AST4-CT-2005-012238

FAR-Wake

Fundamental Research on Aircraft Wake Phenomena

Specific Targeted Research Project

Start: 01 February 2005
Duration: 40 months

Final Report on vortex interactions with jets and wakes

Prepared by: T. Schönfeld (CERFACS, lead)
J.-F. Boussuge (CERFACS)

Document control data

<table>
<thead>
<tr>
<th>Deliverable No.:</th>
<th>D 2.F</th>
<th>Due date:</th>
<th>April 2008 (m39)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Version:</td>
<td>1.0</td>
<td>Task manager:</td>
<td>T. Schönfeld</td>
</tr>
<tr>
<td>Date delivered:</td>
<td>23 May 2008</td>
<td>Project manager:</td>
<td>T. Leweke</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EC Officer:</td>
<td>S. Stoltz-Douchet</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</td>
</tr>
<tr>
<td>PP</td>
</tr>
<tr>
<td>RE</td>
</tr>
<tr>
<td>CO</td>
</tr>
</tbody>
</table>
Summary

In this final report, a global synthesis is presented of the results obtained in work package 2 “Vortex interactions with jets and wakes from aircraft components” of the FAR-Wake project. The overall objective of this work package is the identification of the main effects and relevant parameters associated with the interactions of vortices with cold or hot jets (engine jets), and with the wakes from different aircraft elements (fuselage, nacelles, landing gear, etc.).

Table of Contents

1. Task 2.1 - Vortex interactions with jets (contributions of CERFACS, CUT, ONERA, NLR, UCL & U-Bath)................................................... ................................................... ................................................... ............................................................................ 3
   1.1  Introduction ............................................................................................................................................. 3
   1.2  Task 2.1.1 - Cold jet / vortex interaction .......................................................................................... 3
         1.2.1    Cold jet / single vortex interaction ......................................................................................... 3
         1.2.2    Cold jet / vortex pair interaction.......................................................................................... 9
         1.2.3    LES Simulations of multi-vortex configurations, including wake roll-up............................ 12
   1.3   Task 2.1.2 - Hot jet / vortex interaction ......................................................................................... 14
         1.3.1  Stability Analysis of Vortex with Temperature Variations Resulting from Hot Jet/Single Vortex Interaction .............................................................................................................. 15
         1.3.2    Experimental Investigation of Hot Jet/Vortex Interaction .................................................... 15
         1.3.3    Numerical simulations using LES .......................................................................................... 18
   1.4   Conclusions Task 2.1 .................................................................................................................... 22
2.   Task 2.2 - Vortex interactions with wakes (contributions of DLR, CENAERO, UCL, TUM & Airbus) ......................................................................................................................... 24
   2.1   Task 2.2.1 - Effect of fuselage on vortex wake .............................................................................. 24
   2.2   Task 2.2.2 - Wing elements .............................................................................................................. 33
   2.3   Conclusions Task 2.2 .................................................................................................................... 37
3.   Overall Conclusions ............................................................................................................................. 38
References ...................................................................................................................................................... 39
1. Task 2.1 - Vortex interactions with jets (contributions of CERFACS, CUT, ONERA, NLR, UCL & U-Bath)

1.1 Introduction
The effects of cold and hot jets on vortex pairs, vortex merging, vortex development and decay were investigated both experimentally and numerically. Generic wing and nozzle geometries were used to produce the vortex and the jet respectively. The simplified experimental setup allowed for a comprehensive parametric study. Experiments were performed in both water and wind tunnel facilities. The main parameters examined were the jet-to-vortex distance, their relative strengths, the jet-to-free stream angle and the Reynolds number. A significant database was collected and analysed. Previous experimental efforts on the effect of a hot jet on a wing tip vortex were expanded in a follow-up study; one of the main findings was that the temperature of hot jet did not change the flow physics.

The numerical investigations were mainly based on the time-dependent Large-Eddy-Simulation approach which allows evaluating the different stages of the dynamics of the interaction: the entrainment of the jet by the vortex, and the emergence and subsequent break-up of 3D azimuthal vorticity structures around the jet.

1.2 Task 2.1.1 - Cold jet / vortex interaction

1.2.1 Cold jet / single vortex interaction
The interaction of a cold jet with a vortex was investigated under both cruise flight conditions and the approach/take-off phase. Parametric studies relevant to isothermal and non-isothermal jets (varying Reynolds number, boundary layer thickness, density ratio, level of turbulence) were carried out. The experimental studies investigated the effect of a cold engine jet on the process of vortex merging in the near wake. Co-rotating vortices of equal and unequal strengths were produced in a water channel (Figures 1 and 2) to replicate the outboard flap-edge and wing-tip vortex structures generated by a real aircraft.

![Figure 1: Schematic of generic wings and jet nozzle model](image-url)
The studies conducted by the partners were both experimental and computational. The studies by NLR [10], focused on the analysis of existing Airbus experimental data from a previous experimental campaign. The experiments were performed using a scaled model of a typical aeroplane. Wake measurements were performed in the near wake (up to 1.3 spans downstream) for four different high lift configurations at a number of thrust settings. The second experimental study was performed at the University of Bath [2] and focused on the effect of a cold jet on a single wing tip vortex. Generic wing and nozzle were used to produce the vortex and the jet respectively. The simplified experimental setup allowed for a comprehensive parametric study. Experiments were performed in both water and wind tunnel facilities. The main parameters examined were the jet-to-vortex distance, their relative strengths, the jet-to-free stream angle and the Reynolds number. A significant database was collected and analysed. The third experimental study used in the present report was conducted at ONERA [7,8] and expanded previous experimental efforts on the effect of a hot jet on a wing tip vortex. Apart from hot jets, cold jets were also tested. One of the main findings of this study was that the temperature of the jet did not change the flow physics. Thus, although the present report aims to collect the results on the cold jet – vortex interaction, the findings from the hot jet experiments are also used. The fourth experimental study was conducted by TU-Delft [3] in a water tank using the PIV measurement technique to obtain the vortex characteristics in the near to mid field.

The experimental studies were complimented by a computational study that used LES to simulate the effect of a cold jet on a typical wing tip vortex. The study was conducted by CERFACS [4], used typical aeroplane properties for the jet and the vortex and examined two different cases: the jet and the vortex being well separated and the jet blowing into the vortex core. Finally, ONERA [30] performed a temporal LES simulation of a simplified configuration of a cold jet/vortex interaction with characteristics parameters corresponding to one configuration of the ONERA experimental campaign [7].

**Jet – vortex interaction dynamics**

The two main parameters that control the interaction between a jet and a single vortex are the relative strengths of the jet and the vortex and their initial separation distance. The experimental investigations [5] have revealed that the jet-vortex interaction is divided into three stages:

1) the jet is entrained around the vortex core;
2) due to the rotational velocity field, significant azimuthal vorticity structures are formed on the jet, which interact with the vortex;
3) finally, these structures decay and only the vortex remains.

For a high ratio between the jet momentum and the vortex strength, the vortex core radius increases, while the total circulation remains constant. Depending on the initial separation distance, the jet can then either penetrate into the vortex core, or the jet only wraps around the
core. The important scaling length was found to be the vortex core radius. When the jet penetrates into the core, the axial velocity of the vortex increases, and the coherence of the vortex can be lost very rapidly. Without penetration, only the axial velocity in the periphery of the vortex is increased due to the jet excess velocity.

The main parameters controlling the effect of the jet on the vortex are their relative strength and their initial separation distance. An increase of the relative strength or a decrease of the jet-to-vortex distance can lead to a more pronounced effect of the jet. However, it was shown that the jet-to-vortex distance also affects the spanwise position of the tip vortex. With the jet positioned closer to the tip vortex, the latter moves further inboard.

Another important parameter is the angle between the jet and the free stream. When the jet is blowing away from the vortex, its effect is reduced, whereas the jet effect is more pronounced when the jet is blowing towards the vortex (even if this case does not represent any realistic flight conditions). In particular, during take-off and landing, the jet is blowing away from the vortex. Although for the approach phase this clearly results in a reduced effect on the vortex, the take-off case is more complex: here the jet angle is not favourable for a fast and effective jet-vortex interaction, but the jet momentum parameter is high and the jet-to-vortex distance is small (because of the flap vortex being closer to the engine than to the tip vortex).

The effect of pulsed jets on a variety of aircraft trailing vortex arrangements (single vortex, co-rotating and counter-rotating vortex pairs) in the near-field was also analysed by U-Bath [6]. The measurements of the cross-flow velocity showed that the pulsing or steady blowing at the same momentum coefficient produced practically identical results for the wake configurations tested. A reason for this could be that any additional turbulence generated close to the jet exit because of pulsing, may decay by the time it interacts with the wake vortices.

In a different experimental study, stereo-PIV measurements were carried out behind a generic flapped wing model (SWIM-J) with jet simulators have been obtained in a towing tank facility. This allows simulating the complete development of the vortex wake from the roll-up process, through vortex merging resulting in the vortex pair of the mid-field, and up to the far-field (~100 wingspans downstream) [3]. The investigation focussed on the direct influence of the jet on the flap end vortex and the (merged) vortex characteristics in the near to mid field.

While the jet effect on the effective circulation strength was shown to be limited, significant effects were found in the velocity distributions and related parameters, such as the vortex core. The main jet effect in the mid-field is a change in the flap vortex vorticity distribution. This directly affects the merging process between tip vortex and flap-end vortex. The form of the final velocity distribution in the wake depends on this merging process, which in turn is directly influenced by the circulation strength ratio of the tip and flap end vortices and the action of the jet.

A preliminary induced rolling moment analysis has been performed to obtain a rough estimate of the effect to the changed velocity distributions due to the jet. For this purpose, combinations of two leader and two follower aircraft were analyzed. The data shows that the merging/jet effect on the induced rolling moment is larger than the difference in the rolling moment caused by the large aircrafts. Hence it may be concluded that the application of a well-tuned jet effect (optimized position and jet velocity), may lead to reduced rolling moment perturbations for follower aircraft.

In complement to these experimental investigations, three-dimensional temporal Large-Eddy Simulations were carried out [4] in order to study the interaction between a cold exhaust jet and a vortex during different flight phases: approach, take-off and cruise. The simulations were performed in two steps for the cruise phase: a first simulation of the jet regime, which allows obtaining a turbulent cold jet, followed by a simulation of the jet interaction with the wake vortex. Two types of interaction were analysed: in the first case, the jet and the vortex are initially well separated, thus modelling an interaction under cruise conditions between the wing tip vortex and the jet. The dynamics of the interaction is mainly controlled by the entrainment of the jet by the vortex and the turbulent diffusion of the jet. Further, the solid-body rotation of the vortex core prevents passive scalars to penetrate inside the vortex. In the second case, the jet and the vortex are close, which corresponds to the approach and take-off phases of a four-engine aircraft (interaction between the external jet and flap vortex). The strong injection of axial flow perturbations leads to the loss of vortex coherence. For approach conditions, the vortex is not
completely annihilated, contrary to take-off conditions. In both cases, the jet affects the vortex by reducing its peak velocity and by increasing its core radius. These results revealed that the vortex is strongly affected by the jet when it is close, and when the velocity ratio between jet and vortex is high. The temporal LES simulation of ONERA [30], compared to the experimental results [7], showed that the global dynamics of jet/vortex interaction indeed is identical but the azimuthal velocity of the vortex is higher in the simulation. This might be explained by the modelling used (vortex model, simulation into two steps, jet regime and interaction regime) and by the motion of the vortex position in the experiment which does not occur in the simulation.

Figure 3 shows the streamwise development of the time-averaged flow from the experiment of U-Bath [2]. Time-averaging of the flow visualization images has been achieved by introducing a degree of transparency in each image and then superimposing all of them. The jet velocity is almost twice the free stream velocity ($U_j/U_\infty = 2.01$, $R = 0.13$). The jet-to-tip distance is $h/d_j = 6.7$. It is clear from this set of images that the jet spreads in the radial direction but also rotates around the vortex. The end of the jet structure that is closer to the vortex rolls around the vortex core.

Figure 4 shows the streamwise development of the standard deviation of the cross-flow velocity for the case ($h/d_j = 4$, $U_j/U_\infty = 2.85$, $R = 0.34$). The jet turbulence gets wrapped around the vortex core exactly as it has been observed in the flow visualization images. In fact, by comparing the flow visualization images with the standard deviation contour plots, it can be seen that the turbulence of the jet can be used to visualize the jet. Moreover, it is observed that the turbulence levels of both the jet and the vortex decrease with downstream distance. However, the decay of turbulence is much faster for the jet. This stresses the importance of the initial jet-to-vortex distance. If the distance is large enough, the jet turbulence is expected to have decayed significantly before interacting with the vortex, thus leading to a minimal effect. It is not clear whether the persistence of unsteadiness in the core is due to the ingestion of jet turbulence only. Some part of the cross-flow velocity fluctuations is probably due to the vortex wandering phenomenon. One last observation from this figure is that the turbulence levels due to the wing wake decay fast so their effect should be negligible about one span downstream of the trailing edge. Hence, this suggests that the wing wake turbulence might not be as important as the jet turbulence when the jet/vortex interaction is considered.

Figure 5 shows the mean instantaneous maximum cross-flow velocity magnitude for the four $x/b$ stations measured in the large wind tunnel. The horizontal dashed line represents the reference (no nozzle) case. As for the previous graph, all the values have been normalized using the time-averaged cross-flow velocity magnitude of the reference case at the first downstream station (found to be 30% of the free stream velocity, which compares well with that reported by Devenport et al. (1996)). It can be seen that at the first downstream location the only effect is for high blowing (large $R$ values) and small $h/d_j$ distance. For the minimum $h/d_j$ distance, the effect of the jet nozzle is obvious at only 40% of the span downstream of the trailing edge (Fig. 17a). By moving downstream (Figs 17b to 17d), the effect of the blowing jet is larger for the low $h/d_j$ cases. The interference of the nozzle is also seen to increase. Moreover, the jet appears to affect the vortex even for larger initial separation distances. In summary, it is clear that the introduction of the jet results in a diffused vortex with lower maximum cross-flow velocity magnitude in the core.
Figure 3: Time-averaged flow visualization images (water tunnel). Streamwise development for $Re_T = 5500$, $h/d_j = 6.7$, $U_j/U_\infty = 2.01$, $R = 0.13$.a) $x/b = 0.35$ ($x/d_j = 26.7$), b) $x/b = 0.7$ ($x/d_j = 53.3$), c) $x/b = 1.05$ ($x/d_j = 80$), d) $x/b = 1.4$ ($x/d_j = 106.7$), e) $x/b = 1.75$ ($x/d_j = 133.3$).
Figure 4: Standard deviation of the cross-flow velocity (water tunnel experiments) for $Re_t = 5500$, $U_j/U_\infty = 2.85$, $R = 0.34$, $h/d_j = 4$, a) $x/b = 0.35$ ($x/d_j = 26.7$), b) $x/b = 0.7$ ($x/d_j = 53.3$), c) $x/b = 1.05$ ($x/d_j = 80$).
Figure 5: Mean value of the instantaneous maximum cross-flow velocity magnitude around the vortex core as a function of jet-to-tip distance and R (large wind tunnel experiments) for \( \text{Re}_{\Gamma} = 14000 \), a) \( x/b = 0.4 \) (\( x/d_j = 26.7 \)), b) \( x/b = 0.8 \) (\( x/d_j = 53.3 \)), c) \( x/b = 1.2 \) (\( x/d_j = 80 \)), d) \( x/b = 1.6 \) (\( x/d_j = 106.7 \)).

1.2.2 Cold jet / vortex pair interaction

In an additional study, the effect of a cold jet on the merging process for a co-rotating vortex pair has been investigated for vortices of both equal and unequal strengths. Rectangular wings were used to generate the vortical flow, and the axial jet was simulated via a generic nozzle. In particular, the sensitivity of vortex merging to the introduction of external turbulence has been investigated experimentally [5]. Important effects on merging can occur if the turbulence interacts with the vortical structures before the decay of its intensity. The parameter that governs whether merging will be promoted or delayed is the initial relative position of the vortices and the jet plume. The largest promotion of merger occurs when the high-intensity jet turbulence interacts directly with just one of the two vortices (as occurring for a four-engine aircraft where the outboard jet is located vertically beneath the flap-edge vortex). Self-induced rotation of the vortex pair tends to
move the flap vortex directly into the path of the exhaust plume. Merging is promoted as the flap vorticity begins wrapping around the unaffected (and more concentrated) tip vortex. The diffusion can also cause additional amounts of vorticity-laden fluid from the flap vortex to cross the separatrices into the outer recirculation region.

Repositioning the jet vertically beneath the centre of the flap-edge and wing-tip vortices is realistic for the outboard engine of a four-engine aircraft. The rotational flow induced by the vortices tends to carry the jet fluid with the vortex pair, causing a more symmetric jet interaction and diffusion of both vortices. Locating the jet along the spanwise plane inboard of the flap is an approximate representation of an aircraft with two engines. It could be predicted that the jet fluid interacts directly with only the flap vortex, therefore promoting merging. However, the results clearly indicate that the collapse of the vortex pair into a single structure is delayed. Analysis revealed that the jet turbulence tends to trail the flap vortex as the vortices rotate. Therefore, negligible interaction between the jet fluid and flap vortex was observed and the jet flux was shown to have little effect on the circulation of the vortices. The likely mechanism responsible for this delay was exposed when viewing the cross-flow rotating reference frame at the most upstream measurement location. The jet turbulence appears to alter the streamline pattern in the outer recirculation region. The disturbance occurs at a point where vorticity is advected radially outwards, which clearly inhibits the convective merger stage, limiting its ability to reduce the separation distance of the vortex pair. Further downstream the jet turbulence decays. This allows the outer recirculation zone to regain its coherence, and in consequence the size of the vortex cores begins to reduce.

The momentum flux is another parameter that was varied. Results revealed that with growing strength of the jet increasingly more turbulence was introduced into the flow, which has a larger effect on the merging process. That is either more diffusion of the vortices or greater disruption to the outer-recirculation region. Similar trends were produced for all combinations of vortex circulation ratio, that is $\Gamma_f = \Gamma_t$, $\Gamma_f > \Gamma_t$ and $\Gamma_f < \Gamma_t$. Overall it appears the data obtained on jet interactions with co-rotating vortices could be useful to alter the merging in the near wake for real aircraft. This is especially true for take-off when the jet flux from the engine is relatively large.

Fig 6a to 6c shows the downstream development of the vortex pair from $x/c = 4$ to 24 with jet flux $C_\mu = 0.025$. The jet fluid is observed to become rotated and stretched by the flow field generated by the vortex pair. However, the counter-clockwise rotation rate of the vortices appears to be greater than that of the jet fluid. It emerges that moving downstream the jet slowly interacts with the vortices. At the greatest distance downstream there are still two distinct vortex structures, suggesting merging is not complete.

The positioning of the jet vertically below the flap, Fig 6d to 6f, produces a vastly different interaction between the jet and vortex structures than that observed in Fig 6a to 6c. It is clear that at $x/c = 4$ the jet fluid has been elongated and wrapped around the flap vortex. Reasoning for this is probably because the rotation of the vortex pair tends to move the flap vortex into the path of the jet flux. Moving further downstream causes the tip vortex to wrap the jet fluid around itself. The images reveal that at $x/c = 24$ there appears to be a single merged structure where the remnants of the jet fluid has been roll-up around the solitary vortex. Hence, the flow visualization reveals that the jet alters the development of the flap and tip vortices when comparing the two nozzle configurations. It appears that configuration I has a reduced rate of rotation compared to configuration II. At $x/c = 24$ this difference is clearly visible because the spanwise jet location (Fig. 6c) demonstrates an unmerged vortex pair whereas configuration II (Fig. 6f) promotes the production of a single axi-symmetric merged structure.
Figure 6: Flow visualization for equal strength co-rotating vortices (T = tip vortex, F = flap vortex), \( h_j/c = 0.75, \ h_v/c = 0.6 \) and \( C_{\mu} = 0.025 \). Left column - configuration I, right column - configuration II. The schematic above figures illustrates the experimental setup.
1.2.3 LES Simulations of multi-vortex configurations, including wake roll-up

Two main numerical activities have been conducted regarding the interaction between a vorticity sheet and jets. The first one by UCL [29], this dynamics was simulated temporally for a model flow of a propelled wing wake. It consists of a vorticity field given by the Prandtl lifting line theory applied to an elliptic wing and two jets. Their characteristics have been chosen to represent a cruise configuration (high Reynolds number, large jet/wing tip distance and a relatively large jet to vortex strength ratio). The jets are wrapped around each wing tip vortex but do not penetrate their core and affect very slightly the vortices. Indeed, the global dynamics is similar to the one without jets, with the same development of instabilities. These results are explained by the large initial jet/wing-tip distance, thus the intensity of the jets is very low when they are close to the wing-tip vortices.

The second numerical activity has been performed jointly by UCL and CERFACS for a relevant realistic configuration. Indeed, the near-wake analysis of NLR [10] showed that there is a significant effect of the jet on the core of the flap tip vortex. Thus, the experimental flow field of Airbus obtained during the C-Wake project has been used to initialise the calculations. The objectives were to validate CFD experiments, to confirm the results of the previous studies using simplified configurations and analytical models, and to obtain results in the mid-field, allowing investigating if the favourable effect of the jet persists downstream.

UCL has considered a configuration with jets (configuration FFLFH1 of D2.1.1-1 [10]) and has performed both Time- and Space-developing simulations while CERFACS has used the Time-developing approach to compare the configurations with jets (configuration FFLFH1) and without jets (configuration FFCTH1). These two studies are reported in deliverable D2.1.1-3 [27].

Results of simulations initialised with an experimental flow field

For this aircraft configuration, the half plane of wake vortex is composed of two main vortices generated at the flap and wing tip. In the case of Level Flight (configuration FFLFH1), there are two engines jets. Both TD simulations of UCL and CERFACS for this configuration showed that the first instances of the vortex dynamics are characterised by the outer jet wrapping around the flap vortex, while instability develops in the inner jet. Then, the two vortices merge into a single vortex, surrounded by turbulent structures from the jets. This external turbulence slowly decays in the following. No global differences were observed between the TD and SD results of UCL. The comparison with the experimental measurements at x/b=1.3 is good for the vorticity fields (Fig. 7a). However, the structures of the jets showed slight differences between the CFD and experiments results (Fig. 7b). In the TD simulations the inner jet is more stretched. The outer jet has significantly lost its coherence in the TD simulations of UCL, while it remained more compact in the TD developing simulation of CERFACS and SD simulation of UCL, as in the experiments. However the comparison between CFD and experimental results on the axial velocity is difficult due to the global velocity deficit in the experimental measurements at this downstream distance. Moreover, in the simulations the initial flow was unperturbed, which is not the case in reality. For the configuration without jets (configuration FFCTH1), the dynamics is governed by the merging of the two vortices, which takes place later than in the case with jets. A good qualitative agreement of the vorticity field is again obtained (Fig. 8).

The comparison with experimental data is in good agreement for the vortex positions, the vortex core radius and the averaged circulation. The main difference comes from the axial velocity. It appeared more stretched and less extended in the CFD simulations (lower effect in Space-Developing approach Fig. 9). The jets positions are nevertheless globally good. For such dynamics flow of jet/vortex interaction, the grid resolution is important, as the jets have a spatio-temporal development and the interaction with the vortex is three-dimensional. This problem concerns the experimental facilities and CFD simulations.
Figure 7: Configuration FFLFH1 at x/b=1.3. (a) Comparison of the averaged vorticity field from TD simulation of CERFACS (left) and experimental data. (b) Comparison of axial velocity (averaged in longitudinal direction in CFD results).

Figure 8: Comparison of vorticity field at x/b=1.3 of FFCTH1 configuration, between TD simulation of CERFACS (right) and experimental data (left).
1.3 Task 2.1.2 - Hot jet / vortex interaction

In the frame of Subtask 2.1.2 "Hot engine jets/compressibility effects", partners CERFACS, CUT and ONERA investigated the temperature and compressibility effects dealing with vortex interactions with hot jets. This activity complements the research work performed in Subtask 2.1.1 with cold jets. The following topics have been considered:

- The density variations which affect the stability of the hot jets,
- The instabilities resulting from slight differences in the temperature of the fluid within the trailing vortex, as could result from the mixing with engine jets,
- The stability of the vortex interaction with turbulent hot jet.

Work performed by partner CUT was devoted to the preparation of the experimental and numerical data base, relevant to isothermal and non-isothermal jets. These data concerned jets in various inflow conditions: Reynolds number, boundary layer thicknesses, density ratio (between jet and ambient fluid). Additional numerical work was carried out by varying turbulence level in the inlet velocity profile, using Large Eddy Simulations (compact pseudo-spectral LES). Detailed results are provided in the Technical Report TR-2.1.2-2 [11].

Figure 9: Space-Developing simulation of UCL [27] for the configuration with jets (FFLFH1), iso-surfaces of vorticity colored by the axial velocity.
A synthesis of the stability analyses of a vortex with temperature variations resulting from a hot jet and a single vortex interaction was completed by partner ONERA, and is reported in the Technical Report T.R. 2.1.2-3 [11]. A first approach examined the stability of swirling flows in a non-homogeneous fluid, while a second approach dealt with a Direct Numerical Simulation (DNS) of a two-dimensional Lamb-Oseen vortex with a heavy internal core.

The analysis of the various ONERA F2 WT test campaigns was completed by partner ONERA, providing a data base for various parameters: distance between the injector axis and the wing tip, as well as jet temperature [hot jet (550K) / cold jet (300K)] for constant momentum rate. The Technical Report T.R. 2.1.2-6 [12].

Temporal Large Eddy Simulations (LES) of turbulent hot jet/vortex interaction was performed by partner ONERA, and the Technical Report T.R. 2.1.2-4 [13]. Finally, temporal Large-Eddy Simulations (LES) of the interaction of a hot jet with a vortex were performed by partner CERFACS, for identical conditions as those of subtask 2.1.1 [14], thus for different flight phases: take-off, approach and cruise (cf. Technical Report T.R. 2.1.2-5 [14]).

1.3.1 Stability Analysis of Vortex with Temperature Variations Resulting from Hot Jet/Single Vortex Interaction

Stabilising mechanisms associated to rotation usually make a vortex very resistant to radial momentum diffusion. The present research activity considered possible density variation effects to achieve this goal. If density effects were significant, vortex control by means of injection of either heated or cooled air could be considered for example when dealing with aircraft wake vortices. Thus, the goal pursued in this activity was to evaluate the potential of such density effects to produce linear instabilities.

In a first part, the stability of swirling flows in a non-homogeneous fluid was investigated by partner ONERA. In the framework of non-homogeneous swirling flow stability, former work carried out at ONERA [15] pointed out the importance of two numbers, the Rayleigh discriminant and some parameter related to the buoyancy frequency. Density gradients were shown to produce two distinct kinds of instabilities. The first was the centrifugal instability which mainly affects axisymmetric, short axial wavelength eigenmodes. The second was the Rayleigh-Taylor instability (RTI) which mainly affects non-axisymmetric, two-dimensional eigenmodes.

In a second phase, a 2-D DNS of a two-dimensional Lamb-Oseen vortex with a heavy internal core was conducted. Thus, the flow field was initialised by the superposition of a basic flow and a perturbation, the latter being constituted of a small amplitude eigenmode of the linearised Navier-Stokes equations around the basic flow. The mesh had 681x681 points, the density peak and vortex core being represented by 30 and 100 points, respectively.

At first, the RTI started growing linearly; the DNS exhibited wavy azimuthal perturbations which were non-linearly distorted into bubble-like patterns characteristic of the standard development of these instabilities. Nevertheless, important differences were observed in the late stage development of the instability: contrary to the standard case, the bubbles were then stretched in the azimuthal direction leading to a strong radial filamentation of the flow.

1.3.2 Experimental Investigation of Hot Jet/Vortex Interaction

The experimental program was carried out in order to provide the various CFD teams with a representative data base for improving computation tools, able to predict with acceptable confidence the mixing phenomena of engine exhaust in the aircraft trailing vortices. The research provided a more complete description of the interaction of two heated jets with the wake vortices generated downstream of a rectangular wing, for conditions representative of an aircraft in cruise conditions. Therefore, different spacing distances between the jets and the vortices were considered, as well as variations of the stagnation temperature of the jets.

The tests were conducted at the ONERA F2 Fauga-Mauzac WT, the test section of which is 5m
long, 1.4m wide and 1.8m high. The maximum possible velocity is $100\,\text{ms}^{-1}$. The flow field was characterized using a 3D-LDV system (mounted on a mobile frame), hot-wire anemometry and several thermocouples.

The experimental set-up consisted of a vortex generator and a hot jet generator (Fig. 10). The vortex generator was a NACA 0012 airfoil section. The setup was stabilized by shrouds. The hot jet generator consisted of two ejectors, 0.01m in diameter, on the pressure side of the airfoil. Jet homogeneity was ensured by a grid located upstream of the ejector exit section. The experimental set-up was chosen to be representative of the case of a transport aircraft in cruising flight. Thus, the similitude ratio between the axial momentum of the jet and that of a vortex was conserved, making possible to set a thrust and lift close to those of cruising flight. The test conditions are provided in the Table 1.

| Model wing span, $b$ | 0.5 m |
| Aspect ratio $AR$ | 4 |
| Circulation $\Gamma_0$ | $0.8 \, \text{m}^2\text{s}^{-1}$ |
| Lift coefficient $C_L$ | 0.50 |
| Free flow velocity $U_0$ | $20 \, \text{ms}^{-1}$ |
| Hot jet velocity $U_j$ | $55.5 \, \text{ms}^{-1}$ |
| Ambient/hot jet density ratio | 1.2 |
| Jet/Vortex separation distance ($d/b$) | 21%, 10%, 5% |
| Jet diameter $D_j$ | 0.01 m |

**Table 1 – Test Conditions**

The impact of the jet momentum on the axial velocity component is illustrated at $X/b=1$ for the case $d/b=10\%$ (Fig. 11). Comparisons were made with results obtained when the heater was switched-off and the jet velocity was slightly decreased so as to conserve the same jet momentum. The presence of the jet led to significant modification in the vortex sheet. Without jet, there was a velocity deficit in the external part of the vortex sheet, which was probably due to the wake of the nacelles. When the jet was present, the flow was accelerated in this region.
Figure 11: Iso-values of the axial velocity component for \( d/b = 10\% \) at \( x/b = 1 \): (a) without jet; (b) hot jet; (c) cold jet (same momentum).

The position of the vortex was sensitive to modification of the jet/vortex spacing. Decreasing \( d/b \) led to changes in both the lateral and the vertical vortex positions. This denotes an influence of the jets on the spatial distribution of the vorticity contained in the vortex sheet which form the vortex. The jet crossed the vortex sheet and provoked lateral displacements of the vorticity. Conservation of the linear momentum should explain the changes in the vortex position, as detailed in by looking at distribution of vorticity.

However, any change of the jet exit temperature had almost no effect on the flow dynamics. This is illustrated in Fig. 12 when comparing, at \( X/b = 1 \), the axial and tangential velocity profiles across the vortex axis for hot and cold jet configurations. Thus, this result confirmed that temperature had no major effect on the development of the vortices.

Figure 12: Comparison of axial (a) and tangential (b) velocity profiles at \( X/b = 1 \), for hot and cold jets.

Following on the large amount of recorded temperature and velocity measurements, the main impact of the jets on the vortex characteristics remained weak. Indeed, slight variations in the final vortex positions were observed when the jet/vortex separation distance was changed, according to slight modifications of the spanwise distribution of the axial vorticity due to the jets. This led to small variations in the vortex center locations, while the jets let the vortex core thickness almost unchanged. Therefore, the statistics of the velocity fluctuations revealed that the jet turbulence promoted vortex meandering, probably through transient growth mechanisms. In most of the cases, the jet plume was just wrapped around the vortices without penetrating significantly into the cores. However, when the case jet/vortex spacing became small, one observed that the jets were quickly trapped into the vortices where they remained confined afterwards. At last, change in the
jet temperature had almost no influence.

1.3.3 Numerical simulations using LES

**LES and Experiments on Stability of a Hot Jet**
Partner Częstochowa University of Technology performed extensive LES studies of cold and hot round free jet stability. The main goals of these studies were to:
- reproduce the experimental results obtained also at the Institute of Thermal Machinery with special attention put to the problem of absolute instability clearly observed in experimental data
- study influence of the governing parameters on the cold and hot jet stability
- study influence of the inflow boundary conditions
- study the effect of external forcing on the cold and hot jet stability, parametric studies of bifurcating jets
- assess quality of LES predictions of the round free jet and mesh resolution required.

The main outcome of the studies performed was that the LES calculations did not reproduce the flow structure observed in the experimental data. The LES calculations performed for the natural jet even with very low inflow turbulence level always showed a maximum at the fluctuating velocity profile along the jet axis by contrasts to experimental data obtained in similar conditions. Some effort was devoted to apply more realistic inflow boundary conditions. The inflow boundary condition prepared with the use of digital filter was more realistic than white noise since no damping of the velocity fluctuations in the near field was observed. However, this new inflow boundary condition did not introduce a qualitative improvement of the LES predictions which were still far from the experimental data.

It was confirmed that the LES simulations are very sensitive to the mesh resolution in all those test cases in which strong large scale vortical structures could develop. In such cases mesh refinement can change qualitatively the results of the mean and fluctuating velocity profiles. One can expect that if the results are affected significantly by the mesh resolution when strong coherent vortices are present, all these test cases would be very challenging for the sub-grid modeling.

The problem of the instability mechanism for the hot jet is worth of careful discussion. The question could be posed whether current LES results actually captured correctly the absolute instability phenomenon. We observed that both convective and absolute instability could generate oscillations with the same frequency. It was confirmed by the velocity spectra for the hot jet shown in Fig. 13 where actually no additional peak is present.
LES of a Turbulent Jet and Wake Vortex Interaction

At partner ONERA Large Eddy Simulation (LES) of the interaction between a turbulent jet and a wake vortex were performed for three jet-vortex separation distances. Three different jet positions were tested. In the two first cases, the jets were located outside the vortex, and in the last case the jet was superimposed to the vortex core; that latter will be studied separately. In the first one (case A) the distance between the jet and the vortex centre is equal to \( 7.2R_j \). In the second one, case B, the jet is closer to the vortex and the separation distance was reduced to \( 3.6R_j \). The last case C was quite different because the jet was blowing in the vortex core making the flow similar to a q-vortex (Batchelor).

Initially, the jet simulation was carried out until the maximum turbulent kinetic was reached. Then, the resulting jet data was injected outside of the vortex in cases A and B, while in the last case C, the jet was blown into the vortex core. For cases A and B, the turbulent kinetic energy first increased and due to the longitudinal jet velocity, large-scale structures appeared around the vortex core as counter-rotating vortex helical structures. As moving downstream, the large-scale vortical structures disappeared and the kinetic energy decayed. In case C, the evolution of the longitudinal vorticity showed up the meandering of the vortex.

The evolution of the passive scalar clearly pointed out that the distribution initially included in the jet decreased rapidly and did not enter the vortex core for cases A and B. When the jet was injected in the vortex core, the passive scalar was concentrated in it and seemed not be able to escape of this region. In case C, the value of the Swirl number was sufficiently high to allow the vortex to evolve toward an equilibrium state and to become persistent, the vortex rotation stabilizing all external perturbations. Even very altered, the vortex core retrieves its initial state after some distance from the interaction and the jet is eliminated.

In Fig. 14, the helical structures surrounding the core are plotted, which are surfaces of azimuthal vorticity for the times mentioned previously. These large-scale helical structures were counter rotating vortices, where the green colour surface indicates a positive value (+0.4) and the orange
colour a negative one (-0.4). The position of the vortex is indicated in black by an iso-surface of vorticity $\Omega_y (+2)$. As the jet spreads, it was progressively deflected by the continuous input of cross-flow momentum so that it acquired azimuthal and radial components of velocity. The vorticity of the jet was progressively stretched and generated spiral-shaped vorticity structures. At the turbulent kinetic energy maximum, the large-scale vortical structures seemed more coherent in case A than in case B. In the dissipation regime, the jet was more rapidly annihilated when injected closer to the vortex. As the increase of turbulent kinetic energy was the same for both cases, this augmentation seemed more related to the vortex than the jet itself. As observed in the figure, the break-up of these large-scale structures took place, however in both cases the jet did not perturb definitively the vortex core. Due to the strong rigid-body-like flow field, the closer the jet was to the vortex, these structures broke up and drove the vortex to a laminar configuration.

![Figure 14](image_url)

**Figure 14:** Three-dimensional view of the azimuthal vorticity $\Omega_\theta$ (green: 0.4, orange: -0.4) at $t=155$ and 250 for case A (left) and $t=25$ and 150 for case B (right); the position of the vortex is plotted with an iso-surface of vorticity $\Omega_y (+2)$ in black.

**LES of Turbulent Hot Jet/Vortex Interaction**

Finally, partner CERFACS studied the hot jet/vortex interaction using a temporal LES approach. The objective was to simulate the hot jet/vortex interaction in realistic flight aircraft conditions. In particular, the influence of the characteristic parameters such as the separation distance between the engine jet and the vortex, and the ratio of jet and vortex intensities has been investigated.

Two types of interactions were analysed: in the first one the jet and the vortex were initially well separated, corresponding to a cruise flight condition. For this case, we assumed that the interaction could be split into two phases: the jet regime and the interaction regime, to model a two-engine aircraft configuration. The second type of interaction was called blowing case, as the jet and the vortex were very close, modelling the interaction in take-off or approach aircraft conditions. The jet characteristic parameters were estimated from a definition of an equivalent single jet to a double-flux jet with the same outflow and thrust.

The separation distances between the jet and vortex position, respect have been chosen equal to the ones employed in the ONERA experiments (cf. section 1.3.2). As, the Reynolds number is very high, all the calculations were performed using Large-Eddy Simulation.
The hot jet/vortex interaction in case of high-lift condition is characterised by a short separation distance. For these configurations, the jet was too close to the vortex in order to assume two regimes. Thus, the calculations were initialized with a laminar hot jet placed just under the vortex position (separation distance of 5.8% of the wingspan). The velocity characteristic ratio between the hot jet and the vortex was higher in case of take-off condition ($\frac{w}{v_{\text{max}}}=4.29$) than the one in case of approach ($\frac{w}{v_{\text{max}}}=1.816$). The interaction started immediately, with a rapid roll-up of the jet around the vortex. Due to the axial velocity interacting with the azimuthal velocity, the interaction resulted in the generation of azimuthal vorticity structures, as in cruise configuration. This process was more pronounced when the jet velocity was higher (Figs. 15 and 16).

**Figure 15:** Visualisation of a selected vorticity isosurface at the time $\tau=0.04$ for the hot jet/vortex interaction in case of high-lift conditions (Left-hand side: approach condition; right-hand side: take-off condition).

**Figure 16:** Temperature field at the time $\tau=0.04$ for the hot jet/vortex interaction in case of high-lift conditions, averaged in axial direction (Left-hand side: approach condition; right-hand side: take-off condition).

The interaction was strong for the take-off condition and an interesting result is that the vortex loses completely its coherency structure. For the approach condition the vortex was surrounded by jet turbulent structures, and its shape was very disturbed. But, contrary to the take-off condition,
there was no penetration of the axial jet velocity in its vortex core. Again, the excess of temperature seemed to play a minor role as similar results were obtained for the cold jet/vortex interaction [14].

In the first type of jet-vortex interaction (large separation distance), the dynamics of the interaction was clearly mainly controlled by the entrainment of the jet by the vortex and the turbulent diffusion of the jet.

In the second case (small separation distance between the jet and the vortex corresponding to the approach and take-off cases of a four-engine type a/c), the interaction process is strongly dependent upon the strength of the injected axial flow perturbations, i.e. stronger effects for take-off than approach phases.

For both cases, the density had no effect on the interaction process but only on the development of the jet.

1.4 Conclusions Task 2.1

The interaction of both cold and jets with a vortex has been investigated under both cruise flight conditions and the approach/take-off phase. Parametric studies were carried out both experimentally and computationally. Wake measurements were performed in the near wake for different high-lift configurations at a number of thrust settings.

The main parameters controlling the effect of the jet on the vortex are their relative strength and their initial separation distance. Indeed, any increase of the relative strength or a decrease of the jet-to-vortex distance, leads to a more pronounced effect of the jet. However, it was shown that the jet-to-vortex distance also affects the spanwise position of the tip vortex. With the jet positioned closer to the tip vortex, the latter moves further inboard. Another important parameter is the angle between the jet and the free stream. When the jet is blowing away from the vortex, its effect is reduced, whereas the jet effect is more pronounced when the jet is blowing towards the vortex.

Complementary three-dimensional temporal Large-Eddy Simulations were carried out in order to study the interaction between a cold exhaust jet and a vortex during the different flight phases. For the configuration where the jet and the vortex are close (which corresponds to the approach and take-off phases of a four-engine aircraft) the strong injection of axial flow perturbations leads to the loss of vortex coherence. For approach conditions, the vortex is not completely annihilated, contrary to take-off conditions. In both cases, the jet affects the vortex by reducing its peak velocity and by increasing its core radius. These results revealed that the vortex is strongly affected by the jet when it is close, and when the velocity ratio between jet and vortex is high.

The effect of the jets on the roll-up of a wing wake and on the resulting vortex systems was also investigated by means of three-dimensional temporal LES. Due to the relatively large initial jet/wing tip distance considered (corresponding to a cruise configuration), the jets do not affect significantly the dynamics and resulting averaged vortex structure compared to those of the same wake with velocity deficit but without jets. The jets contribute, similarly to the velocity deficit, to the development of successive instabilities, generating vortical structures and resulting in a deformation of the vortex core.

Similar experimental investigations, this time with hot jets, have revealed that any change of the jet exit temperature had almost no effect on the flow dynamics. Further, the temperature had no major effect on the development of the vortices. Corresponding LES studies confirmed that the excess of temperature seemed to play a minor role and results for hot jet/vortex interaction were similar to those obtained for the cold jet/vortex interaction.

Overall, comparison of LES results with experimental data was in good agreement for the vortex positions, the vortex core radius and the averaged circulation. For such dynamics flow of jet/vortex interaction, the grid resolution is important, as the jets have a spatio-temporal development and the interaction with the vortex is three-dimensional.

Finally, experimental investigations on the effect of a cold jet on the merging process for a co-rotating vortex pair revealed that the jet turbulence appears to alter the streamline pattern in the
outer recirculation region. Results revealed that with growing strength of the jet increasingly more
turbulence was introduced into the flow, which has a larger effect on the merging process. That is
either more diffusion of the vortices or greater disruption to the outer-recirculation region. Overall it
appears the data obtained on jet interactions with co-rotating vortices could be useful to alter the
merging in the near wake for real aircraft. This is especially true for take-off when the jet flux from
the engine is relatively large.
2. Task 2.2 - Vortex interactions with wakes (contributions of DLR, CENAERO, UCL, TUM & Airbus)

2.1 Task 2.2.1 - Effect of fuselage on vortex wake

Introduction
The aim of task 2.2 is to obtain a systematic insight into the interactions of a vortex with wake flows. Especially a further analysis of existing data from previous projects EuroWake, C-Wake, AWIATOR and numerical simulations (RANS and hybrid RANS-LES codes) to investigate the effect of fuselage wake on the wake vortex system of TAK four-engine large transport aircraft geometry (which represents a typical high lift configuration of a large transport aircraft) was done. As a reference data base wind tunnel experiments were performed at TUM-AER with hot wire measurements at different downstream locations behind the TAK model. With this comparison the quality and reliability of current CFD codes simulating the wake vortices of such an aircraft was shown.

First, the fuselage of the TAK configuration alone was simulated and compared to measurements. From this comparison, the choice of grid generation technique and the choice of an appropriate turbulence model were derived for such types of flow. To show the influence of the wind tunnel and the half model measurement technique a numerical simulation of the TAK model in the wind tunnel (half model on peniche) compared to a free flight simulation was done. Finally, the complete TAK model was simulated in free flight using the parameters derived from the fuselage simulations for such types of wake flow and the results are compared with wind tunnel measurements. Further on the influence of the numerical discretization was shown with a comparison of DLR-TAU and CENAERO Argo code. These codes present different modeling approaches as well as different numerical methods (e.g. turbulence modeling), leading to variations in the results. Finally analyses of AWIATOR measurements to get the influence of the wing-fuselage vortex were conducted.

Numerical Flow Simulation
The RANS equations are solved by a hybrid unstructured three dimensional finite volume code, the DLR TAU-code [17]. Some key features are: implicit time integration, central method with 80% matrix dissipation, local time stepping, multi grid technique, Mach number preconditioning, k-\omega-SST turbulence model of Menter [18] with a rotation correction and Reynolds stress model (RSM) [19]. The second code used is the Argo code of CENAERO. Further details can be found in [17], some key features are: unstructured tetrahedral meshes, edge-based hybrid finite volume and finite element discretization, low-diffusion flux-splitting scheme (AUSM+), diffusion terms are evaluated using a P1 Galerkin finite element discretization, Turbulence model Spalart-Allmaras model with Morton's rotation correction.

Wind tunnel model geometry, measurement techniques and simulated configurations

Wind tunnel model
The geometry can be split in two parts: the TAK model itself and the wind tunnel C of TUM-AER. The TAK Model (Fig. 17) is a half model of a four engine "Large Transport Aircraft" (LTA) with a scale of 1:19.25. Table 2 shows the dimensions of the TAK model, Table 3 shows the settings of the flaps, slats, ailerons and horizontal tail plane referring to a typical landing configuration. The wind tunnel C has a closed test section with dimensions of 21 m x 2.7 m x 1.8 m (length x width x height). The model is positioned on the tunnel floor with the reference point 2.8 m downstream of the nozzle exit and the wing tip pointing upwards. A peniche of 0.095 m height is used to raise the model fuselage above the wind tunnel floor boundary layer. The test section is further equipped with a three degree of freedom probe traversing system giving minimum steps of ±0.2 mm in axial, lateral and vertical directions. The wake vortex system of the TAK model can therefore be observed up to 4.7 wing spans downstream of the model.
Angle of attack $\alpha$ 7.0°
Lift coefficient $C_L$ 1.43
Wing span $b$ 2.982 m
Area $S$ 0.8802 m²
Aspect ratio $\Lambda$ 10.1
Mean aerodynamic chord MAC 0.3569 m
Fuselage length 2.90687 m
Fuselage diameter 0.29298 m

Table 2: Dimensions of the TAK model

<table>
<thead>
<tr>
<th>Flaps (i/b, o/b)</th>
<th>26.0°, 26.0°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slats (i/b, m/b, o/b)</td>
<td>19.6°, 23.0°, 23.0°</td>
</tr>
<tr>
<td>Ailerons (i/b, o/b)</td>
<td>5.0°, 5.0°</td>
</tr>
<tr>
<td>Horizontal Tail Plane</td>
<td>-6.0°</td>
</tr>
</tbody>
</table>

Table 3: Settings of flaps, slats, ailerons and horizontal tail plane

<table>
<thead>
<tr>
<th>Value</th>
<th>Low Re-number</th>
<th>High Re-number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re</td>
<td>530397</td>
<td>26537144</td>
</tr>
<tr>
<td>$T_\infty$</td>
<td>302.65 K</td>
<td>302.65 K</td>
</tr>
<tr>
<td>$P_\infty$</td>
<td>96000 Pa</td>
<td>96000 Pa</td>
</tr>
<tr>
<td>$V_\infty$</td>
<td>25 m/s</td>
<td>65 m/s</td>
</tr>
<tr>
<td>$M_\infty$</td>
<td>0.071691</td>
<td>0.186364</td>
</tr>
<tr>
<td>$L_{Ref}$</td>
<td>0.3569 m</td>
<td>6.870325 m</td>
</tr>
<tr>
<td>Scale</td>
<td>1:19.25</td>
<td>1:1</td>
</tr>
</tbody>
</table>

Table 4: Free stream conditions for the

Measurement techniques
A hot wire probe consisting of three wires was positioned downstream of the model and the time dependent velocities $u$, $v$ and $w$ were measured at a sampling rate of 3 kHz for 6.4 s at specific measuring planes. The voltages of the hot-wire anemometer were low-pass filtered at 1000 Hz and digitized with 16 bit precision. The measured velocities are then processed in order to obtain the mean and fluctuation velocities. The mean velocities are used to calculate the vorticity. An analysis of the turbulent flow field and a spectral analysis are performed using the unsteady data.

Simulated configurations
The numerical simulations are based on the Reynolds number for the wind tunnel and the free flight case. The corresponding free stream conditions are listed in Table 4. The variables are made non-dimensional using the free stream velocity and the wing span. The origin of the reference system is set at the trailing edge of the winglet tip at $\alpha = 0$°. For the TAK model, four configurations by combination of fuselage, wing and horizontal tail plane were considered at low and at high Reynolds number. The size of the hybrid unstructured grids for the numerical simulations varies from 0.5 - 8.4 $10^6$ depending on the investigated cases. The simulations have been performed fully turbulent. To resolve the flow features in the vicinity of the configuration grid adaptation was used for the isolated fuselage and the complete TAK geometry in the free flight cases.
Table 5: Simulated config. (FW: FAR-Wake, l/h: low/high Reynolds number, f/w: free flight/wind tunnel)

<table>
<thead>
<tr>
<th>Case</th>
<th>Fuselage</th>
<th>Wing</th>
<th>Horizontal tail plane</th>
<th>Peniche and Wind tunnel</th>
<th>Low Reynolds number</th>
<th>High Reynolds number</th>
<th>Grid Adaptation</th>
</tr>
</thead>
<tbody>
<tr>
<td>FW-01lf</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>FW-02lf</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>FW-03lf</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>FW-04lf</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>FW-01hf</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>FW-02hf</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>FW-03hf</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>FW-04hf</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>FW-04lw</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 18: Initial grid of the cross flow plane at $x^* = 1.0$ with TAK model as reference (FW-04lf).

Figure 19: Grid adaptation level "6" of the cross flow plane at $x^* = 1.0$ with TAK model as reference (FW-04lf)

Results

**Numerical simulation: wind tunnel vs. free flight**

When comparing wind tunnel results with free flight measurements or numerical simulations of free flight, the question of wind tunnel influence appears. There are a number of good validated corrections for this influence, but in some areas, e.g. high lift or half model tests, corrections are not reliable. In order to get the difference between wind tunnel and free flight for the TAK model in the wind tunnel C of TUM-AER, the wind tunnel in combination with the TAK model is simulated numerically [20].
The complete TAK model in free flight (FW-04lf) and the TAK model in the wind tunnel (FW-04lw) are shown respectively together in Fig. 20. The vortices found in the wind tunnel case are colored red, the vortices from the free flight are colored blue. Comparing both cases, the differences in the position of all the vortices can be found. The two vortices emanating from the outboard end of the outboard flap and the inboard end of the aileron are closer together in the wind tunnel case, the same effect can be found for the vortices emanating from the lower and upper part of the winglet. In general, the vortices of the inboard wing are more inboard for the wind tunnel case, on the outboard wing however more outboard compared to free flight. Further on, the vortices behind the wing are displaced further downwards compared to the wind tunnel due to the wall influence there. It can be concluded from this figure that for measurements taking place further downstream a reduced displacement of the wake can be found in the wind tunnel case compared to free flight.

In Fig. 21 the lift distribution $F_{z}(y)$ is shown for the low Reynolds number configurations. Comparing the curves for configurations FW-04lf and FW-04lw, a shift of the lift from the outboard to the inboard wing can be found changing from free flight to the wind tunnel configuration. This is mainly due to the peniche influence, whereas the wind tunnel influence gives an increased lift over the complete wing span.

**Wake vortex of the fuselage of the TAK model**

The comparison between numerical and experimental results concentrate on the non-dimensional axial vorticity distribution $\omega_\alpha$ on the configuration FW-01lf for a cross flow plane at $x^* = 0.37$ located close behind the fuselage end. Clearly, three vortices can be found, Fig. 22: two co-rotating vortices above and below the fuselage (color red, positive rotation) and one counter-rotating vortex.
(color blue, negative rotation). The lower vortex with positive rotation is caused by the belly fairing. The flow separates at the upper edge between the belly fairing and the fuselage causing a vortex with positive axial vorticity. The vortex on the upper side of the fuselage is caused by the vertical velocity component due to the positive angle of attack. The flow separates at the upper part of the fuselage cross section, which can be seen as an inclined cylinder, forming a vortex of positive vorticity. In between a counter-rotating vortex can be seen, which is caused by the flow separating from the fuselage rear part, which is narrowing down towards the end, and by induction of the two vortices rotating in positive direction.

Thus, the main influence of the fuselage wake on the wake vortex development is as follows:

- Adding the wing, the two vortices with positive sense of rotation are suppressed. Here, the wing circulation drops at the fuselage junction that the wing-fuselage vortex is the pre-dominant effect, Fig. 23.
- The inclined fuselage produces a strong turbulent wake. Downstream, this wake is expanded in vertical direction, on the one hand in upper direction by the induced vertical velocity due to fuselage inclination and on the other hand in downward direction when the downwash of the wing is added. During the roll-up process, this expanded turbulent wake enhances the diffusion of inboard vortices such as the wing-fuselage vortex, an inboard flap edge vortex or the horizontal tail plane vortex. Therefore, this effect contributes to the decrease in strength of these vortices, typically counter-rotating in sense to the wing tip vortex, within the extended near field.
- This vortex diffusion hampers for example the persistence of favorable four-vortex systems which are characterized by strong co-operative instabilities leading to a more rapidly wake vortex decay.

![Figure 22: Axial vorticity distribution $\omega_x$ for the fuselage of the TAK model at $x^* = 0.37$ by measurement at TUM-AER.](image)

Comparing these results with the numerical simulations (RANS, Fig. 26(a)) a clear loss of axial vorticity in this cross flow plane can be found in the simulation. To clarify the influence of the discretization and the influence of enhanced turbulence modeling three simulations were done. First, a grid adaptation sequence with overall 10 steps was performed. The result is shown in Fig. 26(b), which depicts the vortex structure found in the experiments clearly more detailed and with increased values in the vortex cores.

<table>
<thead>
<tr>
<th>Case</th>
<th>$\omega_x$ upper vortex</th>
<th>$\omega_x$ middle vortex</th>
<th>$\omega_x$ lower vortex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment</td>
<td>20.5</td>
<td>-28.3</td>
<td>16.7</td>
</tr>
<tr>
<td>$k-\omega$ SST</td>
<td>5.7</td>
<td>0</td>
<td>11.4</td>
</tr>
<tr>
<td>$k-\omega$ SST &amp; Adaptation</td>
<td>17.0</td>
<td>-15.4</td>
<td>24.0</td>
</tr>
<tr>
<td>RSM</td>
<td>10.8</td>
<td>-2.0</td>
<td>10.5</td>
</tr>
<tr>
<td>RSM &amp; Adaptation</td>
<td>23.4</td>
<td>-24.2</td>
<td>29.5</td>
</tr>
</tbody>
</table>
Table 6: Maximum of non-dimensional axial vorticity $\omega_x$ for the TAK fuselage (Case FW-01lf).

Figure 23: Dimensionless axial vorticity distribution for the wing-fuselage configuration (nacelles off) at station $x/b = 0.37$.

(a) $k-\omega$-SST TU-model.
(b) $k-\omega$-SST TU-model & grid adaptation.
(c) RSM TU-model.
(d) RSM turbulence model & grid adaptation.

Figure 24: Axial vorticity distribution $\omega_x$ for conf. FW-01lf at $x^* = 0.37$, simulation with DLR-TAU code

Because there are no assumptions about the Reynolds stress tensor in the Reynolds stress model, in contrast to the most other turbulence models, no vortex correction is required. Further on, it has a noticeable lower dissipative effect on the flow. In Fig. 24(c) the result is shown for the baseline mesh. Compared to Fig. 22 the result is obviously improved compared to the measurement, but the values of the vorticity are still too low.

Combining grid adaptation with the RSM turbulence model again an improvement can be found, Fig. 24(d). Now the position, the number and the strength of the vortices are in good comparison with the experimental results, Fig. 24 and Table 6. Only the size of the vortical structure is not fully the same, which can be an effect of an e.g. unsteady flow field in the measurements combined
with a still too coarse mesh. Concluding from these results grid adaptation and enhanced turbulence modeling should be used to get a better agreement between measurement and numerical simulation in case of wake vortex flows based on the Reynolds Averaged Navier-Stokes equations.

Reynolds-Number influence
The influence of the Reynolds-number is shown on configuration FW-04lf (Re = 0.53 $10^6$) and FW-04hf (Re = 26.5 $10^6$). In Fig. 25 the vortices are shown for both configurations. The main effect can be found on the inboard wing. There to additional vortices with small radius can be found behind the inboard engine in case FW-04lf, whereas a bigger vortex emanating between the inboard engine and the fuselage can be found in case FW-04hf. Further on a movement of the vortices on the outboard wing more outboard and at the same time a movement vortices at the inboard wing more inboard can be observed in case FW-04hf.

Figure 25: Config. FW-04lf & FW-04hf, vortex structures of FW-04lh in red, of FW-04lf in blue

Figure 26: Lift distribution for all simulated configurations (Low- and High Reynolds-number)

Configurations with higher Reynolds-number (dashed lines) show a higher lift compared to those at the lower Reynolds-number (solid lines), Fig 26. The spanwise lift distribution is, however, nearly unchanged by varying the Reynolds-number in this case for all four configurations.

RANS-LES of a fuselage wake (near-field study)
Partner CENAERO conducted unsteady flow simulations. Given the Reynolds number under investigation, a wall-resolved Large Eddy Simulation (LES) approach was not affordable, and a hybrid RANS-LES approach has been selected where the turbulence is modeled by a RANS method near the walls and a LES approach away from these boundaries (DES [21]). It turned out that the flow remained steady whatever the turbulence modeling used (RANS or DES) and the computed vortical structures behind the aircraft are in very good agreement with the experiments.
Nevertheless, numerical tests showed that the spatial discretization has a strong influence on the solution quality, well before the impact of the choice of a turbulence model. The convective term in the Argo code is spatially discretized using the AUSM+ scheme [22] or a central scheme that conserves the discrete kinetic energy [23] here termed K-scheme, ensuring that no artificial dissipation needs to be added in order to reach stability. The high-order dissipation is done using an incompressible scaling well-posed for the present low-Mach application.

Figure 27: Streamwise vorticity for the coarse mesh, measured in a plane corresponding to $x^* = 0.37$: each figure is labeled using the turbulence model and then the spatial discretization used

Figure 28: Streamwise vorticity for the medium mesh, measured in a plane corresponding to $x^* = 0.37$: each figure is labeled using the turbulence model and then the spatial discretization used

A first analysis can be done considering all the approaches applied to a same coarse mesh. From Fig. 27 it can be deduced that the numerical dissipation has a strong influence on the solution quality. In fact, the Argo code solutions, Fig 27(a) and (b), only differ by the spatial discretization. The AUSM+ scheme, Fig 27(a), clearly filters out the vortical structures. On the contrary, a low-dissipation scheme, like the K-scheme, Fig. 27(b), can give a prediction of the vortical pattern in good agreement with the experiment, Fig. 27(a), even though the mesh is rather coarse. Considering the DLR results, the increase of the turbulence model refinement and complexity, from the SA, Fig.27(a), to the k-ω, Fig. 27(c), and finally to the RSM, Fig. 27(d), is visible but less important that the gain obtained from a less dissipative scheme, Fig. 27(b). As a conclusion, it is worth mentioning that these remarks are not meant to be extended to all RANS simulations. It is to the author opinion that the prevalence of the spatial discretization quality on the turbulence model quality is strongly dependant on the application (here capturing vortical structure at a rather low Mach number). The present test case shows clearly that discretization issues have to be considered carefully.

A second analysis can be done, comparing the CENAERO results on a medium mesh, Fig. 28(b) and 28(c), where the central K-scheme is used for SA and DES approaches. The DES simulations gave steady results, Fig. 28(b), and a grid refinement study up to 8 million nodes mesh confirmed
this statement. This can be explained by the low angle of attack of the geometry and the slenderness of the fuselage (it is clearly not a massively detached flow). The large scales of the flow are thus steady. Nonetheless, in reality, unsteady turbulent structures exist but are far smaller in size (i.e. in the boundary layers or probably in the wake) so that major scale discrimination is present. Their influence on the large structures of the flow should be integrated properly by the turbulence model. Comparing Fig. 28(b) and (c), it can be seen that the solution quality is equivalent between the S-A model and DES approaches. This conclusion is not surprising as the large structures of the wake are steady. Comparing Fig. 27(b) and 28(c) shows the beneficial effect of the grid refinement from the coarse mesh to the medium mesh. A mesh refinement study has showed that the vortical structures are not changing significantly with a finer mesh. Finally, it can be seen that the grid adaptation, Fig. 28(d), improved the initial $k-\omega$ solution, Fig. 27(c), but the solution is not yet totally grid-converged explaining that the vorticity magnitudes are less well predicted.

**Wake vortex of the complete TAK model (experiment)**

The non-dimensional axial vorticity distributions of the complete TAK model obtained in the wind tunnel by hot-wire anemometry at $x^* = 0.37$ is depicted in Fig. 29. Five main vortices can be identified, namely from outboard to inboard, the Wing Tip Vortex (WTV), the Outboard Nacelle Vortex (ONV), the Outboard Flap Vortex (OFV), the Inboard Nacelle Vortex (INV) and the Horizontal Tail plane Vortex (HTV). The step in the vorticity layer between $y^* = 0.6$ and $y^* = 0.7$ corresponds to the position of the outer flap edge. Further outboard on the wing the ailerons are positioned at $5^\circ$ causing only a small downwash of the shear layer, whereas inboards the flaps are positioned at $+26^\circ$ causing a larger downwash and hence a kink in the shear layer results. The bump at $y^* = 0.4$ indicates the inboard nacelle vortex caused by the inboard nacelle. This bump is not evident at the position of the outboard nacelle, as the outboard nacelle vortex and the outboard flap vortex have turned around the roll up center by almost 180°. The winglet is also reflected by a kink at the outer end of the shear layer. In comparison, the result for the six times refined grid is shown in Fig. 30.

Comparing these results the overall flow field is met very well. The positions of the vortices differ slightly due to the influence of the wind tunnel as mentioned above. The peak vorticity of the horizontal tail plane vortex at $(y^*; z^*) \sim (0.3; 0.0)$ matches the measurement very well and the vortex sheet rolling up into the vortex is also visible in the calculation. The diameter of the horizontal tail plane vortex is larger in the simulation due to dissipation effects. The vorticity sheet emanating from the wing can be seen, but its shape differs slightly and the peak vorticities are clearly underestimated. Although a grid adaptation was performed, this result suggests that the adaptation was not performed far enough to capture the gradients and peaks. Further adaptation would be possible, but very expensive.

**Figure 29:** Axial vorticity distribution $\omega_x$ for configuration FW-04lw at $x^* = 0.37$, measurement at TUM-AER.

**Figure 30:** Axial vorticity distribution $\omega_x$ for configuration FW-04lf at $x^* = 0.37$, simulation with DLR-TAU code, RSM turbulence model & grid adaptation.
Continuing downstream to $x^* = 1.0$ the measurement results are illustrated in Fig. 31 and the simulation results in Fig. 32. The four remaining vortices can clearly be seen and it is evident that all vortices have turned counter clockwise. The shear layer of the horizontal tail plane is in the process of rolling up into the horizontal tail plane vortex. The outboard nacelle vortex (ONV) and the outboard flap vortex (OFV) have merged. The vortex location and size in the simulation appears smeared, again due to dissipation effects. The overall movement of the vortices, i.e. the counter clockwise rotation, is reproduced correctly in the simulation. The peak vorticity again is underestimated.

Comparing measurement and numerical results differences in vortex positions can be found. As shown above the influence of the wind tunnel on the vortex sheet is the main reason for this effect. To eliminate this difference a numerical simulation of the complete TAK model in the wind tunnel including grid adaptation and the RSM turbulence model was initially planned. Running this case it was found out that the main memory of the used super-computer was too small for this case. The reason is the nearly doubled memory consumption of the flow solver due to the additional equations from the RSM turbulence model and the increased grid sizes due to grid adaptation.

The parameters derived for wake vortex simulations resulted in a reasonably well prediction of the vortex positions and movements, whereas the peak vorticity levels are calculated too small probably due to a still too coarse mesh. In the case of the fuselage of the TAK model, where a mesh with significantly lesser nodes could be used as only the fuselage region needed adaptation, the result could be enhanced drastically. A similar behavior of the solution is expected, if further grid adaptation would be used on the entire TAK model.

### 2.2 Task 2.2.2 - Wing elements

Subtask 2.2.2 focuses on wakes generated by wing elements to characterize the effect of such elements on the wake vortex evolution and development. Special emphasis is on vortex merging in the near and extended near field and also on turbulence characteristics and unsteady effects affecting the properties of the remaining rolled-up trailing vortex persisting in the far field. In this context, the wake flow fields of the following components of a typical large transport aircraft are studied in detail investigating six different configurations which can be grouped in four categories:

1. Baseline (reference) configuration (TAK model with winglet and horizontal tail plane).
2. Fuselage configuration (TAK fuselage alone) to study the effect of the fuselage wake on the wake vortex structure.
3. Configurations removing or exchanging different wing elements to characterize their influence on the wake vortex system including the configurations without nacelles, without winglet and without horizontal tail plane.
4. Configuration with landing gear referring to the baseline with the main landing gear attached to study the landing gear wake and its influence on the wake vortex system.

**Nacelles**
Removing the outboard and inboard nacelles changes the wing load distribution. Following effects on the vortex wake occur, Fig. 33:
- The near field vortex topology changes accordingly by missing the strong inboard and outboard nacelle vortices.
- The increased load on the outboard wing results in higher levels of axial peak vorticity for the wing tip vortex (WTV) and the outboard flap vortex (OFV).
- The final rolled-up trailing vortex exhibit no significant differences compared to the baseline case.

![Figure 33: Dimensionless axial vorticity distributions comparing nacelle-on and nacelle-off configurations at stations x/b = 0.37 and 3.0.](image)

**Winglet**
There is also no remarkable difference in the overall vortex topology between the wing tip and the winglet configuration. Changes are present in vorticity levels:
- The wing tip causes a much stronger vortex than the winglet. For the winglet configuration, a decrease in axial peak vorticity of the WTV is expected because the winglet is aimed to reduce induced drag.
- Also in the extended near field, the vorticity peak of the WTV for the configuration without winglet is still higher than for the baseline.
- Comparing the angular velocity with which the ONV/OFV and the WTV rotate counter clockwise around each other with that of the baseline configuration, the rotation has progressed far further for the configuration without winglet.

**Horizontal Tail Plane**
Again, the aircraft loading changes when the upstream downwash effect of the tail plane on the wing is missing.
Therefore, the wing tip vortex shows an increased level in axial peak vorticity.

As the horizontal tail plane vortex diminishes in strength within the extended near field region the properties of the final rolled-up trailing vortex do not change markedly if that vortex is not present.

Landing gear influence
The landing gear consists of the stay and the four wheels which are inclined with respect to the landing configuration investigated. The stay and the wheels create a bluff body wake which interferes with the shear layer emanating from the wing and the wing-fuselage junction. Therefore, compared to the baseline configuration the flow field features attributed to the deployed landing gear are as follows:

A) Near field characteristics (x/b ≤ 1.0)

- The landing gear wake is associated with additionally vorticity spots of moderate levels forming a low energy landing gear vortex system
- It is also indicated by an area of increased turbulence intensities. This area is shaped like an "eight" which corresponds to the two inclined wheel pairs. The upper turbulence bubble refers to the inclined front wheel pair, the lower one to the inclined rear wheel pair. The vertical extension of the landing gear wake turbulence area is therefore about twice the lateral one and the turbulence area of the wing vortex sheet becomes expanded also.
- The spectral densities of the axial velocity fluctuations show generally broadband characteristics with some peaks of moderate energy concentration attributed to coherent periodic structures of the landing gear wake. A strong energy concentration at specific frequencies can not be detected.

As the leading geometric parts of the landing gear are related to cylindrical elements one may expect some frequency dependent energy concentrations linked to periodic vortex shedding mechanisms. Characteristic length scales are given by d = 0.019 m (landing gear stay), D = 0.1 m (lateral extension of wheel pair), and h = 0.13 m (vertical extension of inclined wheels). A Strouhal number of Sr = 0.2 ± 0.01 is attributed to periodic vortex shedding for the given Reynolds number range Re(d, D, h) = 0.28 - 1.9 x 10^5: laminar to transition). Considering the velocity of U_∞ = 25 m/s, the corresponding reduced frequency values are in the range of k(d) = 14.9 - 16.4, k(D) = 2.8 - 3.2 and k(h) = 2.2 - 2.4. The landing gear wake spectra show some moderate energy concentrations at these reduced frequencies, but there is no significant increase in the power spectral densities, Fig. 34.

- At x* = 0.37, the axial vorticity distribution still indicates the landing gear vortex system. Due to the wing downwash the area of the landing gear wake turbulence moves downward spreading out the whole area of high turbulence intensities in the wing-fuselage region. Again, the spectral densities exhibit a broadband behavior with some moderate energy peaks which are similar to the ones for the wing vortex sheet.
- The displacement effect of the landing gear wake shifts the vortex centers of the main vortices slightly outboard while the Horizontal Tail Plane Vortex (HTV) shows a more noticeable outboard shift of about Δy/(b/2) = 0.04 at x/b = 1.0. The landing gear wake interference retards the roll up process and, especially, the inboard movement of the HTV.
B) Extended near field characteristics (x/b = 1.0 - 4.7):

- The landing gear wake interference continues to retard the inboard movement of the HTV. Downstream, the difference in the lateral HTV position reaches a value of $\Delta y/(b/2) = 0.1$ at $x/b = 4.7$.
- The inboard areas of high turbulence intensities are further enlarged showing clearly the annularly shaped region of the landing gear wake turbulence.
- Beside the overall moderate outboard shift in vortex positions, the wake roll up process is not markedly affected by the presence of the deployed landing gear. The main influence is attributed to the inboard region where the area of high velocity fluctuations becomes significantly enlarged in lateral and vertical direction.

Summarizing, the influence of the landing gear on the wake vortex development is small for downstream stations of the extended near field. Strength and position of the wake vortices stay almost unchanged and thus, the impact on reducing aircraft separation distances is negligible. The enhancement of inherent wake instabilities is also small.

**Influence of the wing-wake with velocity deficit**

The temporal evolution of a wing wake with initial velocity deficit due to boundary layers is investigated at high Reynolds number by means of Large Eddy Simulations (LES) [28, 29]. An efficient combination of Vortex-In-Cell and Parallel Fast Multipole methods, the VIC-PFM method, is used. The initial condition consists in a thin vortex sheet that will roll-up into two counter-rotating far wake vortices. The initial streamwise vorticity component is obtained from Prandtl lifting line theory, applied to an elliptic wing. In this wake model, the boundary layers effects are taken into account by adding a velocity deficit inside the vortex sheet, defining transverse vorticity components. The analysis includes the comparison to the vortex wake without velocity deficit, to the velocity deficit alone and to the same configuration at higher Reynolds number. The
longitudinally averaged and three-dimensional dynamics and the time-evolution of the wake structure, including the axial velocity component, are analyzed (Fig. 35). The work is globally in very good agreement with previous investigations (mainly experimental) dedicated to near field wake vortices. The careful numerical investigation, complementary to the existing experimental ones, provides insights into previously reported features as well as new details concerning the complex dynamics of this flow field. The wake roll-up appears to be drastically affected by the presence of the axial velocity deficit (and of the corresponding vorticity components).

Figure 35: Isocontours of vorticity norm ($|\omega|$ $t_0 = 400$ (high opacity) and $|\omega|$ $t_0 = 200$ (low opacity)) colored by the axial component of vorticity, showing the time evolution of the three dimensional structure of the wake with velocity deficit at $Re_{\Gamma} = 10^4$ for $\tau = [0.05, 0.07, 0.25]$.

2.3 Conclusions Task 2.2
RANS computations were performed on the fuselage and the complete TAK model representing a typical four engine large transport aircraft. Experiments for both configurations are also available. It is observed that RANS computations are qualitatively comparable to experiments for the isolated fuselage case, whereas the strength of the axial vorticity patterns shows considerable differences. Using grid adaptation and enhanced turbulence modeling (RSM turbulence model) a significantly improved agreement can be found. This approach leads to the recommendation to use these
techniques for the simulation of wake vortex sheets by means of CFD. Form the RANS-LES computations it was found the prevalence of the spatial discretization quality on the turbulence model quality is strongly dependant on the application (here capturing vortical structure at a rather low Mach number). The present test case shows clearly that discretization issues have to be considered carefully.

To capture the wind tunnel effect versus free flight the complete TAK model in free flight was compared with the TAK model in the wind tunnel on the initial grid. Differences in the positions of all the vortices were observed. Overall, the vortices of the inboard wing are located more inboard in the wind tunnel, on the outboard wing however further outboard compared to free flight. Further, the vortices behind the wing are displaced more downwards compared to the wind tunnel due to the wall influence there.

The influence of the Reynolds-number was shown. A movement of the vortices in the area of the outboard wing outboard and at the same time a movement inboard of the vortices on the inboard wing in the high Reynolds-number case was observed. Further on, nearly unchanged lift distribution by varying the Reynolds-number was found, but an overall increasing lift for the high Reynolds-number case.

The flow topology of four configurations was analyzed in detail. For the configuration with fuselage a vortex-pair can be found above the fuselage. Behind the belly a vortex-pair is formed - these vortices are called belly-vortex. Finally, incorporated between both vortices a counter-rotating vortex can be found. With the additional tail a vortex sheet behind the HTP can be found with an incorporated vortex on the outboard end of the HTP. Because of the vortex sheet the fuselage vortex has a smaller span-wise extent. The belly-vortex is unchanged, running beneath the HTP. Because of the span-wise lift change vortex can be found in the HTP-fuselage junction.

In case of the fuselage with complete wing the fuselage vortex is weaker and superposed by a counter-rotating vortex in the tail of the fuselage.

The influence of the wing elements are discussed in detail. For the nacelles, the winglet and the horizontal tail plane after the rollup of the vortex sheet no remarkable influences can be found. For the landing gear the influence on the wake vortex development is small for downstream stations of the extended near field. Strength and position of the wake vortices stay almost unchanged and thus, the impact on reducing aircraft separation distances is negligible. The enhancement of inherent wake instabilities is small.

Partner UCL performed temporal LES simulations of the wake roll-up behind an elliptically loaded wing with a finite vortex sheet thickness. Without simulated velocity defect the wake roll-up behaves laminar-like. With simulated velocity defect, the wake develops instabilities due to the stretching of spanwise and vertical vorticity components. Only a mildly faster decay of peak cross-flow velocity is observed for the case with simulated velocity defect. Later the same wake was also computed with a simulated jet.

Finally based on the analysis of existing wake measurements it was shown, that it is possible to reconstruct the local lift distribution from a measured velocity field in a plane sufficiently close to the aircraft. The reconstructed or fictitious load distribution becomes less accurate if the distance of the plane from the aircraft is increased. Based on this lift distribution it was found that according to Betz theory the separation distance is 4-5% smaller with the aforementioned consequences on circulation, sink speed and vortex life time.

3. Overall Conclusions

The investigations carried out in the framework of the European project FAR-Wake have led to new insights into previously unresolved issues concerning the dynamics of aircraft trailing wakes. Regarding vortex interactions with jets and wakes, systematic experimental and numerical studies have demonstrated that temperature variations (such as those caused by the aircraft engine jets) do not have an important effect on the vortex evolution. Finally, the effect of the fuselage wake, and its interaction with the wakes and vortices generated by other aircraft elements, has been clarified.
References


[22] Liou, M.; A Further Development of the AUSM+ Scheme Towards Robust and Accurate Solutinos for All Speeds. AIAA Paper 2003-4116.


