FUNDAMENTAL VORTEX PHENOMENA: INSTABILITIES AND INTERACTIONS WITH JETS AND WAKES

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OVERVIEW

In this contribution, a synthesis of the recent results obtained in the frame of the ongoing European FP6 project FAR-Wake (Fundamental Research on Aircraft Wake Phenomena, 2005-2008), is presented. The main objective of this upstream research project is to gain better knowledge about open issues of vortex dynamics relevant to aircraft wakes, by investigating the following main topics, each treated in a separate work package: 1) the role of vortex instabilities on wake decay, 2) the influence of engine jets and of the turbulent wakes behind different aircraft components, and 3) the influence of ground effects, relevant for the wake evolution in the airport environment. The present paper deals with the first two topics, results from the work package on ground effects are shown in a different CEAS 2007 session on "Wake Vortex Advisory Systems".

1. VORTEX INSTABILITIES AND DECAY

The overall objective of the FAR-Wake project is to obtain a better understanding on the wake vortices and identify possible means of controlling them. In the work package on "Vortex Instabilities and Decay" several studies have been performed in order to improve the interpretation of point measurements of velocity fields in experimental facilities. A physical mechanism for the vortex meandering phenomenon has been proposed. The characteristics of the waves propagating on vortices, generated by local perturbations, have been analysed, leading to new fundamental results relevant to end effects in experimental facilities. It was also shown how the nonlinear interaction of these waves can lead to vortex bursting and thereby enhance dissipation.

The instabilities and dynamics of multiple-vortex systems have been analysed in detail. Using complementary theoretical, numerical and experimental approaches, the effect of axial core flow (present in real aircraft vortices) on the short-wavelength instabilities has been identified. It has been shown that axial flow modifies the characteristics of the instability modes and can accelerate the merging of co-rotating vortices. Several studies have also focused on the dynamics of 4-vortex systems, characteristic of aircraft wakes in take-off/landing configuration. It was demonstrated that medium- and long-wavelength instabilities can be used to enhance the global wake decay. A most promising 4-vortex configuration has been selected and is currently being tested in a large towing-tank facility in Potsdam.

1.1. Wave propagation phenomena

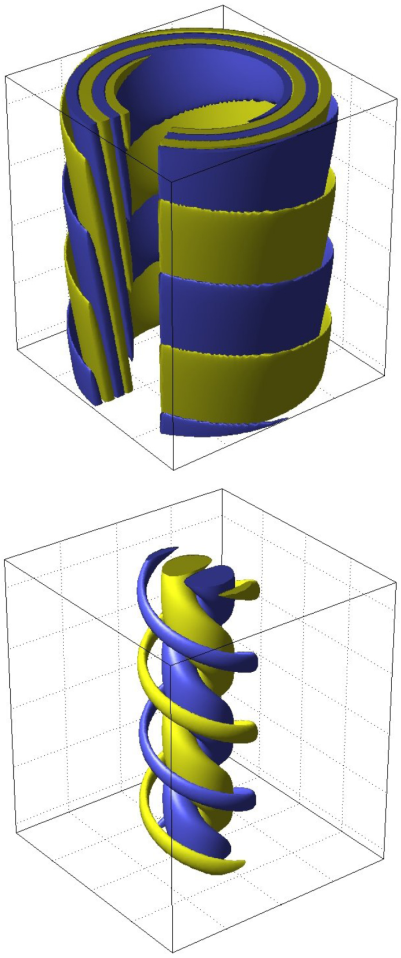
1.1.1. Vortex meandering

Vortex meandering denotes the rapid and erratic displacements of the vortices observed in trailing vortex experiments. It is a recurrent feature which is now considered as the main source of uncertainties in point measurements of vortices in wind tunnels.

Since its first identification in the 1970s,[1] numerous studies have been performed, either to filter out this spurious unsteadiness[2] or to diminish its impact, but no clear physical explanation was provided so far.

In the FAR-Wake project, two original ideas have been explored. The first idea was motivated by the recent discovery[3] of new unstable modes which could have characteristics in accordance with the vortex meandering phenomenon. These modes are viscous in nature, localised in the vortex core and characterised by a long axial wavelength. A comprehensive asymptotic stability study has been performed which has permitted to obtain the characteristics of these modes for any vortex with axial flow. Explicit expressions for the instability growth rate and for the marginal stability curve have been obtained.[4,5] Recent numerical results[6] on the spatial stability of the *q*-vortex model are in agreement with the asymptotics. However, they have also recently demonstrated that non-parallel effects can be very important. They have shown that the frequency of these modes were not in agreement with the characteristics of vortex meandering and concluded that vortex meandering could not be associated with a viscous instability.

A second explanation of vortex meandering has been explored in the FAR-Wake project. It was motivated by a recent observation[7] that a simple vortex model (Lamb-Oseen vortex) can exhibit a non-trivial transient behaviour resulting in intense short-time amplification of specific perturbations. The optimal perturbation analysis of the Lamb-Oseen vortex has therefore been performed for several azimuthal and axial wavenumbers. It was shown that the optimal perturbation (see FIG. 1) could lead to a displacement of the vortex, whose characteristics resemble vortex meandering. By a stochastic forcing analysis, it was demonstrated that the same displacement mode is preferentially excited by background turbulence. Although a precise comparison with experimental data is still lacking, it is believed that vortex meandering could indeed be associated with this transient phenomenon.



(a)

(b)

FIG. 1. Optimal perturbation for the excitation of vortex core deformations, possibly relevant for understanding vortex meandering. Isosurfaces of axial vorticity at (a) initial and (b) optimal times.

1.1.2. End effects and bursting

End effects are ubiquitous in experimental facilities such as catapults and towing tanks. They are known to create sudden modifications of the vortex structure, which can propagate along the vortices in the form of wave packets and affect unperturbed regions. These waves have often been associated with the linear non-viscous waves obtained by Kelvin[8] or to nonlinear solitary waves as described in the formalism of vortex filaments.[9] Recent studies[10] have shown that linear non-viscous waves are not as simple as Kelvin waves when the vortex is not top-hat. Some linear waves are damped and exhibit a complex spiral structure around the vortex.

The properties of these waves have been analysed in detail in the FAR-Wake project for a Lamb-Oseen vortex.[11,12] A numerical tool allowing the determination of the linear evolution of any initial localized perturbation has also been developed.[13] This tool has been used to validate the first direct numerical simulations performed with the code FLUDILES. It was shown that the fast-propagating waves are mainly composed of axisymmetric waves (with azimuthal wavenumber m=0) and bending waves (m=1). Simulations with perturbations of larger amplitude are currently being performed for a quantitative assessment of the impact of the results on the exploitation of laboratory facilities.

Wave propagation can also result in vortex bursting, when two waves propagating in opposite directions collide. In a recent numerical study[14] it was demonstrated how vortex bursting could be generated by the collision of two axisymmetric pressure waves. As an archetype of strong localised nonlinear interaction, vortex bursting constitutes an important fundamental phenomenon, which is worth studying for a better understanding of the nonlinear dynamics of a vortex. A characterisation of this often-observed phenomenon has been provided for generic configurations. The influence of vortex bursting on the global balance of the wake (evaluation of energy dissipation, circulation profiles, etc.) is currently being quantified.

1.2. Instability in vortex systems

1.2.1. Short-wavelength instabilities

Short-wavelength instabilities are expected to be important phenomena when vortices interact closely. These instabilities have been known for quite a long time in the context of strained vortices[15,16] or for general elliptical flows,[17] but its analysis for a system of vortices is much more recent.[10,18,19] These studies suggest that short-wavelength instabilities could influence the merging process of co-rotating vortices, and therefore play an important role in the evolution process of the vortex system. However, the characteristics of this instability for vortices generated by a wing, *i.e.*, in which an axial velocity field is present, were so far unknown. One of the objectives here was to provide such instability characteristics, in order to clearly identify the role that this instability can play in the evolution of the vortex system. Several complementary studies have been performed involving stability analyses, different types of numerical simulations (Direct Numerical Simulations, Large-Eddy Simulations, vortex methods), and experiments, in order to reach this objective.

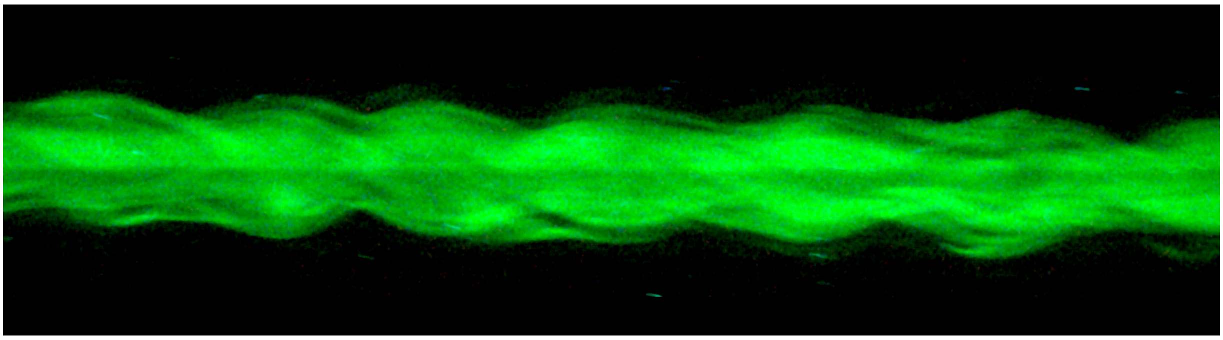


FIG. 2. Short-wave instability of a trailing vortex with axial core flow. Dye visualisation in a water channel.

The effect of axial flow on the elliptic instability characteristics has been analysed by theoretical methods, considering a configuration of counter-rotating Batchelor vortices.[20] Numerical simulations of the linear temporal evolution of the instability developing in both two counter-rotating vortices and two co-rotating vortices have been performed and good agreement with the theoretical predictions hasbeen demonstrated.[20,21] The nonlinear evolution of the instability and its influence on vortex merging, as well as the spatial development of this phenomenon, are still under investigation.

Experimental set-ups (flapped wing and a rig with two facing wings) were designed and constructed to study counter- and co-rotating vortices in a wind tunnel and a water channel. Preliminary results, showing evidence of short-wave instability have been obtained[22] (FIG. 2).

1.2.2. Medium and long-wavelength instabilities

These instabilities, which scale on vortex separation distances, were found in recent studies in the USA[23,24] and in previous European projects (C-Wake, AWIATOR)[25] as very promising phenomena, which could provide an efficient way to accelerate vortex decay. These instabilities are mostly governed by global parameters such as the vortex separation distances and the circulation (or circulation ratios) of the vortices, which allow a parameter study for a limited number of vortices. In the FAR-Wake project, the focus has been on four-vortex configurations. The first objective was to identify the most efficient four vortex configuration. This has been achieved through extensive numerical computations using several methods (spectral LES, combined Vortex-in-Cell and Parallel Fast Multipole method, fourth-order finite difference DNS and LES). The different results were also compared using the Berkeley experimental case[24] and an AWIATOR benchmark. The configuration which has been retained as most-promising corresponds to counter-rotating vortex pairs with a circulation ratio Γ_2/Γ_1 = -0.3 and a relative vortex spacing b_2/b_1 = 0.3.

Experimental measurements using this vortex configuration, generated by a specific generic aircraft model, are currently being performed, and a large-scale experiment, using the same wing model in a towing tank facility in Potsdam, is being prepared to fully characterise this configuration and validate the numerical results.

Physical mechanisms involved in the decay have also been studied by simulating the reconnection process of two perpendicular vortices.[26]

2. VORTEX INTERACTIONS WITH JETS AND WAKES FROM AIRCRAFT COMPONENTS

The objective of the work package on “Vortex Interactions with Jets and Wakes” of the project FAR-Wake 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, in particular the fuselage and the landing gears.

2.1. Vortex interactions with jets

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.

2.1.1. 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 (FIG. 3) to replicate the outboard flap-edge and wing-tip vortex structures generated by a real aircraft.

The experimental investigations[27] 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.

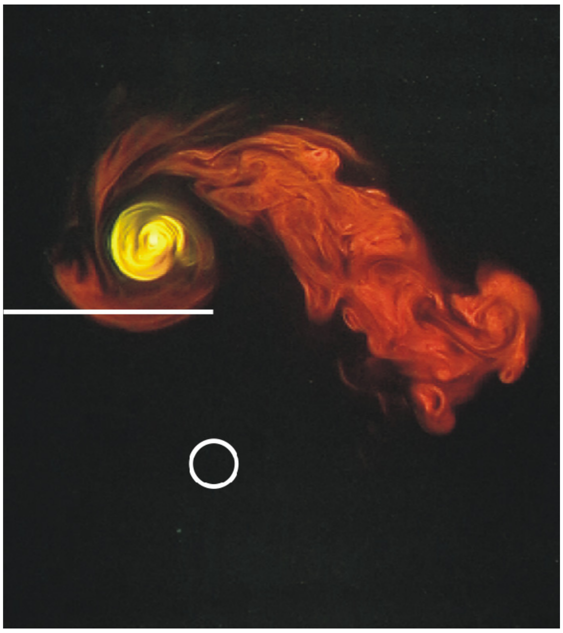


FIG. 3. Ingestion of jet turbulence (red) into a vortex (yellow). Dye visualisation in a water channel.

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, 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).

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).[28] 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,[29] 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 configuration: 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.

2.1.2. 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.[30] 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.

2.1.3. Hot jet interaction

Experimental and numerical studies wee conducted on the interaction of a hot jet with the vortex wake of a NACA 0015 airfoil. In the experimental part[31] (see FIG. 4) several parameters were analyzed, in particular the distance between the centres of the jets and the vortices, as well as the density ratio between surrounding fluid and jet fluid. The measurements reveal a negligible effect of the jet temperature on the jet/wake interaction. The effect of the distance between the jet and the wingtip vortex was illustrated and quantified. It leads to changes in the vortex sheet development, the vortex position and the temperature distributions. In the numerical study,[32] three different configurations (jet positions) have been tested:
Case A: the first position is the same as in the experimental set-up;
Case B: the jet is closer to the vortex;
Case C: the jet is located in the centre of the vortex.
Temporal Large-Eddy Simulations have been carried out using a hybrid mixed-scale model on a moderately refined mesh. The computations are

advanced in two steps; the first computation is stopped when it provides an estimation of the end of the jet regime, and in the second step, the interaction with a Lamb-Oseen vortex field is accounted for.

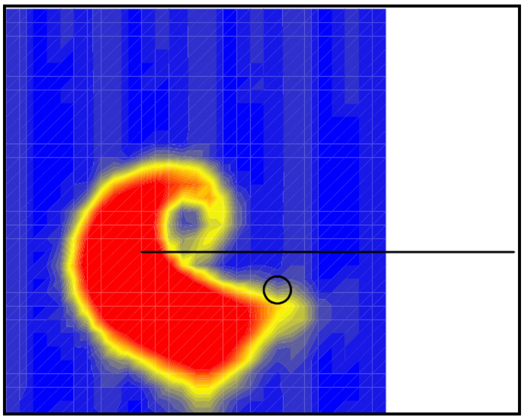


FIG. 4. Ingestion of a hot jet into a vortex. Isoncontous of temperature from wind tunnel experiments.

Initially, the jet simulation is carried out until the maximum turbulent kinetic energy is reached. Then, the resulting jet data is injected outside of the vortex in cases A and B, while in case C, the jet is blown into the vortex core. For cases A and B, the turbulent kinetic energy increases and, due to the longitudinal jet velocity, large-scale structures appear around the vortex core as counter-rotating helical vortex structures. As the downstream distance increases, the large-scale vortical structures disappear and the kinetic energy decays. The vortical structures rapidly lose coherence and the stabilizing effect of the flow rotation suppresses small-scale motions of turbulence. During all the simulations, the vortex core keeps its positive axial vorticity. In case C, the jet is superimposed onto the vortex, and the longitudinal vorticity shows the meandering of the vortex.
For all three jet positions, the vortex eventually recovers its initial shape. The evolution of a passive scalar marking the jet fluid clearly shows that the distribution initially included in the jet decreases rapidly and does not enter the vortex core for cases A and B. For case C, with the jet injected into the vortex core, the passive scalar remains confined in the core.
Further LES simulations were carried out[33] concerning the interaction between a turbulent hot exhaust jet and a vortex during the different flight phases: approach, take-off and cruise. Two types of interactions were analysed. In the first case, the jet and the vortex are initially well separated thus modelling the interaction under cruise conditions between the wing tip vortex and the jet. The dynamics of interaction is mainly controlled by the entrainment of the jet by the vortex and the turbulent diffusion of the jet. The solid-body rotation of the vortex core prevents hot jet fluid to penetrate inside the vortex. In the second case, the jet and the vortex are close to each other, 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 the vortex coherence in case of take-off condition, contrary to the approach configuration, where the axial perturbation is weaker. For either case, the density variations have no effect on the interaction process, but only on the development of the jet. Moreover, the jet effect reduces the peak tangential velocity of the vortex by 30 to 60%.
These results, similar to those for the cold jet-vortex interaction, reveal that the vortex is only affected by the jet when the two are close and when the intensity of the axial velocity perturbation is high.

2.2. Vortex interactions with wakes

2.2.1. Fuselage wake

The aim of these investigations was is to compare CFD simulations and experimental data of the flow around transport aircraft geometry to examine the effect of the fuselage on the structure of the wake vortex system. The geometry selected for this study was the TAK-Model (FIG. 5); a physical half-model of a four-engine large transport aircraft at a scale of 1:19.25, used for wind tunnel investigations. A numerical CAD-model, to be used in the numerical simulations, was obtained by scanning the physical model. An angle of attack of 7° was considered.

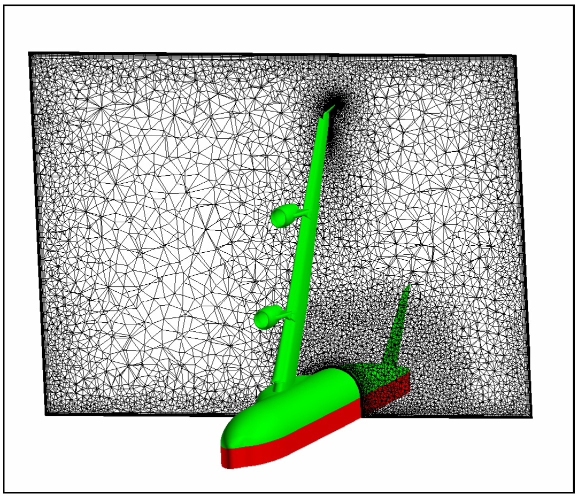


FIG. 5. Geometry of the TAK half-model of a 4-engine aircraft, including peniche (red), and unstructured mesh used for the simulations.

Reynold-Averaged Navier-Stokes (RANS) simulations were performed, using two different unstructured flow solvers, and hot-wire measurements were performed in a wind tunnel.[34] In addition, the TAK half-model on a "peniche" (an additional support structure used in the wind tunnel (see FIG. 5) was investigated numerically. With these simulations the effect of the wind tunnel and the half-model test technique on the vortex sheet could be assessed. Finally, the flow topology for four configurations of the TAK model, including fuselage, fuselage with horizontal tail plane (HTP), fuselage with wing, and the full configuration were analyzed to examine the effect of the different aircraft elements on the structure of the wake vortex system.

The results from the RANS computations are qualitatively comparable to the experimental findings. Indeed, one observes the presence of an upper- and lower-side vortex, even though these structures are strongly diffused compared to the experimental results. As expected, the choice of the turbulence model has a significant impact on the vorticity patterns and on the intensity of vortical cores.

The half-model technique is strongly coupled with the experimental realisation of high-lift configurations in a wind tunnel, where the so-called peniche is used to displace the symmetry plane of the supposed underlying full aircraft model outside the tunnel wall boundary layer. In order to evidence the influence of the variation of the peniche height and of the wind tunnel walls, a high-lift configuration was simulated in a low-speed wind tunnel. Due to the peniche influence, the local angle of attack and the flow velocity were increased, mainly for the inboard part of the wing. The wind tunnel wall effect also has an influence on the inboard wing, but of smaller amplitude.

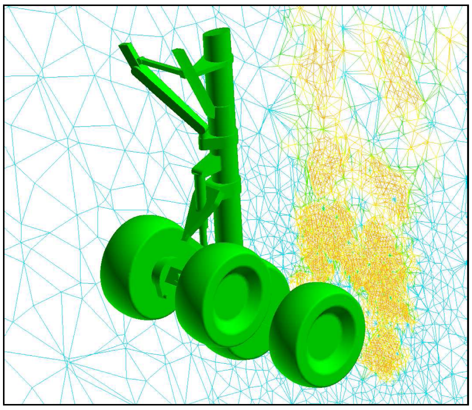
The influence of the Reynolds number (*Re*) was shown on the complete configuration by comparing results for the values $Re = 0.53\times10^6$ and $Re = 26.5\times10^6$. An outboard movement of the vortices was seen in the outboard region of the wing and at the same time an inboard movement of the vortices on the inboard part of the wing in the high-Reynolds number case. Further, whereas nearly Reynolds number independent lift distribution was observed, an increase of total lift appears for the higher- Reynolds number case.

For the configuration with fuselage, a vortex-pair can be found above the fuselage, while downstream of the belly a vortex-pair is formed. Finally, embedded in-between both vortices, a counter-rotating vortex occurs. With the additional tail plane, a vortex sheet appears behind the HTP, with a corresponding vortex behind its outboard end. Due to this vortex sheet, the fuselage-vortex has a smaller spanwise extent. The belly-vortex is unchanged, running beneath the HTP.

In the case of a fuselage with a complete wing, the fuselage vortex is weaker and superposed by a counter-rotating vortex in the tail of the fuselage. The belly vortex is influenced by the flap and inboard-engine vortices. When comparing the vortex strengths and positions behind the fuselage, it can be concluded that, as expected, grid adaptation and enhanced turbulence modelling are helpful to obtain a better agreement between measurement and numerical simulation.

2.3. Landing gear

The flow behind the landing gear of the TAK model (FIG. 6a) was also studied experimentally and numerically. Although the landing gear does not present any primary lift-generating components, the flow around this geometry, with regions of stagnation and separation, still lead to the creation of vortices. The vortex in the wake of the wheels (FIG. 6b) originates from a flow separation on the front wheel with the rotational direction defined by the oncoming flow. The flow accelerates going around the outer side of the wheel, whereas the velocity is lower on the opposite side because of blockage by the attachments. This accelerated flow runs from the lower to the upper side in the wake of the wheel, thus defining the rotation direction of the vortex. A counter-rotating vortex is generated by the flow around the rear wheel, due to a separation line which is more upstream. The dead water region behind this wheel is obviously bigger than for the front wheel.

(a)


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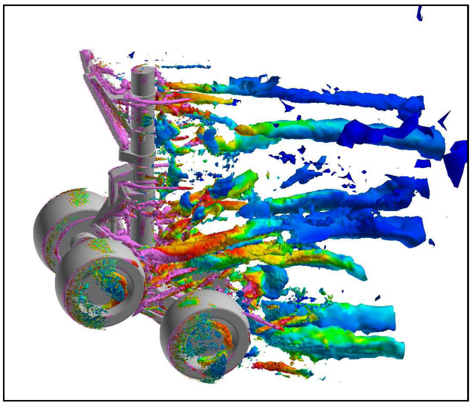

FIG. 6. Landing gear of the TAK model. (a) Geometry and grid; (b) vortical structures.

3. CONCLUSIONS

The investigations carried out in the framework of the ongoing European project FAR-Wake have led to new insights into previously unresolved issues concerning the dynamics of aircraft trailing wakes. Concerning the work on vortex instabilities, an explanation for the vortex meandering phenomenon was proposed, involving the transient growth of perturbations excited by background turbulence, and the effect of axial core flow on short-wave instabilities was analysed. Multiple-vortex instabilities and their effect on the long-term decay characteristics of the vortex wake are still under investigation. 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.

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