>type of facility:</td>
</tr>
<tr>
<td>test medium:</td>
<td>air</td>
</tr>
<tr>
<td>average kinematic viscosity:</td>
<td>1.46E-05 [m²/s]</td>
</tr>
<tr>
<td>maximum test velocity:</td>
<td>10 [m/s]</td>
</tr>
<tr>
<td>simulated wingspan:</td>
<td>0.762 [m]</td>
</tr>
<tr>
<td>simulated wingchord:</td>
<td>0.15 [m]</td>
</tr>
<tr>
<td>typical lift coefficient (CL):</td>
<td>0.5 - 1.0 [-]</td>
</tr>
<tr>
<td>x/b range (downstream):</td>
<td>0-0.6 [-]</td>
</tr>
</tbody>
</table>

**Topic specific information**

The experiments will be conducted in an open section wind tunnel. Nozzle diameter = 0.762m, test section length = 1m. Free stream velocity = 10m/s. Re = 10^5 (based on chord). Jet diameter = 15mm (0.1c), Jet velocity = 20m/s (Cmjv=0.025), Jet distance from wing tip = 0.0c - 0.4c, Jet parallel to free stream. Jet temperature: ambient.

**Measurements:**

- pressure probe (traverses): N
- PIV (2C): Y
- PIV (3C): N
- Flow visualisation: N
- expected grid resolution (Dy,Dz): (1.5,1.5) [mm]

**Planning (specify month number m1-m36 with respect to kick-off):**

- model available: m1
- first tests completed: m6
- final tests completed: m11
- first analysis reported: m12
- all analysis finished/reported: m15
- related DoW deliverable numbers D2.1.1-1

**Further details of model and test set-up**

Sketch of the test setup can be found in attached Word document

The model is a half wing (semi-span = 0.381m)

x/c = 0.0, 1.0, 3.0 (x/b = 0.0, 0.2, 0.6)

**References**

FAR-Wake questionnaire for EXPERimental activities

Subtask number: 211 partner: UBA Y1_2

Short description of the activity:
Tests of the interaction of a cold jet with a single vortex.
The measurements will be for the near wake.

existing EXP data? N
Source of existing data
experimental parameter range (expected):
type of facility:
test medium: air windtunnel Y
average kinematic viscosity: 1.46E-05 [m2/s] watertunnel N
maximum test velocity: 20 [m/s] water towing tank N
simulated wingspan: 1 [m] field trials (real aircraft) N
simulated wingchord: 0.1 [m] T(z) profile (deg K) measured? N
typical lift coefficient (CL): 0.5 - 1.0 [-] flow turbulence level in facility -
x/b range (downstream): 0.2-1.2 [-] cross-section dims. of facility [b]

Topic specific information
The experiments will be conducted in an closed section wind tunnel. Cross-section = 2.13m*1.52m
test section length = 2.7m. Free stream velocity = 10-20m/s. Re = 7e4-1.4e5 (based on chord)
Jet diameter = 15mm (0.15c), Jet velocity = 20-40m/s (Cmju=0.025-0.1),
Jet distance from wing tip = 0.0c - 1.0c, Jet parallel to free stream. Jet temperature: ambient.

Measurements:
pressure probe (traverses): N hotwire: N
PIV (2C): Y LDA: Y
PIV (3C): N LIDAR: N
Flow visualisation: N Model forces: N
expected grid resolution (Dy,Dz): (1.0,1.0) [mm]

Planning (specify month number m1-m36 with respect to kick-off):
model available: m1 first analysis reported: m15
first tests completed: m6 all analysis finished/reported: m12
final tests completed: m11 related DoW deliverable numbers D2.1.1-1

Further details of model and test set-up
Sketch of the test setup can be found in attached Word document
The model is a half wing (semispan = 0.5m)
x/c = 2.0, 4.0, 8.0, 12.0 (x/b = 0.2, 0.4, 0.8, 1.2)

References
FAR-Wake questionnaire for experimental activities

Subtask number: 211  partner: UBA  Y1_3

Short description of the activity:
Tests of the interaction of a cold jet with a single vortex. The measurements will be for the near - mid wake.

existing EXP data?  N

Source of existing data

experimental parameter range (expected):
- test medium:  water
- average kinematic viscosity:  1.16E-06 [m2/s]
- maximum test velocity:  0.3 [m/s]
- simulated wingspan:  0.5 [m]
- simulated wingchord:  0.04 [m]
- typical lift coefficient (CL):  0.5 - 1.0 [-]
- x/b range (downstream):  0-2.5 [-]

Type of facility:
- wind tunnel
- water towing tank
- field trials (real aircraft)
- T(z) profile (deg K) measured?
- flow turbulence level in facility:  <1%
- cross-section dims. of facility:  [b]

Topic specific information

The experiments will be conducted in a water tunnel. Cross-section = 0.51m*0.38m, test section length = 1.5m. Free stream velocity = 0.1-0.3m/s, Re = 4000-12000 (based on chord)
Jet diameter = 6mm (0.15c), Jet velocity = 0.2-1.2m/s (Cmju=0.025-0.1), Jet distance from wing tip = 0.0c - 1.0c, Jet parallel to free stream. Jet temperature: ambient.

Measurements:
- pressure probe (traverses):  N
- hotwire:  N
- hotwire:  N
- LDA:  Y
- LIDAR:  N
- Model forces:  N
- expected grid resolution (Dy,Dz):  (0.4,0.4) [mm]

Planning (specify month number m1-m36 with respect to kick-off):
- model available:  m1
- first analysis reported:  m12
- first tests completed:  m6
- all analysis finished/reported:  m15
- final tests completed:  m11
- related DoW deliverable numbers:  D2.1.1-1

Further details of model and test set-up

Sketch of the test setup can be found in attached Word document

The model is a half wing (semispan = 0.25m)
- x/c = 2.0, 4.0, 8.0, 12.0, 16.0, 24.0 (x/b = 0.16, 0.32, 0.64, 0.96, 1.28, 1.92)

References
**FAR-Wake** questionnaire for EXPERimental activities

**Subtask number:** 211  
**partner:** UBA  
**Y2_1**

**Short description of the activity:**
Tests of the interaction of a cold jet with a vortex pair.  
The measurements will be for the near wake.

<table>
<thead>
<tr>
<th>Source of existing data</th>
<th>Confid. Restrictions</th>
<th>Y/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>existing EXP data?</td>
<td></td>
<td>N</td>
</tr>
</tbody>
</table>

**experimental parameter range (expected):**

<table>
<thead>
<tr>
<th>parameter</th>
<th>type of facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>test medium:</td>
<td>air</td>
</tr>
<tr>
<td>average kinematic viscosity:</td>
<td>1.46E-05 [m2/s]</td>
</tr>
<tr>
<td>maximum test velocity:</td>
<td>20 [m/s]</td>
</tr>
<tr>
<td>simulated wingspan:</td>
<td>1 [m]</td>
</tr>
<tr>
<td>simulated wingchord:</td>
<td>0.1 [m]</td>
</tr>
<tr>
<td>typical lift coefficient (CL):</td>
<td>0.5 - 1.0 [-]</td>
</tr>
<tr>
<td>x/b range (downstream):</td>
<td>0.2-1.2 [-]</td>
</tr>
</tbody>
</table>

**Source of existing data**

<table>
<thead>
<tr>
<th>parameter</th>
<th>type of facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>test medium:</td>
<td>windtunnel</td>
</tr>
<tr>
<td>maximum test velocity:</td>
<td>watertunnel</td>
</tr>
<tr>
<td>simulated wingspan:</td>
<td>water towing tank</td>
</tr>
<tr>
<td>simulated wingchord:</td>
<td>field trials (real aircraft)</td>
</tr>
</tbody>
</table>
| typical lift coefficient (CL): | T(z) profile (deg K) measured |}

**Topic specific information**

The experiments will be conducted in a closed section wind tunnel. Cross-section = 2.13m*1.52m  
Test section length = 2.7m. Free stream velocity = 10-20m/s. Re = 7e4-1.4e5 (based on chord)  
Jet diameter = 15mm (0.15c), Jet velocity = 20-40m/s (Cmju=0.025-0.1),  
Jet distance from wing tip = 0.0c - 1.0c, Jet parallel to free stream. Jet temperature: ambient.

**Measurements:**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Y/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure probe (traverses):</td>
<td>N</td>
</tr>
<tr>
<td>PIV (2C):</td>
<td>Y</td>
</tr>
<tr>
<td>PIV (3C):</td>
<td>N</td>
</tr>
<tr>
<td>Flow visualisation:</td>
<td>N</td>
</tr>
<tr>
<td>expected grid resolution (Dy,Dz):</td>
<td>(1.0,1.0) [mm]</td>
</tr>
</tbody>
</table>

**Planning (specify month number m1-m36 with respect to kick-off):**

<table>
<thead>
<tr>
<th>Planning Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>model available:</td>
<td>m6</td>
</tr>
<tr>
<td>first tests completed:</td>
<td>m15</td>
</tr>
<tr>
<td>final tests completed:</td>
<td>m23</td>
</tr>
</tbody>
</table>

**Further details of model and test set-up**

Sketch of the test setup can be found in attached Word document

**References**
**FAR-Wake questionnaire for EXPerimental activities**

**Subtask number:** 211  
**partner:** UBA  
**Y2_2**

**Short description of the activity:**

Tests of the interaction of a cold jet with a single vortex. The measurements will be for the near - mid wake.

---

**existing EXP data?**  
N

**Source of existing data**

<table>
<thead>
<tr>
<th>Confid. Restrictions</th>
<th>Y/N</th>
</tr>
</thead>
</table>

**experimental parameter range (expected):**

<table>
<thead>
<tr>
<th>Type of facility</th>
<th>N</th>
</tr>
</thead>
</table>

**test medium:** water

**average kinematic viscosity:** 1.16E-06 [m2/s]

**maximum test velocity:** 0.3 [m/s]

**simulated wingspan:** 0.5 [m]

**simulated wingchord:** 0.04 [m]

**typical lift coefficient (CL):** 0.5 - 1.0 [-]

**x/b range (downstream):** 0-2.5 [-]

---

**Topic specific information**

The experiments will be conducted in a water tunnel. Cross-section = 0.51m*0.38m, test section length = 1.5m. Free stream velocity = 0.1-0.3m/s. Re = 4000-12000 (based on chord) Jet diameter = 6mm (0.15c), Jet velocity = 0.2-1.2m/s (Cmju=0.025-0.1), Jet distance from wing tip = 0.0c - 1.0c, Jet parallell to free stream. Jet temperature: ambient.

---

**Measurements:**

<table>
<thead>
<tr>
<th>Type</th>
<th>Y/N</th>
</tr>
</thead>
</table>

**pressure probe (traverses):** N

**hotwire:** N

**PIV (2C):** Y

**LDA:** Y

**PIV (3C):** N

**LIDAR:** N

**Flow visualisation:** Y

**Model forces:** N

**expected grid resolution (Dy,Dz):** (0.4,0.4) [mm]

---

**Planning (specify month number m1-m36 with respect to kick-off):**

<table>
<thead>
<tr>
<th>Model available:</th>
<th>m6</th>
</tr>
</thead>
</table>

**first tests completed:** m15

**all analysis finished/reported:** m24

**related DoW deliverable numbers:** D2.1.1-2

---

**Further details of model and test set-up**

Sketch of the test setup can be found in attached Word document

The model is a half wing (semispan = 0.25m)

x/c = 2.0, 4.0, 8.0, 12.0, 16.0, 24.0 (x/b = 0.16, 0.32, 0.64, 0.96, 1.28, 1.92)

---

**References**
FAR-Wake questionnaire for EXPERimental activities

Subtask number: 211  partner: UBA  Y3_1

Short description of the activity:
Tests of the interaction of a cold jet with a single vortex, at low momentum coefficients aimed at controlling the vortex.
All the measurements will be for the very near wake.

existing EXP data?  N
Source of existing data  Confid. Restrictions  Y/N

experimental parameter range (expected):

test medium:  air
average kinematic viscosity:  1.46E-05 [m2/s]  watertunnel  Y
maximum test velocity:  10 [m/s]  water towing tank  N
simulated wingspan:  0.762 [m]  field trials (real aircraft)  N
simulated wingchord:  0.15 [m]  T(z) profile (deg K) measured?  N
typical lift coefficient (CL):  0.5 - 1.0 [-]  flow turbulence level in facility  0.30%
x/b range (downstream):  0-0.6 [-]  cross-section dims. of facility [b]

Topic specific information

D=0.762m
The experiments will be conducted in an open section wind tunnel. Nozzle diameter = 0.762m, test section length = 1m. Free stream velocity = 10m/s. Re = 10^5 (based on chord)
Jet diameter = 15mm (0.1c), Jet velocity = 20m/s (Cmju=0.025),
Jet distance from wing tip = 0.0c - 0.4c, Jet parallell to free stream. Jet temperature: ambient.

Measurements:

pressure probe (traverses):  N  hotwire:  N
PIV (2C):  Y  LDA:  Y
PIV (3C):  N  LIDAR:  N
Flow visualisation:  N  Model forces:  N
expected grid resolution (Dy,Dz):  1.5,1.5 [mm]

Planning (specify month number m1-m36 with respect to kick-off):

model available:  m6  first analysis reported:  m30
first tests completed:  m27  all analysis finished/reported:  m36
final tests completed:  m34  related DoW deliverable numbers D2.1.1-2

Further details of model and test set-up
Sketch of the test setup can be found in attached Word document
The model is a half wing (semispan = 0.381m)
x/c = 0.0, 1.0, 3.0 (x/b = 0.0, 0.2, 0.6)

References
**FAR-Wake** questionnaire for EXPERimental activities

**Subtask number:** 211  
**partner:** UBA  
**Y3_2**

**Short description of the activity:**
Tests of the interaction of a cold jet with a single vortex.  
The measurements will be for the near wake.

**existing EXP data?** N

**Source of existing data**

**Confid. Restrictions** Y/N

**experimental parameter range (expected):**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>test medium:</td>
<td>air</td>
</tr>
<tr>
<td>average kinematic viscosity:</td>
<td>1.46E-05 [m2/s]</td>
</tr>
<tr>
<td>maximum test velocity:</td>
<td>20 [m/s]</td>
</tr>
<tr>
<td>simulated wingspan:</td>
<td>1 [m]</td>
</tr>
<tr>
<td>simulated wingchord:</td>
<td>0.1 [m]</td>
</tr>
<tr>
<td>typical lift coefficient (CL):</td>
<td>0.5 - 1.0 [-]</td>
</tr>
<tr>
<td>x/b range (downstream):</td>
<td>0.2-1.2 [-]</td>
</tr>
</tbody>
</table>

**type of facility:**

<table>
<thead>
<tr>
<th>Facility</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>windtunnel</td>
<td>Y</td>
</tr>
<tr>
<td>watertunnel</td>
<td>N</td>
</tr>
<tr>
<td>water towing tank</td>
<td>N</td>
</tr>
<tr>
<td>field trials (real aircraft)</td>
<td>N</td>
</tr>
<tr>
<td>T(z) profile (deg K) measured?</td>
<td>N</td>
</tr>
<tr>
<td>flow turbulence level in facility</td>
<td>-</td>
</tr>
<tr>
<td>cross-section dims. of facility</td>
<td>2.13m*1.52m</td>
</tr>
</tbody>
</table>

**Topic specific information**

The experiments will be conducted in an closed section wind tunnel. Cross-section = 2.13m*1.52m  
Test section length = 2.7m. Free stream velocity = 10-20m/s. Re = 7e4-1.4e5 (based on chord)  
Jet diameter = 15mm (0.15c), Jet velocity = 20-40m/s (Cmju=0.025-0.1),  
Jet distance from wing tip = 0.0c - 1.0c, Jet parallel to free stream. Jet temperature: ambient.

**Measurements:**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure probe (traverses):</td>
<td>N</td>
</tr>
<tr>
<td>PIV (2C):</td>
<td>Y</td>
</tr>
<tr>
<td>PIV (3C):</td>
<td>N</td>
</tr>
<tr>
<td>Flow visualisation:</td>
<td>N</td>
</tr>
<tr>
<td>expected grid resolution (Dy,Dz):</td>
<td>(1.0,1.0) [mm]</td>
</tr>
</tbody>
</table>

**Planning (specify month number m1-m36 with respect to kick-off):**

| Model available: | m6 |
| First tests completed: | m27 |
| Final tests completed: | m34 |
| First analysis reported: | m30 |
| All analysis finished/reported: | m36 |

**Further details of model and test set-up**

**Sketch of the test setup can be found in attached Word document**

**The model is a half wing (semispan = 0.5m)**

<table>
<thead>
<tr>
<th>x/c</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0, 4.0, 8.0, 12.0</td>
<td>x/b = 0.2, 0.4, 0.8, 1.2</td>
</tr>
</tbody>
</table>

**References**
FAR-Wake questionnaire for EXPERimental activities

Subtask number: 211 partner: UBA Y3_3

Short description of the activity:
Tests of the interaction of a cold jet with a single vortex. The measurements will be for the near-mid wake.

existing EXP data? N
Source of existing data

Experimental parameter range (expected):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected Range</th>
<th>Current Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test medium</td>
<td>water</td>
<td>windtunnel</td>
</tr>
<tr>
<td>Average kinematic viscosity</td>
<td>1.16E-06 m²/s</td>
<td>1.16E-06</td>
</tr>
<tr>
<td>Maximum test velocity</td>
<td>0.3 m/s</td>
<td></td>
</tr>
<tr>
<td>Simulated wingspan</td>
<td>0.5 m</td>
<td></td>
</tr>
<tr>
<td>Simulated wingchord</td>
<td>0.04 m</td>
<td></td>
</tr>
<tr>
<td>Typical lift coefficient (CL)</td>
<td>0.5 - 1.0</td>
<td></td>
</tr>
<tr>
<td>x/b range (downstream)</td>
<td>0-2.5</td>
<td></td>
</tr>
</tbody>
</table>

Type of facility:

<table>
<thead>
<tr>
<th>Facility Type</th>
<th>Y/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windtunnel</td>
<td>Y</td>
</tr>
<tr>
<td>Water towing tank</td>
<td>N</td>
</tr>
<tr>
<td>Field trials (real aircraft)</td>
<td>N</td>
</tr>
<tr>
<td>T(z) profile (deg K) measured?</td>
<td>N</td>
</tr>
<tr>
<td>Flow turbulence level in facility</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Cross-section dims. of facility</td>
<td></td>
</tr>
</tbody>
</table>

Data specific information

The experiments will be conducted in a water tunnel. Cross-section = 0.51*0.38 m, test section length = 1.5 m. Free stream velocity = 0.1 - 0.3 m/s. Re = 4000 - 12000 (based on chord) Jet diameter = 6 mm (0.15c), Jet velocity = 0.2 - 1.2 m/s (Cmju=0.025 - 0.1), Jet distance from wing tip = 0.0c - 1.0c, Jet parallel to free stream. Jet temperature: ambient.

Measurements:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>N / Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure probe (traverses)</td>
<td>N</td>
</tr>
<tr>
<td>Hotwire</td>
<td>N</td>
</tr>
<tr>
<td>PIV (2C)</td>
<td>Y</td>
</tr>
<tr>
<td>LDA</td>
<td>Y</td>
</tr>
<tr>
<td>PIV (3C)</td>
<td>N</td>
</tr>
<tr>
<td>LIDAR</td>
<td>N</td>
</tr>
<tr>
<td>Flow visualisation</td>
<td>Y</td>
</tr>
<tr>
<td>Model forces</td>
<td>N</td>
</tr>
</tbody>
</table>

Planning (specify month number m1-m36 with respect to kick-off): model available: m6 first analysis reported: m30 first tests completed: m27 all analysis finished/reported: m36 final tests completed: m34 related DoW deliverable numbers D2.1.1-2

Further details of model and test set-up

Sketch of the test setup can be found in attached Word document

The model is a half wing (semi-span = 0.25 m)
\( x/c = 2.0, 4.0, 8.0, 12.0, 16.0, 24.0 \) (x/b = 0.16, 0.32, 0.64, 0.96, 1.28, 1.92)

References
FAR-Wake questionnaire for EXPERimental activities

Subtask number: 212 partner: CUT

Short description of the activity:
The measurements were performed for isothermal and hot jet and the influence of the governing parameters like density ratio and boundary layer thickness was examined. The data base of measured flow parameters included axial mean and fluctuating velocity as well as spectra of axial velocity component.

existing EXP data? Y-in part

Source of existing data State funded grant 7T07A007-15 - Confid. Restrictions N

Experimental parameter range (expected):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test medium</td>
<td>air</td>
</tr>
<tr>
<td>Average kinematic viscosity</td>
<td>[m2/s]</td>
</tr>
<tr>
<td>Maximum test velocity</td>
<td>20 [m/s]</td>
</tr>
<tr>
<td>Simulated wingspan</td>
<td>[m]</td>
</tr>
<tr>
<td>Simulated wingchord</td>
<td>[m]</td>
</tr>
<tr>
<td>Typical lift coefficient (CL)</td>
<td>[-]</td>
</tr>
<tr>
<td>X/b range (downstream)</td>
<td>[-]</td>
</tr>
</tbody>
</table>

Type of facility:

<table>
<thead>
<tr>
<th>Facility</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind tunnel</td>
<td>Y</td>
</tr>
<tr>
<td>Water tunnel</td>
<td>N</td>
</tr>
<tr>
<td>Water towing tank</td>
<td>N</td>
</tr>
<tr>
<td>Field trials (real aircraft)</td>
<td>N</td>
</tr>
<tr>
<td>T(z) profile (deg K) measured?</td>
<td>N</td>
</tr>
<tr>
<td>Flow turbulence level in facility</td>
<td>0.3 %</td>
</tr>
<tr>
<td>Cross-section dims. of facility [lb]</td>
<td></td>
</tr>
</tbody>
</table>

Topic specific information

- Nozzle diameter: 15 mm
- Jet oriented vertically
- Temperature range 273-540 K
- Velocity range: 5-20 m/s
- Diameter to momentum thickness of the boundary layer at the nozzle exit: 40-180

Measurements:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure probe (traverses)</td>
<td>N</td>
<td>Y</td>
</tr>
<tr>
<td>PIV (2C)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>PIV (3C)</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Flow visualisation</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Expected grid resolution</td>
<td>(  ,  ) [mm]</td>
<td></td>
</tr>
</tbody>
</table>

Planning (specify month number m1-m36 with respect to kick-off):

<table>
<thead>
<tr>
<th>Event</th>
<th>Value</th>
<th>Date</th>
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</thead>
<tbody>
<tr>
<td>Model available</td>
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<tr>
<td>First tests completed</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>All analysis finished/reported</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Final tests completed</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Related DoW deliverable numbers</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Further details of model and test set-up D2.1.2, TR2.1.2-2,
details and scheme of the experimental set-up in the attached powerpoint presentation

References


A. Boguslawski, S. Drobiaz: Absolute and convective instability of the round variable density jet, Advances in Turbulence IX, Southampton, 2002
FAR-Wake questionnaire for CFD activities

Subtask: 212 partner: CUT

Short description of the activity:
Give a short description of the activity

Purpose of the CFD study
parametric study Y validation against EXP Y

Description of CFD method and its limitations

<table>
<thead>
<tr>
<th>CFD-code name:</th>
<th>SAILOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD method(s):</td>
<td>LES</td>
</tr>
<tr>
<td>if other, specify:</td>
<td></td>
</tr>
<tr>
<td>calc. method:</td>
<td>3D spatial and 3D temporal</td>
</tr>
<tr>
<td>Boundary conditions:</td>
<td>inlet velocity/temperature at inflow; convective outlet; lateral b.c. periodic or constant pressure</td>
</tr>
<tr>
<td>Discret. schemes:</td>
<td>high order compact/pseudospectral</td>
</tr>
<tr>
<td>Turbulence models:</td>
<td>Smagorinsky, structure function, dynamic</td>
</tr>
<tr>
<td>gridding strategy:</td>
<td>stretched</td>
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</tr>
<tr>
<td>grid cells in core:</td>
<td>depends on grid sensitivity analysis</td>
</tr>
<tr>
<td>grid studies planned:</td>
<td>Y</td>
</tr>
<tr>
<td>if not</td>
<td></td>
</tr>
<tr>
<td>initialisation method</td>
<td></td>
</tr>
<tr>
<td>if other, then specify</td>
<td>mean theoretical profile plus random noise or based on assumed spectrum</td>
</tr>
</tbody>
</table>

simulated parameter range

| max Reynolds ($\Gamma/\nu$): | $10^5$ |
| x/b range: | near field study of the vortices generated by flaps x/b < 1 |
| Tau* range: | not decided yet |
| flow turbulence | random noise or based on the assumed energy spectrum |

Topic specific information

The jet is simulated in non-dimensional form for the Reynolds number in range $2 \times 10^4$ - $10^5$

The parameters studied are: the temperature ratio of the jet and ambient air which varies in the range 1.0 - 2.0; the strength of the vortex and its distance from the jet will also vary.

Analysis of data will include comparison of mean/fluctuating quantities, spectral investigation will also be performed.

Further details

The SAILOR code has been widely used in computations of the jet in iso- and non-isothermal conditions with large temperature differences. The numerical solutions were compared with available experimental and numerical literature data. The results of the temporal simulations will be compared with the numerical data of Paoli et al. (Phys. Fluids, 2003)

Planning (specify month number (m1-m36) with respect to kick-off):

first CFD results reported: m12
all CFD results reported: 14 related DoW deliverable numbers

References

D2.1.2, TR2.1.2-2
**FAR-Wake** questionnaire for CFD activities

**Subtask:** 212  
**partner:** CERFACS

**Short description of the activity:**  
Simulations (LES) of hot jet/vortex interactions at high Reynolds numbers in same configurations as Subtask 2.1.1

**Purpose of the CFD study**

| parametric study | Y | validation against EXP | Y |

**Description of CFD method and its limitations**

- **CFD-code name:** NTMIX3D
- **CFD method(s):** LES
  - if other, specify: 3D
- **Boundary conditions:** Symmetric, Non-reflecting, Periodic
- **Discret. schemes:** 6th order Compact scheme for the discretisation in space  
  - 3rd order Rung Kutta method for the time integration
- **Turbulence models:** LES model: Filtered Structure Function
  - gridding strategy: stretched or uniform
  - max number gridcells: $301^2301^161$ (estimation)
  - gridcells in core: $n>10$
  - grid studies planned: Y
- **initialisation method**
  - other
  - if other, then specify: Lamb-Oseen vortex model

**Simulated parameter range**

<table>
<thead>
<tr>
<th>max Reynolds ($\Gamma/\nu$):</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>x/b range:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau^*$ range:</td>
<td>$t \sim 16 t_{eddy}$ ($t_{eddy} = 2 \pi rc/\nu_{max}$)</td>
<td></td>
</tr>
<tr>
<td>flow turbulence</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Topic specific information**

Parameters to be varied are: vortex and jet intensities/diameters, jet location/inclination and density ratio $S=r_j/ro$ between the jet flow and the ambient air.

**Further details**


**Planning (specify month number (m1-m36) with respect to kick-off):**

- first CFD results reported: m18
- all CFD results reported: m30  
  - related DoW deliverable numbers D2.1.2

**References**

### FAR-Wake questionnaire for CFD activities

**Subtask:** 212  
**partner:** ONERA/DMPH

**Short description of the activity:**
Simulations (DNS) of hot jet/vortex interactions at low Reynolds numbers in same configurations as Subtask 2.1.1

**Purpose of the CFD study**

- parametric study: Y
- validation against EXP: Y

**Description of CFD method and its limitations**

- CFD-code name: FLUDILES
- CFD method(s): DNS
- if other, specify: 3D
- Boundary conditions: Symmetric, Non-reflecting, Periodic
- Discret. schemes: 6th order Compact scheme for the discretisation in space, 3rd order Rung Kutta method for the time integration
- Turbulence models: stretched or uniform
- max number gridcells: 327*327*61 (estimation)
- gridcells in core: n~10
- grid studies planned: N
- if not initialisation method: other
- if other, then specify: Lamb-Oseen vortex model

**Simulated parameter range**

- max Reynolds (Γ/ν): 5000
- x/b range: 
- Tau* range: t ~ 210 tv (tv = 2 rc/vqmax)

**Flow turbulence**

**Further details**

- **Planning (specify month number (m1-m36) with respect to kick-off):**
  - first CFD results reported: m18
  - all CFD results reported: m30
  - related DoW deliverable numbers: D2.1.2

**References**

FAR-Wake questionnaire for EXPERimental activities

Subtask number: 212  partner: ONERA/DAFE

Short description of the activity:
Experiment in F2 Wind tunnel on the following configuration: interaction between a hot jet and a vortex

existing EXP data? N
Source of existing data

experimental parameter range (expected):
- test medium: air
- average kinematic viscosity: 0.000014 [m2/s]
- maximum test velocity: 75 [m/s]
- simulated wingspan: 0.5 [m]
- simulated wingchord: 0.125 [m]
- typical lift coefficient (CL): 1 [-]
- x/b range (downstream): 3 [-]

Type of facility:
- wind tunnel Y
- water tunnel N
- field trials (real aircraft) N

Simulated jets:
- jet diameter (10 mm)
- jet temperature (600°K)

Measurements:
- pressure probe (traverses): N
- hotwire: Y
- LDA: Y
- LIDAR: N
- Flow visualisation: N
- PIV (2C): N
- PIV (3C): N
- expected grid resolution (Dy,Dz): (, ) [mm]
- Thermocouple Y

Planning (specify month number m1-m36 with respect to kick-off):
- model available: m3
- first analysis reported: m18
- first tests completed: m7
- all analysis finished/reported: m30
- final tests completed: m8
- related DoW deliverable numbers D2.1.2

Further details of model and test set-up

All the stability analyses (hot jet / single vortex and vortex with temperature variations) are replaced by this new experiment.

References
main references of previous work, using same test set-up or techniques
**FAR-Wake** questionnaire for CFD activities

Subtask: 221  
Partner: DLR

**Short description of the activity:**  
*Numerical simulation of an high-lift configuration (AIRBUS TAK-model) to investigate the effect of fuselage wake on the wake vortex system*

**Purpose of the CFD study**  
parametric study  
validation against EXP  
Y

**Description of CFD method and its limitations**

<table>
<thead>
<tr>
<th>CFD-code name:</th>
<th>DLR TAU</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFD method(s):</td>
<td>RANS</td>
</tr>
<tr>
<td>if other, specify:</td>
<td></td>
</tr>
<tr>
<td>calc. method:</td>
<td>3D</td>
</tr>
<tr>
<td>Boundary conditions:</td>
<td>Farfield, Symmetrie, SlipWall</td>
</tr>
<tr>
<td>Discret. schemes:</td>
<td>Central</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Turbulence models:</th>
<th>k-w SST</th>
</tr>
</thead>
<tbody>
<tr>
<td>gridding strategy:</td>
<td>unstructured</td>
</tr>
<tr>
<td>max number gridcells:</td>
<td>about 10^6</td>
</tr>
<tr>
<td>gridcells in core:</td>
<td>unknown</td>
</tr>
<tr>
<td>grid studies planned:</td>
<td>Y</td>
</tr>
<tr>
<td>if not</td>
<td></td>
</tr>
<tr>
<td>initialisation method</td>
<td>none</td>
</tr>
</tbody>
</table>

**Simulated parameter range**

<table>
<thead>
<tr>
<th>max Reynolds (Γ/ν):</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>x/b range:</td>
<td>about 1</td>
</tr>
<tr>
<td>Tau* range:</td>
<td>-</td>
</tr>
</tbody>
</table>

flow turbulence: *only in turbulence model due to (mue_t/mue_l)init*

**Topic specific information**

Configuration: complete half-model (with peniche), Tunnel Re-number  
full-model, Tunnel Re-number  
full-model, Flight Re-number  
multi-vortex systems: as it run from the aircraft  
simulated ground effect: maybe simulate the wind-tunnel floor/walls to get the right ground effect

**Further details**

Turbulence: using turbulence-models (kw-SST, Spalart-Allmaras), initialisation: free-stream values  
TAU: validated for this type of configurations, not in detail validated for vortex flows,  
but this task should increase this part

**Planning (specify month number (m1-m36) with respect to kick-off):**

first CFD results reported:  
all CFD results reported: related DoW deliverable numbers

**References**

main references of previous related CFD work by your institute
**FAR-Wake questionnaire for CFD activities**

**Subtask:** 221  
**partner:** CENAERO

**Short description of the activity:**

*Effect of the fuselage on wake vortex:*

The precise influence of the aircraft fuselage on the development of the vortex wake system will be studied. The goal is to study in detail the effect of the wake turbulence generated by the fuselage on the roll-up/formation of the aircraft vortex wake.

**Purpose of the CFD study**

<table>
<thead>
<tr>
<th>parametric study</th>
<th>validation against EXP</th>
<th>Y</th>
</tr>
</thead>
</table>

**Description of CFD method and its limitations**

<table>
<thead>
<tr>
<th>CFD-code name:</th>
<th>NA</th>
<th>NA = Not Applicable</th>
</tr>
</thead>
<tbody>
<tr>
<td>if other, specify:</td>
<td>RANS or/and LES</td>
<td></td>
</tr>
<tr>
<td>calc. method:</td>
<td>3D steady or unsteady</td>
<td></td>
</tr>
<tr>
<td>Boundary conditions:</td>
<td>Finite Volume Discretization</td>
<td></td>
</tr>
<tr>
<td>Discret. schemes:</td>
<td>RANS: Roe’s approximate Riemann solver (linear reconstruct. of variables)</td>
<td></td>
</tr>
<tr>
<td>LES: Kinetic energy discretization of the convective term (central scheme)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbulence models:</td>
<td>RANS: Spalart-Allmaras</td>
<td></td>
</tr>
<tr>
<td>LES: Wale model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>gridding strategy:</td>
<td>Unstructured (tetrahedra)</td>
<td></td>
</tr>
<tr>
<td>max number gridcells:</td>
<td>50 (10^3) nodes per processor</td>
<td></td>
</tr>
<tr>
<td>grid cells in core:</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>grid studies planned:</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>if not:</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>initialisation method:</td>
<td>Uniform field</td>
<td></td>
</tr>
<tr>
<td>if other, then specify:</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>initial core sizes:</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>axial flow profile:</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>inverse Swirl number:</td>
<td>NA</td>
<td></td>
</tr>
</tbody>
</table>

**Simulated parameter range**

| max Reynolds (\(\Gamma/\nu\)): | NA |
| x/b range: | NA |
| Tau* range: | NA |
| flow turbulence: | NA |

**Topic specific information**

Numerical simulations (RANS or Hybrid RANS-LES) to investigate the effect of fuselage wake on the wake vortex system. The simulations will be performed on the Airbus-TAK four-engine large transport aircraft geometry. This one will be built up in successive steps: first, the fuselage only, second, the fuselage plus the wings, third, the complete aircraft with horizontal tail plane.

**Further details**

The RANS methodology for unstructured grids was extensively validated on a wide range of benchmarks. The Spalart-Allmaras is implemented in the CENAERO code following the same methodology. The LES methodology, applying non-dissipative central schemes, is validated on the turbulent flow past a sphere at a Reynolds number of 10,000. This geometry, yet simple, generates a complex flow physics which is very complicated to captured.

**Planning (specify month number (m1-m36) with respect to kick-off):**

| first CFD results reported: | M4+4 |
| all CFD results reported: | M12+4 |

**References**

### FAR-Wake questionnaire for EXPERimental activities

<table>
<thead>
<tr>
<th>Subtask number: 222</th>
<th>partner: TUM</th>
</tr>
</thead>
</table>

#### Short description of the activity:
Systematic survey of flow behind wing elements and influence of landing gear applying hotwire anemometry

- **existing EXP data?** Y (baseline data)
- **Source of existing data** AWIATOR
- **Confid. Restrictions** Y

#### Experimental parameter range (expected):
- **type of facility:**
  - test medium: air
  - average kinematic viscosity: $17 \times 10^{-6}$ [m²/s] (waternnel) N
  - maximum test velocity: 25.0 [m/s]
  - simulated wingspan: 2.982 [m]
  - simulated wingchord (mac): 0.3569 [m]
  - typical lift coefficient (CL): 1.4 [-]
  - x/b range (downstream): 5 [-]

- **topic specific information**

- **measurements**:
  - pressure probe (traverses): N
  - hotwire (traverses): Y
  - PIV (2C): N
  - PIV (3C): Y (optional)
  - LIDAR: N
  - PIV (3C): Y (optional)

- **planning**
  - model available: m3
  - first analysis reported: m18
  - first tests completed: m11
  - all analysis finished/reported: m30
  - final tests completed: m27

- **Further details of model and test set-up**

- **TAK model**: half model configuration, 1:19.25 scale
- **four engine large transport aircraft model, through flow nacelles (TFN), horizontal tail, winglet**

- **Model configuration**:
  - approach, AoA: 7 deg, Horizontal tail: -6 deg
  - Slat (deg) - i/b, m/b, o/b: 19.6, 23.0, 23.0; flap (deg) - i/b, o/b: 26.0, 26.0; aileron (deg): 5
  - x/b stations: 0.37, (1.0), (2.0), 3.0, (4.0), (4.5), 4.9

- **Normalised spatial resolution**: Dy/b: 0.0050, Dz/b: 0.0034

- **Recording mean flow field velocity components u, v, and w and flow field velocity fluctuations u' u', v' v', w' w', u'v', u'w', and v'w' (Reynolds stresses), statistics and spectral densities.**

- **References**


**FAR-Wake questionnaire for CFD activities**

| Subtask: 222 | partner: UCL | Activity 6 |

**Short description of the activity:**

Wake generated by wing elements

Numerical simulations (time developing) of wake vortex roll-up from flow emanating from wing with velocity deficit, due to boundary layer on wing.

**Purpose of the CFD study**

- parametric study
- validation against EXP

**Description of CFD method and its limitations**

| CFD-code name: | NA |
| CFD method(s): | LES |
| if other, specify: | |
| calc. method: | 3D temporal |
| Boundary conditions: | Unbounded boundary conditions + longitudinal periodicity (VIC-FMM) |
| | Fully periodic boundary conditions (parallel spectral code) |
| Discret. schemes: | Parallel Vortex In-Cell and fast multipole methods (VIC-FMM) |
| | Parallel spectral code: Fourier expansions of velocity field. |
| Turbulence models: | Various (e.g.: hyper-viscosity, modified Smagorinsky (WALE), etc.) |
| gridding strategy: | Uniform (both VIC-FMM and parallel spectral code) |
| max number gridcells: | 20 to 80 millions of VIC grid points |
| gridcells in core: | 6-8 / diameter (targeted but depends of roll-up process) |
| grid studies planned: | Yes |
| if not initialisation method | Other |
| if other, specify: | Span loading and boundary layer velocity deficit (cf. further details) |
| initial core sizes | NA |
| axial flow profile | NA |
| inverse Swirl number | NA |

**simulated parameter range**

<table>
<thead>
<tr>
<th>Simulated parameter</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>max Reynolds (Γ/ν)</td>
<td>According to experimental measurements</td>
</tr>
<tr>
<td>x/b range:</td>
<td>NA</td>
</tr>
<tr>
<td>Tau* range:</td>
<td>Max. of about 10</td>
</tr>
<tr>
<td>flow turbulence</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Topic specific information**

The objective is to study the effects of boundary layer velocity deficits on the formation of the wake vortices, possibly showing new instability mechanisms.

**Further details**

Near field from theoretical model of an elliptically loaded wing to which a boundary layer-type momentum deficit will be added. Boundary layer velocity profiles (momentum deficit) to be based on turbulent boundary layer estimates.

**Planning (specify month number (m1-m36) with respect to kick-off):**

- first CFD results reported: m24
- all CFD results reported: m30 related DoW deliverable numbers D2.2.2-2

**References**


Reports on roll-up simulations done in the ongoing European project AWIATOR (T1.1.4)
**FAR-Wake** questionnaire for EXPERimental activities

**Subtask number:** 222  **partner:** IRPHE

**Short description of the activity:**

Wind tunnel experiments on the effect of a bluff-body wing-tip device (cylinder) on wake vortex structure and stability

<table>
<thead>
<tr>
<th>existing EXP data?</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source of existing data</td>
<td>see right</td>
</tr>
</tbody>
</table>

**experimental parameter range (expected):**

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>test medium</td>
<td>air</td>
</tr>
<tr>
<td>average kinematic viscosity</td>
<td>1.50E-05 [m²/s]</td>
</tr>
<tr>
<td>maximum test velocity</td>
<td>60 [m/s]</td>
</tr>
<tr>
<td>simulated wingspan</td>
<td>~0.8 [m]</td>
</tr>
<tr>
<td>simulated wingchord</td>
<td>0.2 [m]</td>
</tr>
<tr>
<td>typical lift coefficient (CL)</td>
<td>[-]</td>
</tr>
<tr>
<td>x/b range (downstream)</td>
<td>4 [-]</td>
</tr>
</tbody>
</table>

**Topic specific information**

The flow considered is a pair of co- or counterrotating vortices with axial flow, generated by a flapped wing. The characteristics are:

- $Re \sim 100000$, axial velocity defect: \(\sim 20-40\%\), "realistic" two-scale velocity profiles
- core radius / separation distance \(\sim 10 \text{ mm} / 75 \text{ mm} \sim 0.1-0.15\)

Cylindrical devices of different diameters (up to 5% of chord) and lengths (up to 40% of chord) can be placed at different positions near the wing or flap tips.

**Measurements:**

<table>
<thead>
<tr>
<th>measurement</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure probe (traverses)</td>
<td>Y</td>
</tr>
<tr>
<td>PIV (2C)</td>
<td>N</td>
</tr>
<tr>
<td>PIV (3C)</td>
<td>N</td>
</tr>
<tr>
<td>Flow visualisation</td>
<td>Y</td>
</tr>
<tr>
<td>expected grid resolution (Dy,Dz)</td>
<td>(1-2,1-2) [mm]</td>
</tr>
</tbody>
</table>

**Planning (specify month number m1-m36 with respect to kick-off):**

<table>
<thead>
<tr>
<th>task</th>
<th>month</th>
</tr>
</thead>
<tbody>
<tr>
<td>model available</td>
<td>m4</td>
</tr>
<tr>
<td>first analysis reported</td>
<td>m9</td>
</tr>
<tr>
<td>first tests completed</td>
<td>m8</td>
</tr>
<tr>
<td>all analysis finished/reported</td>
<td>m24</td>
</tr>
<tr>
<td>final tests completed</td>
<td>m23</td>
</tr>
<tr>
<td>related DoW deliverable numbers</td>
<td>TR2.2.2-4</td>
</tr>
</tbody>
</table>

**Further details of model and test set-up**

The flow is generated by a symmetric rectangular NACA0018 wing profile (half-model) of chord 20 cm and (half-)span 40 cm (=b/2), equipped with a symmetric flap over 32 cm. 3-component hot-wire measurements of velocity profiles and spectra can be made between x/b=0.5 and x/b=3.5 (between 5 and 35 vortex spacings) downstream of the trailing edge.

**References**

Related work includes:

Appendix C  Overview of work, parameter ranges and planning for Task 3.1: Dynamics and decay in idealised conditions

**FAR-Wake questionnaire for EXperimental activities**

<table>
<thead>
<tr>
<th>Subtask number:</th>
<th>311</th>
<th>Partner:</th>
<th>IRPHE</th>
</tr>
</thead>
</table>

**Short description of the activity:**

Water tank experiments on the dynamics and 3D instabilities of vortex pairs near the ground existing EXP data? Y

Source of existing data Master Thesis of Cornell Universi
Confid. Restrictions

**Experimental parameter range (expected):**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test medium</td>
<td>water</td>
<td>windtunnel</td>
</tr>
<tr>
<td>Average kinematic viscosity</td>
<td>1.00E-06 [m2/s]</td>
<td>water tank</td>
</tr>
<tr>
<td>Maximum test velocity</td>
<td>NA [m/s]</td>
<td>field trials (real aircraft)</td>
</tr>
<tr>
<td>Simulated wingspan</td>
<td>NA [m]</td>
<td>flow turbulence level in facility</td>
</tr>
<tr>
<td>Simulated wingchord</td>
<td>NA [m]</td>
<td>T(z) profile (deg K) measured?</td>
</tr>
<tr>
<td>Typical lift coefficient (CL)</td>
<td>NA [-]</td>
<td>~0</td>
</tr>
<tr>
<td>x/b range (downstream)</td>
<td>NA [-]</td>
<td>cross-section dims. of facility [f/b] (50cm)*5</td>
</tr>
</tbody>
</table>

**Topic specific information**

The flow under consideration is a pair of uniform counter-rotating laminar vortices without axial flow, approaching a wall in the normal direction. The main parameters are:

Re = 1000 - 10000; core size / separation distance = 0.1 - 0.25; initial height / separation distance = 2 - 5.

Velocity profiles are Gaussian for low Reynolds numbers and close to the Jacquin 2-scale model for higher Re. Evolution can be followed up to tau* ~10.

**Measurements:**

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure probe (traverses)</td>
<td>N</td>
</tr>
<tr>
<td>PIV (2C)</td>
<td>Y</td>
</tr>
<tr>
<td>PIV (3C)</td>
<td>(Y)</td>
</tr>
<tr>
<td>Flow visualisation</td>
<td>Y</td>
</tr>
<tr>
<td>Expected grid resolution (Dμ,Dz)</td>
<td>(&lt;1,&lt;1) [mm]</td>
</tr>
</tbody>
</table>

**Planning (specify month number m1-m36 with respect to kick-off):**

<table>
<thead>
<tr>
<th>Planning</th>
<th>Month</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model available</td>
<td>m8</td>
</tr>
<tr>
<td>First analysis reported</td>
<td>m11</td>
</tr>
<tr>
<td>First tests completed</td>
<td>m10</td>
</tr>
<tr>
<td>All analysis finished/reporting</td>
<td>m18</td>
</tr>
<tr>
<td>Final tests completed</td>
<td>m12</td>
</tr>
<tr>
<td>Related DoW deliverable numbers</td>
<td>TR3.1.1-4</td>
</tr>
</tbody>
</table>

**Further details of model and test set-up**

The vortex pairs are generated by impulsively rotating two flat plates from rest inside a water tank. Low-amplitude sinusoidal perturbations can be added to the plate edges, in order to force different wavelengths and/or phases of the Crow instability.

Light-sheet or full-volume flow visualisation is achieved using florescent dye illuminated by laser light. Velocity fields are measured by Particle Image velocimetry.

**References**

A similar set-up was used in the following studies:


**FAR-Wake questionnaire for CFD activities**

**Subtask:** 311  
**partner:** CENAERO

**Short description of the activity:**
Longitudinally uniform wakes

Characterisation of the development of intrinsic 3D instabilities in two- or four- vortex systems near the ground with LES calculations. Numerical studies to investigate the effect of cross wind, head wind, mixed wind and the ground roughness on vortex evolution and decay

**Purpose of the CFD study**
parametric study

**Description of CFD method and its limitations**

<table>
<thead>
<tr>
<th>Validation against EXP</th>
<th>Y</th>
<th>N</th>
</tr>
</thead>
</table>

**CFD-code name:** NAPALM

**CFD method(s):** LES

**calc. method:** 3D unsteady

**Boundary conditions:** Fourth order central finite differences with good conservation properties (kinetic energy) and incompressible flow solver

**Discret. schemes:**

- Smagorinsky, WALE
- Dynamic Smagorinsky

**Turbulence models:**

- Multiblock stretched structured meshes

**gridding strategy:**

- Initialisation method: To be determined
- initial core sizes: To be determined
- axial flow profile: To be determined
- inverse Swirl number: To be determined

**max number gridcells:** 2.000.000 nodes per processor

**gridcells in core**

<table>
<thead>
<tr>
<th>To be determined</th>
</tr>
</thead>
</table>

**grid studies planned:**

<table>
<thead>
<tr>
<th>To be determined</th>
</tr>
</thead>
</table>

**if not**

<table>
<thead>
<tr>
<th>To be determined</th>
</tr>
</thead>
</table>

**initialisation method**

<table>
<thead>
<tr>
<th>To be determined</th>
</tr>
</thead>
</table>

**if other, then specify**

<table>
<thead>
<tr>
<th>To be determined</th>
</tr>
</thead>
</table>

**Turbulence models**

<table>
<thead>
<tr>
<th>Smagorinsky, WALE</th>
</tr>
</thead>
</table>

- Dynamic Smagorinsky

<table>
<thead>
<tr>
<th>Fourth order central finite differences with good conservation properties (kinetic energy) and incompressible flow solver</th>
</tr>
</thead>
</table>

**simulated parameter range**

<table>
<thead>
<tr>
<th>max Reynolds ($\eta/\eta$): To be determined</th>
</tr>
</thead>
<tbody>
<tr>
<td>x/b range: To be determined</td>
</tr>
<tr>
<td>Tau* range: To be determined</td>
</tr>
<tr>
<td>flow turbulence: To be determined</td>
</tr>
</tbody>
</table>

**Topic specific information**

Investigate wake vortex evolution “in ground effect” (IGE) under idealised and controlled computational LES conditions. Characterise and understand the principal physical mechanisms and instabilities as the wake vortices interact viscously with a rigid wall (ground) and the resulting opposite signed vortices. Obtain relevant information about the effect of wind conditions and ground roughness on wake vortex evolution IGE situations.

**Further details**

The LES methodology was validated on different benchmarks: taylor-green vortices, channel flow, fourth vortex system. The development is followed by the UCL group of G. Winckelmans: in particular, the validation of the WALE model implementation and the dynamic procedure.

**Planning (specify month number (m1-m36) with respect to kick-off):**

<table>
<thead>
<tr>
<th>first CFD results reported: M12</th>
</tr>
</thead>
<tbody>
<tr>
<td>all CFD results reported: M24</td>
</tr>
</tbody>
</table>

**References**

- Georges L.: “Développement d’un code numérique parallèle en différences finies de haut ordre pour la simulation directe ou des grandes échelles d’écoulements turbulents avec paroi” DEA, Université catholique de Louvain (2004)
- Related deliverables D.311-3 and D.311-4
**FAR-Wake questionnaire for CFD activities**

**Subtask:** 311  
**partner:** UCL  
**Activity 7**

**Short description of the activity:**

*Longitudinally uniform wakes*

Span loading evaluation and numerical simulations in 2-D of wake roll-up in ground effects.

---

**Purpose of the CFD study**

<table>
<thead>
<tr>
<th>parametric study</th>
<th>validation against EXP</th>
<th>N</th>
</tr>
</thead>
</table>

**Description of CFD method and its limitations**

| CFD-code name | NA |
| CFD method(s) | Other |
| if other, specify | Span-loading model + DNS/RANS |
| calc. method | 2D temporal |
| Boundary conditions | Unbounded domain + rigid wall (no-slip) |
| Discret. schemes | Parallel Vortex In-Cell and fast multipole methods (VIC-FMM) |
| Turbulence models | Effective turbulent viscosity |
| Possibly: clipped tensor diffusivity model (tbd) | |

| gridding strategy | NA |
| max number gridcells | |
| grid studies planned | Y |
| if not | |
| initialisation method | Other |
| if other, then specify | Field from span loading model IGE |
| initial core sizes | NA |
| axial flow profile | NA |
| inverse Swirl number | NA |

**simulated parameter range**

| max Reynolds ($\Gamma/\nu)$ | $10^6 - 10^7$ |
| x/b range | NA |
| Tau* range | Tbd according to initial height of WV system and interaction with ground flow turbulence |
| NA | |

**Topic specific information**

Span loading NGE/IGE obtained using a modified "lifting line" theory to account for image vortex system below ground.  
Model of span loading NGE/IGE will serve to determine initial condition for the 2-D simulations to study wake roll-up and resulting wake vortex system topology.

---

**Further details**

Parameters to be varied include span loading, initial height, and Reynolds number.

**Planning (specify month number (m1-m36) with respect to kick-off):**

| first CFD results reported | m6 |
| all CFD results reported | m8 |

related DoW deliverable numbers D3.1.1-1

**References**


### FAR-Wake questionnaire for CFD activities

**Subtask:** 311  
**partner:** UCL  
**Activity 8**

**Short description of the activity:**

Longitudinally uniform wakes  
Numerical simulations (time developing) of intrinsic 3-D instabilities development in two- and four-vortex systems near the ground.

**Purpose of the CFD study**

| parametric study | validation against EXP | N |

| Description of CFD method and its limitations |

- **CFD-code name:** NA  
- **CFD method(s):** Euler / inviscid vorticity equation  
- **calc. method:** 3D temporal  
- **Boundary conditions:** Unbounded conditions with periodicity in filament's direction + slip wall  
- **Discret. schemes:** Lagrangian vortex filament method  
- **Turbulence models:** None  
- **gridding strategy:** Uniform initial distribution of nodes along each filament  
- **max number gridcells:** Maximum number of nodes ~2000  
- **grid cells in core:** 1 filament to represent each vortex tube  
- **grid studies planned:** None  
- **if not initialisation method:** Analytical condition on ratio between node separation and vortex core size  
- **initial core sizes:** $r_c/b \sim 0.05$  
- **axial flow profile:** NA  
- **inverse Swirl number:** NA  

**Simulated parameter range**

- **max Reynolds ($\Gamma/\nu$):** Inviscid simulations  
- **x/b range:** NA  
- **Tau* range:** Max.: up to reconnection time  
- **flow turbulence:** No  

**Topic specific information**

Effect of initial height of vortex system and configuration of multiple vortex system configuration.  
Longitudinal periodicity length to be set at one equivalent Crow long wavelength for uniform WV

**Further details**

Instabilities triggered by random small scale perturbation of filament's node coordinates.  
Characterisation of most unstable wavelength and corresponding growth rate.

**Planning (specify month number (m1-m36) with respect to kick-off):**

- first CFD results reported: $m12$  
- all CFD results reported: $m18$  

**Related DoW deliverable numbers D3.1.1-2**

**References**

FAR-Wake questionnaire for CFD activities

Subtask: 311  
partner: IMFT-UPS

Short description of the activity:
Longitudinally uniform wakes
3D instabilities in two and four vortex systems near the ground.
Numerical studies on the effects of cross wind, head wind, and mixed wind with smooth ground.

Purpose of the CFD study
parametric study  
validation against EXP

Description of CFD method and its limitations

CFD-code name: JADIM
CFD method(s): LES
if other, specify:
calc. method: 3D unsteady
Boundary conditions:
Discret. schemes: second order in space and RK3 in time

Turbulence models: ZANG dynamic mixed model
gridding strategy: stretched structured grid
max number gridcells: from 17 to 34 millions of grid points
gridcells in core: To be determined
grid studies planned: N
if not
initialisation method: To be determined
if other, then specify:
initial core sizes: To be determined
axial flow profile: To be determined
inverse Swirl number: To be determined

simulated parameter range
max Reynolds ($\text{Re}$):
To be determined
x/b range:
To be determined
$\tau^*$ range:
To be determined
flow turbulence:
To be determined

Topic specific information
For the case of co-rotating and unequal two-vortex system (tip + flap) and the case of four-vortex system (the same as investigated experimentally by DLR) we plan to investigate the mechanisms of merging, the onset and amplification of instabilities in the situation of interaction with the ground and viscous creation of opposite sign vortices. Concerning the influence of wind, numerical studies of head, cross, and mixed winds will be performed with atmospheric boundary layer velocity profiles and turbulence on smooth ground.

Further details
The LES code has been extensively validated at IMFT in boundary layers and vortex dynamics situations.

Planning (specify month number (m1-m36) with respect to kick-off):
first CFD results reported: m15
all CFD results reported: m24  
related deliverable D3.1.1-3 & D3.1.1-4

References
**FAR-Wake questionnaire for CFD activities**

**Subtask:** 311  
**partner:** IST

**Short description of the activity:**  
Stochastic solution of Navier-Stokes equations applied to vortex-pair near the ground under cross wind

**Purpose of the CFD study**  
parametric study \( Y \)  
validation against EXP \( N \)

**Description of CFD method and its limitations**

- **CFD-code name:** own IST code
- **CFD method(s):** DNS-2D
- **calc. method:** 2 D SPACE-TIME
- **Discret. schemes:** CENTRAL DIFFERENCE, Runge KUTTA Runge Kutta-4
- **Turbulence models:** cartisian-ORTHOGONAL
- **max number gridcells:** 512*2048
- **gridcells in core:** 6
- **grid studies planned:** \( Y \)
- **initialisation method:** OTHER
- **initial core sizes:** \( rc=3, b=24 \)
- **axial flow profile:** 2D
- **inverse Swirl number:** 2D
- **simulated parameter range**
  - **max Reynolds (\( \nu \)/):** 2D
  - **x/b range:** 2D
  - **\( \tau^* \) range:** 120 s
  - **flow turbulence:** VISCOSITY IS A Gaussian RANDOM FUNCTION

**Topic specific information**

- especially required for the tests mentioned below:
  - **simulated jets:** jet diameter, velocity, temperature range, positions, jet direction, swirl, etc.
  - **dynamic tests:** amplitude, frequency range, etc.
  - **multi-vortex systems:** spacing \( b1/b2 \), strengths \( \Gamma1/\Gamma2 \), etc.
  - **simulated ground effect:** height above ground, etc. 150 m

**Further details**

- Validation against analytical solutions of model equations. Studies on convergence of the series of the polynomial chaos expansion that describe the stochastic processes

**Planning (specify month number (m1-m36) with respect to kick-off):** D3.1.1-4

- first CFD results reported: m6
- all CFD results reported: m14

**References**

**FAR-Wake questionnaire for CFD activities**

**Subtask:** 312  
**Partner:** UCL  
**Activity:** 9

**Short description of the activity:**  
Spatially-evolving wake

**Purpose of the CFD study**  
parametric study  
validation against EXP  
N

**Description of CFD method and its limitations**

- **CFD-code name:** NA  
- **CFD method(s):** LES  
- **calc. method:** 3D spatial  
- **Boundary conditions:** Unbounded boundary conditions + generic inflow condition + zero normal gradient outflow  
- **Discret. schemes:** Parallel Vortex In-Cell and fast multipole methods (VIC-FMM)  
- **Turbulence models:** Various (e.g.: hyper-viscosity, modified Smagorinsky (WALE), etc.)  
- **gridding strategy:** Uniform  
- **max number gridcells:** 20 to 80 millions of VIC grid points  
- **gridcells in core:** 6-8 / diameter  
- **grid studies planned:** Y

**initialisation method**  
Other  
Initial analytical WV configurations (VM2 and/or low-order algebraic core function)  
Initial core sizes  
$r_c/b \sim 0.05$  
Axial flow profile  
NA  
Inverse Swirl number  
NA

**simulated parameter range**

- **max Reynolds ($\Gamma/\nu$):** $10^6 - 10^7$  
- **x/b range:** cf. details  
- **Tau* range:** flow turbulence

**Further details**

Wing modelled using unsteady lifting line.  
Viscous ground effects will be taken into account.  
Longitudinal extent of computational domain fixed; effective x/b value considered will be as large as possible. It also depends on inflow condition and free stream velocity.

**Planning (specify month number (m1-m36) with respect to kick-off):**

- first CFD results reported: m19  
- all CFD results reported: m24  
- related DoW deliverable numbers: D.3.1.2

**References**


Cocle, R., Simulation of high Reynolds number flows using an efficient combination of vortex-in-cell and fast multipole methods. PhD thesis (in preparation), Université catholique de Louvain (UCL), Louvain-la-Neuve, Belgium
### FAR-Wake questionnaire for EXPerimental activities

#### Subtask number: 312  
**Partner:** UCL  
**Activity 10**

#### Short description of the activity:
Spatially-evolving wake  
Visualisations of two-vortex systems produced by a generic wing model towed at a constant altitude in a water tank.

<table>
<thead>
<tr>
<th>existing EXP data?</th>
<th>Y</th>
<th>Source of existing data</th>
<th>Confid. Restrictions</th>
<th>N</th>
</tr>
</thead>
</table>

#### experimental parameter range (expected):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>test medium</td>
<td>Water</td>
<td>windtunnel</td>
</tr>
<tr>
<td>average kinematic viscosity</td>
<td>10E-6 [m2/s]</td>
<td>watertunnel</td>
</tr>
<tr>
<td>maximum test velocity</td>
<td>3 [m/s]</td>
<td>water towing tank</td>
</tr>
<tr>
<td>simulated wingspan</td>
<td>0.2 - 0.35 [m]</td>
<td>field trials (real aircraft)</td>
</tr>
<tr>
<td>simulated wingchord</td>
<td>0.03 - 0.05 [m]</td>
<td>T(z) profile (deg K) measured</td>
</tr>
<tr>
<td>typical lift coefficient (CL)</td>
<td>0.4 - 0.5 [-]</td>
<td>flow turbulence level in facility</td>
</tr>
<tr>
<td>x/b range (downstream)</td>
<td>NA [-]</td>
<td>cross-section dims. of facility [lb]</td>
</tr>
</tbody>
</table>

#### Topic specific information

* A parametric study of the altitude track (in the range of z/b from 0.5 to 0.2) will be done.

#### Measurements:

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pressure probe (traverses)</td>
<td>N</td>
</tr>
<tr>
<td>PIV (2C)</td>
<td>N</td>
</tr>
<tr>
<td>PIV (3C)</td>
<td>N</td>
</tr>
<tr>
<td>Flow visualisation</td>
<td>Y</td>
</tr>
<tr>
<td>expected grid resolution (Dy,Dz)</td>
<td>( , ) [mm]</td>
</tr>
</tbody>
</table>

#### Planning (specify month number m1-m36 with respect to kick-off):

<table>
<thead>
<tr>
<th>Planning</th>
<th>m1-m36</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>model available</td>
<td>m14</td>
<td>first analysis reported: m18</td>
</tr>
<tr>
<td>first tests completed</td>
<td>m15</td>
<td>all analysis finished/reported: m24</td>
</tr>
<tr>
<td>final tests completed</td>
<td>m22</td>
<td>related DoW deliverable numbers D3.1.2</td>
</tr>
</tbody>
</table>

#### Further details of model and test set-up

The towing tank is a 12 x 1 x 1 [m].  
The wing models will be rectangular NACA 0012 with an aspect ratio of about 7. The present one has b=0.36 m. We expect to build a new one with b=0.2 m, so as to reduce the side effects due to the lateral walls of the towing tank.  
2-D visualisations will be done using the Laser Induced Fluorescence (LIF) method.  
3-D visualisations will be done using a Black Light method (cf. references).

#### References

Desenfans, O. & Gigantelli, S. 2004 Instabilities of wake vortices with fast deceleration: investigation in a towing tank, Graduation thesis for Mechanical Engineer degree, Université catholique de Louvain (UCL), Louvain-la-Neuve, Belgium
**FAR-Wake** questionnaire for EXPerimental activities

**Subtask number:** 312  
**partner:** DLR

**Short description of the activity:**
*Towing tank PIV measurements on 2- and 4-vortex systems IGE*

*existing EXP data?*  N

**Source of existing data**  

**experimental parameter range (expected):**  

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected Value</th>
<th>Type of facility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test medium</td>
<td>water</td>
<td>watertunnel</td>
</tr>
<tr>
<td>Average kinematic viscosity</td>
<td>$1e-06$ [m²/s]</td>
<td>watertunnel</td>
</tr>
<tr>
<td>Maximum test velocity</td>
<td>3.0 [m/s]</td>
<td>water towing tank</td>
</tr>
<tr>
<td>Simulated wingspan</td>
<td>0.3 [m]</td>
<td>field trials (real aircraft)</td>
</tr>
<tr>
<td>Simulated wingchord</td>
<td>0.05 [m]</td>
<td>T(z) profile (deg K) measured?</td>
</tr>
<tr>
<td>Typical lift coefficient (CL)</td>
<td>1.1 [-]</td>
<td>Flow turbulence level in facility</td>
</tr>
<tr>
<td>X/b range (downstream)</td>
<td>0 - ca. 80 [-]</td>
<td>Cross-section dims. of facility [b]</td>
</tr>
</tbody>
</table>

**Topic specific information**

*Using towing tank measurements by means of Stereo PIV wake-vortices are investigated in ground effect. The utilized model (F13) is able to generate a 2- or 4 vortex system.*

*A broad range of vortex spacing b1/b2 and strength Gamma1/Gamma2 are achieved by exchangeable horizontal tip wings. The towing tank will be equipped with a plate simulating a flat ground.*

**Measurements:**

- Pressure probe (traverses): N
- Hotwire: N
- PIV (2C): N
- LDA: N
- Flow visualisation: Y
- Model forces: Y

**Expected grid resolution (Dy,Dz):** (3-6, 3-5) [mm]

**Planning (specify month number m1-m36 with respect to kick-off):**

- Model available: m16
- First analysis reported: m24
- First tests completed: m16
- All analysis finished/reported: m24
- Final tests completed: m16
- Related DoW deliverable numbers: TR 312-2

**Further details of model and test set-up**

*Instantaneous velocity data is obtained in planes perpendicular to the flight path of the model. For the investigations of the instabilities of a 4-vortex system selected cases in the range of b1/b2 from 0.3 to 0.4 and Gamma1/Gamma2 from -0.3 to -0.6 are chosen.*

**References**


Appendix D  Additional information on test set-ups given by some partners

Main parameters of experimental set-up:
• nozzle area contraction ratio – 144
• turbulence intensity at the nozzle exit < 0.3%
• Reynolds number up to 20,000
• density ratio: S = 0.5-1
• boundary layer thickness: D/θ = 40-180

Measuring equipment:
• hot- wire anemometer – 55M-DISA
• LDV – DANTEC – forward scatter mode

Fig. D.1  Hot jet experimental facility of Czestochowa University (CUT)

Fig. D.2  Dimensions of the Delft University Towing Tank
Fig. D.3  Dimensions of model and towing tank (TU-Delft)

Fig. D.4  PIV laser sheet arrangement in towing tank (TU-Delft)
Fig. D.5  DLR-F13X model to be tested in windtunnel C of TUM-FLM

Fig. D.6  TAK model in windtunnel C (TUM-FLM)
Fig. D.7  Experimental Facility 1  Open Section Wind Tunnel (University Bath)

Fig. D.8  Model to be tested by University Bath
Fig. D.9  Experimental Facility 2  Closed Section Wind Tunnel (university Bath)

Fig. D.10  Model to be tested in Facility 2 (university Bath)
Fig. D.11  Experimental Facility 3 Water Tunnel (University Bath)

Fig. D.12  Model details for Water tunnel facility 3 (University Bath)
Fig. D.13  Tests by DLR-Göttingen with the F-13 model in the small towing tank HSVA facility in Hamburg (depth 3m, width 5 m). Schematic arrangement of laser setup, the illuminated measurement area and the towing model. Laser and stereo camera can translate with the downward motion of the vortex.