LES of cold turbulent jet/vortex interaction.

RT 5/10262 DAFE/DSNA - February 2007
FAR-WAKE TECHNICAL REPORT T.R.2.1.1-2

O. Labbé
COMPUTATIONAL FLUID DYNAMICS AND AEROACOUSTICS DEPARTMENT

Technical Report N° RT 5/10262 DAFE/DSNA

FAR-WAKE TECHNICAL REPORT T.R.2.1.1-2

February 2007

LES of cold turbulent jet/vortex interaction.

Written by:
O. Labbé

Approved by:
Director of
Computational Fluid Dynamics and Aeroacoustics
Department
J-M Le Gouez

UNCLASSIFIED
(SANS MENTION DE PROTECTION)
Abstract:
The present study is a part of the Work Package 2 of the FAR-Wake European project on aircraft wakes. This part of the project focuses on the effect of a cold jet on a single vortex. Temporal Large Eddy simulation of the interaction between a turbulent cold jet and a wake vortex has been performed with the FLUDILES code. The parameters of the simulation have been chosen in order to reproduce an experimental campaign conducted in the framework of the European FAR WAKE project in the DAFE department of ONERA. The simulation is carried out in two phases: firstly the jet is carried out until the maximum streamwise velocity corresponds to the experimental data. Then, a Lamb-Oseen vortex is added to the flow. The fully turbulent jet is deflected and entrained by the vortex velocity field and starts to wrap around it. During that process the jet vorticity is progressively stretched and leads to the production of large structures in the form of helical sheets of vorticity. The turbulence does not penetrate into the vortex core. As the downstream distance increases, the large-scale vortical structures disappear, the kinetic energy decays and the radius vortex slightly increases.

Key words:
LAMB OSEEN VORTEX ; LARGE EDDY SIMULATION ; LOW SUBSONIC ; SUBGRID SCALE MODEL ; TURBULENT JET ; WAKE VORTEX
DISTRIBUTION LIST of ONERA REPORT N°RT 5/10262 DAFE/DSNA
FAR-WAKE TECHNICAL REPORT T.R.2.1.1-2

Distribution of report

- **Outside ONERA** :
  - NLR Amsterdam
    - M. Anton DE BRUIN ................................................................. 1 ex.
  - UCL Louvain
    - M. Grégoire WINCKELMANS .................................................. 1 ex.
  - Airbus-D Bremen
    - M. Geza SCHRAUF ................................................................. 1 ex.
  - U-Bath
    - M. Ismet GURSUL .................................................................... 1 ex.
  - CERFACS
    - MM. Thilo SCHÖNFELD, Jean-François BOUSSUGE, Laurent NYBELEN 3 ex.
  - E.C. Brussels
    - M. Jean-Luc MARCHAND ......................................................... 1 ex.
  - IRPHE Marseille
    - M. Thomas LEWEKE .................................................................... 1 ex.

- **Inside ONERA** :
  - DSNA/ETRI
    - Mme Odile LABBÉ, M. Thien-Hiep LÊ ........................................ 2 ex.
  - DSNA/D
    - M. Jean-Marie LE GOUEZ ........................................................ 1 ex.
  - DMAE/CM
    - M. Éric COUSTOLS ................................................................... 1 ex.
  - DAFE/MFLU
    - M. Denis SIPP ........................................................................ 1 ex.
  - DAFE/D
    - M. Laurent JACQUIN ................................................................ 1 ex.
  - DSNA/ST
    - Archives ................................................................................ 1 ex.
  - DSNA/ST
    - Archives ................................................................................ 1 ex.
  - ISP
    - Documentation ......................................................................... 1 ex.

Distribution of identification card only

- **Outside ONERA** :
  - IRPHE Marseille
    - M. Thomas LEWEKE .................................................................... 1 ex.

- **Inside ONERA** :
  - DSNA/ADG
    - Mme Brigitte MOSSANT, M. Jean-Claude BOHL ......................... 2 ex.
  - DAFE/G
    - Mme Claire PLANCHARD .......................................................... 1 ex.
  - DSB/MFE
    - M. Jean-Jacques THIBERT ........................................................ 1 ex.
  - DSNA
    - Mme Mossant, M. Bohl .............................................................. 2 ex.
  - DSB/MFE
    - Chefs d'Unité ........................................................................... 7 ex.
  - DSNA
    - M. Thibert ................................................................................ 1 ex.
  - Systematic distribution : DSG, DTG, DAI, DCV/ND .......................... 4 ex.
AST4-CT-2005-012238

FAR-Wake

Fundamental Research on Aircraft Wake Phenomena

Specific Targeted Research Project

Start: 01 February 2005
Duration: 36 months

LES OF COLD TURBULENT JET/VORTEX INTERACTION

Prepared by: Odile Labbé (ONERA)

---

Document control data

<table>
<thead>
<tr>
<th>Technical Report No.:</th>
<th>T.R. 2.1.1-2</th>
<th>Due date: October 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Version:</td>
<td>Version 1.0</td>
<td>Task manager: T. SCHÖNFELD (CERFACS)</td>
</tr>
<tr>
<td>Date delivered:</td>
<td>February 2007</td>
<td>Project manager: T. Leweke (CNRS-IRPHE)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EC Officer: J.-L. Marchand (E.C.)</td>
</tr>
</tbody>
</table>

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)

<table>
<thead>
<tr>
<th>Dissemination Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>PU Public</td>
</tr>
<tr>
<td>PP Restricted to other programme participants (including the Commission Services) X</td>
</tr>
<tr>
<td>RE Restricted to a group specified by the consortium (including the Commission Services)</td>
</tr>
<tr>
<td>CO Confidential, only for members of the consortium (including the Commission Services)</td>
</tr>
</tbody>
</table>

* Indication à rayer par l'émetteur quand il n'y a pas lieu de prévoir cette étape du circuit
TABLE OF CONTENTS

1 INTRODUCTION .............................................................................................................6
2 EXPERIMENTAL SET-UP .............................................................................................7
3 GOVERNING EQUATIONS AND SUBGRID MODELING .............................................7
4 NUMERICAL METHOD AND BOUNDARY CONDITIONS ............................................10
5 COMPUTATIONAL PARAMETERS ................................................................................10
6 JET PHASE .....................................................................................................................11
7 INTERACTION PHASE ..................................................................................................15
8 CONCLUSION ...............................................................................................................19
9 REFERENCES ...............................................................................................................20
1 Introduction

The Far-Wake project 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. The present study is a part of the Work Package 2 of the FAR-Wake European project on aircraft wakes. This part of the project focuses on the effect of a cold jet on a single vortex. The jet can affect the stability of the vortex when the jet axis is close to the vortex core. This situation has an influence on the dynamics and decay of the vortex. Numerical simulations of generic configurations and small-scale experiments in ground-based facilities of simplified geometries have been carried out as a function of the vortex and jet parameters in order to characterize the final vortex structure. Experimental studies have been performed by Onera’s DAFE department on jet/wake interactions [2]. The report [6] describes all the data collected in the course of the different test campaigns. In this context, the aim of the present study is to simulate a turbulent cold jet and vortex interaction of which characteristics are issued from the test campaign conducted in 2005.

In WP2 of the European Far-Wake project, Large Eddy simulations of the interaction between a turbulent hot jet and a wake vortex have been performed for three configurations [7] with the FLUDILES code. In the present study, one position of the cold jet has been taken into account. The FLUDILES code solves the fully compressible Navier-Stokes equations with a sixth-order compact finite differences for convective terms and with a third-order Runge–Kutta method for time integration [4]. The Mixed-Scale Model proposed by Sagaut [12] has been chosen among the different turbulence models proposed by the code. Moreover, in the streamwise direction (x), periodic conditions are applied on boundaries in order to reduce the number of discretization points, which leads to a time-developing simulation, which means that the mean flow gradients in the axial direction are neglected. The computation is advanced in two steps; the first step is stopped when the velocity maximum is close to experimental data and in the second step, the interaction with a Lamb-Oseen vortex field is accounted for. The dynamics are then dominated by the entrainment of the jet into the vortex flow in the interaction regime.

The structure of the report is as follows. In Section 2 the experimental set-up is succinctly described and the governing equations and subgrid modeling are given in Section 3. Numerical methods and simulation parameters are given in Section 4. Sections 5 and 6 present the results obtained respectively in the jet and interaction phases. Finally, in Section 7 the conclusions are presented.
2 Experimental set-up

The tests were run in the F2 wind tunnel at the Fauga-Mauzac centre. The report [6] describes the data collected in the course of three test campaigns. The experimental device was dimensioned to try to simulate as best as possible the case of a transport aircraft in cruising flight. The experimental device consists in a vortex generator (NACA0012 wing profile) and a jet generator (Figure 1). The distance $\Delta_j$ between the centre of the jets and the wing tips can vary. During these tests, different distances have been measured: $\Delta_j = 25, 50, 100 \, \text{mm}$. In the second campaign (2005), the effect of the jet/vortex distance $\Delta_j$ on the wake was studied. Among the different tests, one was chosen to carry out the numerical simulation: a cold jet ($290^\circ\text{K}$) and a distance $\Delta_j = 50 \, \text{mm}$ or $\Delta_j / b = 0.1$, the wing span $b=0.5\,\text{m}$.

![Experimental device](image)

*Figure 1: Experimental device*

The maximum of jet velocity is 43m/s at the exit of the ejector, and the free flow velocity is 20m/s. The lift coefficient is 0.5 and the circulation $\Gamma_0$ is estimated to $0.8\,\text{m}^2/\text{s}$

Three measuring methods were used to qualify the aerodynamic field:
- Thermocouple probe measurements.
- Three-directional laser velocimetry measurements at different downstream distances: $X/b=1,3,5$ for hot jet and $X/b=1,3$ for cold jet.
- One-dimensional hot wire probe measurements.

3 Governing equations and subgrid modeling
In the LES approach, the dimensionless formulation of compressible 3D Navier-Stokes equations are filtered spatially so that any variable \( f \) may be decomposed into a resolved (or large scale) part \( \bar{f} \) and a non resolved (or subgrid scale) part \( f' \), with \( f = \bar{f} + f' \). This procedure may be obtained by a convolution integral of the variable with a filter function depending on a filter width \( \Delta \). Practically, the filter width is simply given by the computational mesh cell size \( \Delta = \Delta_{iso} \), where \( \Delta_{iso} = (\Delta_x, \Delta_y, \Delta_z)^{1/3} \).

For compressible flows, it is usual to introduce the Favre filter \([3]\) defined as: \( \bar{\rho} f = \bar{\rho} \bar{f} \), we obtain the Favre-filtered equations of mass and momentum:

\[
\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_j} (\bar{\rho} \bar{u}_j) = 0
\]

(1)

\[
\frac{\partial}{\partial t} (\bar{\rho} \bar{u}_j) + \frac{\partial}{\partial x_j} (\bar{\rho} \bar{u}_j \bar{u}_i) + \frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \hat{\sigma}_{ij}}{\partial x_j} = -\frac{\partial}{\partial x_j} \tau_{ij} + \frac{\partial}{\partial x_j} (\hat{\sigma}_{ij} - \hat{\sigma}_{ij})
\]

(2)

\[
\tau_{ij} = \bar{\rho} (\bar{u}_i \bar{u}_j - \bar{\rho} \bar{u}_i \bar{u}_j)
\]

As usually assumed in LES, the contribution of the second term of the right-hand sides of eq. (2), which results from the non-linearity of the viscous term, will not be accounted for.

The viscous stress tensor is given by: \( \hat{\sigma}_{ij} = \frac{\mu(\bar{T})}{Re} \left\{ \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial \bar{u}_k}{\partial x_k} \right\} \), \( \delta_{ij} \) being the Kronecker delta and \( Re \) the Reynolds number. The right-hand sides of eq. (2) contain the so-called subgrid stress tensor \( \tau_{ij} = \bar{\rho} (\bar{u}_i \bar{u}_j - \bar{\rho} \bar{u}_i \bar{u}_j) \), which represent the effects of unresolved scales of motion on the large scales and need to be modeled. The first model is the well-known Smagorinsky model \([13]\)

\[
\tau_{ij} = -\frac{1}{3} \tau_{ik} \delta_{ij} = \tau_{ij}^D = -\bar{\rho} \nu_{sm} S_y(\bar{u})
\]

\[
\nu_{sm} = \frac{C_s \Delta^2}{S(\bar{u})}
\]

\[
S(\bar{u}) = S_y(\bar{u}) S_z(\bar{u})
\]

\[
\tau_{ij} = -\bar{\rho} (C_s \Delta)^2 |S(\bar{u})| S_y(\bar{u}) \quad \text{with} \ C_s = 0.2
\]

The excessive dissipation of the Smagorinsky model can be overcome if the constant is replaced by a coefficient depending on both large and small scales of turbulence. Such model has been proposed by Sagaut \([12]\). The Mixed-Scale Model could be considered as a dynamic adjustment of the Smagorinsky coefficient.

\[
\tau_{ij} = -\frac{1}{3} \tau_{ik} \delta_{ij} = \tau_{ij}^D = -\bar{\rho} \nu_{sm} S_y(\bar{u})
\]
\[ \nu_{sm} = C_m [S^{(1-\alpha)} q_c^2]^{(1-\alpha)} \] with \( \alpha = 0.5 \) and \( C_m = C_m (\alpha) = 0.06 \)

where \( q_c^2 \) is the kinetic energy of the small scales evaluated by the following formula:

\[ q_c^2 = \frac{1}{2} \tilde{u}_j \tilde{u}_j' \]

The fluctuating resolved scales \( \tilde{u}_j' \) are extracted from the resolved velocity field employing a discrete filter denoted by a wide hat: \( \tilde{u}_j = \tilde{u}_j - \hat{\tilde{u}}_j \)

The discrete filter is given by:

\[ \hat{\tilde{u}}_j = \frac{1}{4} \tilde{u}_{j-1} + \frac{1}{2} \tilde{u}_j + \frac{1}{4} \tilde{u}_{j+1} \]

It can be interpreted as a second-order approximation of a Gaussian filter whose characteristic length is \( \Delta = \sqrt{6} \Delta \).

After commonly adopted simplifications, the filtered equations for the energy equation has the following form:

\[
\frac{\partial \hat{E}}{\partial t} + \frac{\partial}{\partial x_j} \left( (\hat{E} + \overline{p}) \hat{u}_j \right) - \frac{\partial}{\partial x_j} \left( \hat{\sigma}_{ij} \hat{u}_i \right) + \frac{\partial \hat{q}_j}{\partial x_j} = -B_1 - B_2 + B_3 + B_4
\]

The computable energy is given by: \( \hat{E} = \frac{\overline{p}}{\gamma - 1} + \frac{1}{2} \overline{\tilde{u}_j \tilde{u}_j} \); the computable heat flux vector by

\[ \hat{q}_j = -\frac{\mu(\overline{T})}{(\gamma - 1) Re Pr M^2} \frac{\partial \overline{T}}{\partial x_j} \]

The Prandtl number \( Pr \) and the ratio of specific heats \( \gamma = C_p / C_v \) are set equal to 0.7 and 1.4 respectively. Furthermore, our simulation is performed by using a low Mach number \( M \) of 0.2, which should make the calculation close to the incompressible limit.

The terms \( B_1, B_2, B_3 \) and \( B_4 \) are expressed as following:

\[ B_1 = \frac{1}{\gamma - 1} \frac{\partial}{\partial x_j} \left( \overline{p u_j} - \overline{\overline{p u}_j} \right) ; \quad B_2 = \frac{\partial}{\partial x_j} \left( \tau_{ij} \tilde{u}_j \right) \]

\[ B_3 = \tau_{ij} \frac{\partial}{\partial x_j} \tilde{u}_k ; \quad B_4 = \sigma_{ij} \frac{\partial}{\partial x_j} u_k - \sigma_{ij} \frac{\partial}{\partial x_j} \tilde{u}_k \]

The subgrid term \( B_1 \) represents the effect of subgrid scales on the conduction of heat in the large scales. In the case of eddy viscosity-type model, it is modeled as follows:

\[ B_1 = -\frac{\partial}{\partial x_j} \left( \overline{\rho \nu_{sm} \overline{\overline{T}}} \right) \]

\[ \overline{\rho \nu_{sm} \overline{\overline{T}}} \]

\[ \overline{\rho \nu_{sm} \overline{\overline{T}}} \]
The SGS terms $B_2$ and $B_3$ depend directly upon the subgrid-scale tensor, they are thus obtained in a straightforward manner reporting the expression used to model the former tensor. Following Ghosal et al. [5] the subgrid term $B_4$ is modeled by: $B_4 = C \frac{k^{3/2}}{\Delta}$.  

The procedure to determine the coefficient $C$ is based on a global balance of the terms in the integrated k-equation, which leads to:

$$C = \frac{\int_{\Omega} \left( (1 - \gamma)B_1 + B_2 - B_3 \right) d\Omega}{\int_{\Omega} - \frac{k^{3/2}}{\Delta} d\Omega} \quad \text{with} \quad k = \frac{\nu_{sm}^2}{\Delta^2}$$

4 Numerical method and boundary conditions

The boundary conditions are the same as in [7]. In convective terms, spatial derivatives are taken with sixth-order compact finite-differences [8]. To minimize the aliasing error, we follow the procedure applied by Boersma and Lele [1]. The non-linear terms have been rewritten in the skew symmetric form i.e.:

$$\frac{\partial \rho u_i u_j}{\partial x_j} = \frac{1}{2} \left[ \frac{\partial \rho u_i}{\partial x_j} u_j + u_i \frac{\partial \rho u_j}{\partial x_j} + \rho u_j \frac{\partial u_i}{\partial x_j} \right]$$

Diffusive terms are discretized by using a second-order accurate finite difference scheme. The time integration is carried out by a third-order Runge-Kutta method [9]. In the present study, an isolated vortex is simulated and non-reflexive conditions introduced by Thompson [14] are used at the lateral boundaries of the computational domain.

5 Computational parameters

The computations are split in two phases: the jet phase and the interaction phase. In order to be as close as possible to the experimental conditions, the numerical simulation needs some data for the initialization. According to the CERFACS [10], it was decided to start the simulation at $X/b=0.1$. At this cross section the jet velocity is known, but not the position of vortex. We have supposed that, it is the same as at $X/b=0.5$. In the experiments, the vortex centre is moving along the downstream distance, as shown in Fig. 50 of experimental results [6], but in the numerical simulation, due to the use of non-reflexive boundary conditions, the initial position of the vortex does not change in the course of the simulation. The initial distance between jet and vortex was chosen at $0.1b$ horizontally and $0.05b$ vertically, but experimental data show that the horizontal distance is closer to $0.07b$, which induces a second shift with the experiments.

The Pitot probe measurements Fig. 39 of [6] show that at the exit of the ejector, the maximum of jet velocity is $43m/s$ with a free flow velocity of $20m/s$. In the simulation, the free flow is taken to $0m/s$ and the velocity maximum was chosen to the value $23m/s$, to obtain the same difference. The Reynolds and Mach numbers correspond to experimental data. Moreover, the jet is fully turbulent at the exit of the ejector, so when the vortex is added to the flow, the difference of velocity imposed in the simulation coincides with the experiments, but the jet is still laminar than turbulent.
The equations presented in Section 3 are non-dimensionalized by scaling the velocities with the centerline velocity of the jet $V_j$, and the characteristic length scale is equal to the radius $R_j$. The Reynolds number is based on jet velocity and jet radius, $Re = V_j R_j / \nu_j = 14,483$ and the Mach number is 0.13, the Prandtl and Schmidt numbers are $Pr=0.7$ and $Sc=0.7$.

The computational domain consists in a box with a regular mesh in the three directions. The cross plane extends from $Y/b:[-0.18,0.18], Z/b:[-0.18,0.18]$ and being the streamwise direction. The streamwise length of the computational domain is $X/b:[0,0.06]$. This corresponds to twice the wavelength of the maximum growth rate of the first azimuthal instability of a spatially evolving jet. The mesh consists in $61 \times 361 \times 361 \approx 8$ millions points.

6 Jet phase

The jet axial velocity is initialized as $V = V_0(1 + \varepsilon \tilde{V})$ where $V_0$ is a tanh profile $V_0(r) = \frac{V_j}{2}(1 - \tanh\left(\frac{1}{4}\frac{R_j}{\theta} \frac{R_j - r}{R_j}ight))$, $r$ being the radial coordinate in a cross-section, and $\varepsilon \tilde{V}$ being a white noise random perturbation with a maximum amplitude 0.5% of $V_0$ and $\| \tilde{V} \| \leq 1$. The momentum boundary layer thickness $\theta$ is defined as: $\theta = \int_0^r \left\{ \frac{V_0(r)}{V_j} \left(1 - \frac{V_0(r)}{V_j}\right) \right\} dr$. We restrict the present investigation to one value of the jet parameter, namely $R/\theta = 10$. Among the cases studied by Michalke and Hermann [11], this value corresponds to the most unstable jet velocity profile.

The jet simulation is stopped when the velocity maximum is close to experimental data at $X/b=0.1$. The velocity in the jet centre has decreased from 43 m/s to about 34 m/s. Contrary to experiments, the axial velocity presents a potential cone and in Figure 2 the jet velocity variation is plotted at different times in order to choose the profile as close as possible to experimental data. For computing the mean flow profiles, the simulated data, which are in Cartesian coordinates $(x,y,z)$, are transformed to cylindrical coordinates $(r, \theta, x)$ using a high order cubic spline interpolation formula. All the results presented as a function of the radius $r/R_j$ are obtained in the following way; the instantaneous quantity is averaged in the axial direction $x$. Then the averaged quantity is interpolated into a polar grid and averaged in the azimuthal direction to obtain a profile which is a function of $r$. No averaging in time is performed; therefore, the mean profile is a function of time.
Figure 2: Axial jet velocity variation at different times
Figure 3: Evolution of vorticity $\Omega_y \in [-5,5]$ through the jet, solid/dashed lines indicate positive/negative vorticity.
The vorticity iso-contours \( \Omega \), plotted at three times in Figure 3 show the transition to turbulence of the jet, associated to the formation of structures with high vorticity. Initially, the vorticity is confined into a circular sheet. The last visualization clearly illustrates the growth of instabilities and transition to fully developed turbulence. The latter corresponds to the jet state when the vortex is added.

![Figure 4: Iso-values of the turbulent kinetic energy \( \sqrt{k/U_0} \) at \( X/b=0.1 \)](image)

At \( X/b=0.1 \) in Figure 4 the turbulent kinetic energy is high in the jet core, the jet centre is here located at \( Y/b=0 \). and \( Z/b=0 \).

![Figure 5: Energy spectrum](image)
Figure 5 presents the energy spectrum $E(k)$ at $X/b=0.1$. It is obtained by taking the Fourier transform of the velocity field in the axial direction and integrating the Fourier coefficients in the $y, z$ plane. At high wave numbers, the energy is low and indicates that the flow is well resolved.

7 Interaction phase

The interaction with the vortex wake is then taken into account, and a Lamb-Oseen vortex, is fitted on the transverse part of the experimental velocity field given by:

$$U_\theta (r) = \alpha U_{\theta \text{max}} \left( \frac{r_c}{r} \right) \left( 1 - \exp \left( -\beta \left( \frac{r}{r_c} \right)^2 \right) \right)$$

and

$$\frac{\partial p}{\partial r} = \rho U_{\theta \text{max}}^2 / r$$

where

$$\alpha = 1 / (1 - e^{-\beta})$$

and

$$\beta = 1.2564$$

The circulation $\Gamma_0$ is estimated by experiments to $0.8\text{m}^2/\text{s}$ and at $X/b=0.5$ the maximum viscous radius of the vortex can be estimated at $6\text{mm}$. If we suppose that the viscous radius $r_c$ with $r_c/R_j=1$ at the beginning of the interaction phase, the Lamb-Oseen model provides a tangential velocity $U_{\theta \text{max}}$ equal to $18.2\text{m/s}$, which is higher than the tangential velocity given in [6] Figure 18, where the maximum is close to $9\text{m/s}$. Once again, the vortex location is unknown at $X/b=1$ and for the simulation it has been supposed it was at $Y/b=0.1$ and $Z/b=-0.05$. To illustrate the relative jet position with respect to the vortex, Figure 6 shows the longitudinal component of vorticity $\Omega_x$ at time $X/b=0.1$, in the median plane normal to the axial direction. The vortex core is concentrated at the centre of the computational domain (i.e. $x/R=0$ and $z/R=0$), positive and concentric contours represent the vorticity distribution of the vortex core, while the jet patterns consist in positive and negative coherent structures.

![Figure 6: Axial component of vorticity $\Omega_x$ at $X/b=0.1$.](image-url)
The analysis of the results is performed in terms of the turbulent kinetic energy, the azimuthal and longitudinal vorticity components, the tangential velocity for the dynamic process. The dimensionless time $t_\ast$ is introduced as $t_\ast = t^*/(R_j/V_j)$ is expressed in distance $X/b$ downstream of the wing.

The evolution of the kinetic energy is shown in Figure 7. When the vortex is added, the turbulent kinetic energy is increasing, but the peak is not yet reached. The maximum is located around $X/b=0.2$ and then due to the jet diffusion process, such as if the jet was alone the curve is decreasing until the interaction occurs at $X/b=1.2$ which induces an increase of energy. Around $X/b=2.3$, the turbulent energy saturates and is higher than the previous peak. The energy then slowly decreases.

![Figure 7: Evolution of the turbulent kinetic energy](image)

To illustrate the dynamics phenomena, four distances were chosen corresponding to start ($X/b=1.2$), growth ($X/b=1.9$), saturation ($X/b=2.3$) and decay ($X/b=5.7$) of the turbulent kinetic energy (Fig.7). At the beginning of the interaction, the turbulent kinetic energy grows to reach a maximum 0.46 at $X/b=2.3$ followed by a period of decay called the dissipation regime.

In Figure 8, the helical structures surrounding the core are surfaces of azimuthal vorticity $\Omega_\theta$ (red: -0.4, orange: 0.4) for the distances mentioned previously. These large-scale helical structures are counter rotating vortices where the orange color surface indicates a positive value (+0.4) and the red color a negative one (-0.4). The position of the vortex is plotted with an iso-surface of vorticity $\Omega_x$ (+2) in yellow. The dynamics of the interaction are first dominated by the entrainment (top/left) and the captation (bottom/left) of the jet by the vortex. As the jet spreads it is progressively deflected by the continuous input of crossflow momentum so that it acquires azimuthal and radial components of velocity. The deflection regime corresponds to the emergence of three-dimensional structures of azimuthal vorticity around it. The vorticity of the jet is progressively stretched and generates spiral-shaped vorticity structures (top/right). At the turbulent kinetic energy maximum, the large-scale vortical structures seem coherent. In the dissipation
regime, the jet is decaying. As observed in the figure, the break-up of these large-scale structures takes place, however the vortex core presents already large distortions (bottom/right).

Figure 8: Views of the azimuthal vorticity $\Omega_\theta$ (red: -0.4, orange: 0.4) at $X/b=1.2$ (top/left), 1.9, (bottom/left) 2.3 (top/right) and 5.7 (bottom/right); the position of the vortex is plotted with an iso-surface of vorticity $\Omega_x (+2)$ in yellow.
In order to study the influence of the jet on the vortex, the vorticity modulus $|\Omega|$ has been plotted in Figure 9 at downstream distances $X/b=1.2$ (top/left), $1.9$ (bottom/left), $2.3$ (top/right) and $5.7$ (bottom/right) in a median plane normal to the axial direction. The fully turbulent jet is deflected and entrained by the vortex velocity field and wraps around it. At $X/b=2.3$ the vortex core seems perturbed by the jet and in the diffusion zone at $X/b=5.7$ the vortex shape is yet altered by the jet and the vorticity has strongly decreased.
Figure 10 gives the iso-values of turbulent kinetic energy at two downstream distances $X/b=0.3$ and $X/b=2.3$, which correspond to the two peaks of Figure 7. It is clear that the turbulent kinetic energy first located in the jet is then wrapped around the vortex, but the vortex core is not reached. The maximum is lower at $X/b=2.3$ than at $X/b=0.3$, but the surface with turbulent kinetic energy is larger, that explains the second peak of Figure 7 is higher than the first one.

The tangential velocity profiles at different distances are plotted in Figure 11. The viscous radius is slowly increasing, while the velocity maximum is decreasing. At $X/b=5.7$ the tangential velocity has lost 25%. Due to the choice of the Lamb-Oseen vortex model used in numerical simulation, the tangential velocity profiles are higher than those obtained in experimental measurements.

**Conclusion**
Temporal Large Eddy simulation of the interaction between a turbulent cold jet and a wake vortex has been performed with the FLUDILES code. The parameters of the simulation have been chosen in order to reproduce an experimental campaign conducted in the framework of the European FAR WAKE project in the DAFE department of ONERA. The simulation is carried out in two phases: firstly the jet is carried out developed until the maximum streamwise velocity corresponds to the experimental data. Then, a Lamb-Oseen vortex is added to the flow. The fully turbulent jet is deflected and entrained by the vortex velocity field and starts to wrap around it. During that process the jet vorticity is progressively stretched and leads to the production of large structures in the form of helical sheets of vorticity. The turbulence does not penetrate into the vortex core. Due to the strong rigid-body-like flow field, these structures break up. The comparison with experimental results are not straightforward, because the vortex in the numerical simulation does not move due to the lateral boundary conditions. Moreover, the tangential velocity maximum is higher in numerical results than in experimental data, because of the Lamb-Oseen vortex model. As the downstream distance increases, the large-scale vortical structures disappear, the kinetic energy decays and the radius vortex slightly increases.

9 References

[1] Boersma B. J., Lele S. K.,
Large Eddy Simulation of a Mach 0.9 Turbulent Jet,
AIAA Paper 99-1874.

[2] Brunet S., Jacquin L., Geffroy P.,
Experiment on heated jets/wake vortex interaction,

[3] Favre A.,
Équations statistiques aux fluctuations turbulentes dans les écoulements compressibles : cas des vitesses et des températures,

[4] Ferreira Gago C., Garnier F., Utheza F.,
Direct testing of subgrid scale models in large-eddy simulation of a non-isothermal turbulent jet,

A Dynamic localization model for large-eddy simulation of turbulent flows,

[6] Jacquin L., Molton P.,
Experiments on cold/hot jet-vortex interaction,
ONERA TR 3/10262 DAFE, 2006-12-05
FAR-WAKE technical report T.R.2.1.2-6.
[7] Labbé O.,
*LES of hot turbulent jet/vortex interactions*,
ONERA RT 1/10262 DAFE/DSNA, 2006
FAR-WAKE technical report T.R.2.1.2-4.

[8] Lele S. K.,
*Compact finite difference scheme with spectral-like resolution*,

[9] Lowery P.S., Reynolds W.C.,
*Numerical simulation of a spatially developing forced mixing layer*,
Rep TF-26, Stanford University, 1986.

[10] Nybelen L., Boussuge J. F., Schönfeld T.,
*LES of turbulent cold jet/vortex interaction*,

*On the inviscid instability of a circular jet with external flow*,

[12] Sagaut P.,
*Large Eddy Simulation for Incompressible Flows: An Introduction*,

[13] Smagorinsky J.,
*General circulation experiments with the primitive equations*,

[14] Thompson K.W.,
*Time dependent boundary conditions for hyperbolic system II*,