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FAR-Wake

Fundamental Research on Aircraft Wake Phenomena

Specific Targeted Research Project

Start: 01 February 2005
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Final Activity Report

Coordinator: **Thomas Leweke**
Centre National de la Recherche Scientifique
Institut de Recherche sur les Phénomènes Hors Equilibre
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Fundamental Research on Aircraft Wake Phenomena

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www.FAR-Wake.org

Background

This project is the continuation of a recent effort, on a European level, to characterize, understand and control aircraft wake turbulence. Aircraft in flight leave behind large-scale swirling flows (vortices), which can represent a significant hazard to following aircraft, and therefore are of great importance for practical applications concerning safety and capacity of air transport. The project focused on unresolved fundamental aspects of wake dynamics, thus complementing the existing, mostly empirical knowledge obtained in previous projects.

Objectives

The main objective was to gain new knowledge about open issues of vortex dynamics relevant to aircraft wakes, and to provide a more systematic description than previously achieved, of the phenomena involved in aircraft wake dynamics. These fundamental developments are necessary to achieve major advances in this domain, in view of a successful application of existing or future strategies for wake characterisation, prediction, and alleviation. The topics include: the precise role of vortex instabilities on wake decay, the influence of engine jets and fuselage wakes, and ground effects in wake evolution, relevant to the airport environment.

Participants

Centre National de la Recherche Scientifique (Coordinator) .... FR
Airbus Deutschland GmbH .... DE
Centre de Recherche en Aéronautique, ASBL .... BE
Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique ... FR
Częstochowa University of Technology .... PL
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR) .... DE
Instituto Superior Técnico .... PT
Stichting Nationaal Lucht- en Ruimtevaartlaboratorium (NLR) .... NL
Office National d' Etudes et de Recherches Aérospatiales (ONERA) .... FR
Technische Universiteit Delft .... NL
Technische Universiteit Eindhoven .... NL
Technische Universität München .... DE
The University of Bath .... UK
Université Catholique de Louvain .... BE
Universidad de Málaga .... ES
Universidad Politécnica de Madrid .... ES
Université Paul Sabatier – Toulouse III .... FR

Description of the work

The FAR-Wake project contains four major work packages. In the first, studies related to the dynamics and instabilities of one or several vortices were considered. The second work package introduced additional features: jets from engine exhaust, and wakes (axial velocity deficits) generated by the fuselage or other wing elements. The third work package considered wake evolution near the ground, with special emphasis on the prediction of wake behaviour in this situation. The fourth work package provided the synthesis and assessment. In the majority of cases, emphasis was put on the study of simplified geometries and generic vortex configurations, which facilitates the use of different complementary approaches. In support of new experimental and numerical investigations, theoretical/analytical treatment was applied, with the aim of obtaining a systematic description and comprehension of the phenomena. Furthermore, extensive use was made of results and data from previous projects or available data bases. The confrontation and comparison of different sets of results validate the findings and make the description of the studied phenomena more complete. At the end, an effort was made to provide a synthesis of all the new fundamental results that were obtained, and to assess their relevance for the wake turbulence problem for real aircraft. Certain features found to be promising for the acceleration of wake decay, such as flows with multiple wake vortices, were analysed and tested in a realistic configuration, using numerical simulations and experiments in a large-scale towing tank facility.

Summary of results achieved

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, such as towing tanks and catapults. The physical mechanism for the previously unexplained phenomenon of vortex meandering has been identified from combined experimental and theoretical work: it is due to the transient growth of a vortex displacement mode, initiated by background turbulence. The characteristics of waves propagating on vortices, generated by local perturbations of the vortex core, have been analysed numerically and through dedicated experiments, leading to new fundamental results and an improved understanding of end effects in experimental facilities. It was shown how the nonlinear interaction of these waves can lead to vortex bursting and thereby enhance dissipation. A complete mapping of viscous core modes has also been achieved, resulting in a number of scientific publications.

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 short-wavelength instabilities has been identified for a large range of parameters. This work permitted to understand why, as the axial flow increases, the sinuous mode (the most unstable mode without axial flow) becomes stable and new instability modes of different azimuthal wavenumbers arise, depending on the axial flow amplitude. At small vortex separation distances, a wide range of instability modes was observed. It was shown that, after a linear growth of these instabilities, a strongly non-linear phase occurs, leading to vortex breakdown and the re-formation of a weaker vortex with a larger core. It was also observed that axial flow can accelerate the merging of co-rotating vortices. Direct numerical simulations of the spatial development of the instability have been performed for co-rotating vortices with axial flow, showing qualitative agreement with the temporal evolution.

Several studies have focused on the dynamics of 4-vortex systems, characteristic of aircraft wakes in take-off/landing configurations. It was demonstrated that medium- and long-wavelength instabilities can be used to enhance the global wake decay. A most promising 4-vortex configuration was selected and tested in a large towing-tank facility in Potsdam, Germany. These experiments showed a strong interaction between main and counter-rotating secondary vortices at around 30 wing spans downstream, with a substantial decay of circulation strength and an increase in core radius, even if the resulting 2-vortex system has a larger lateral spacing and decays slower than a conventional 2-vortex configuration with the same lift. Large-Eddy Simulations of various 4-vortex systems showed that a significantly enhanced vortex decay can already be obtained for a lower-than-optimal, but much more practical, circulation strength ratio. Interesting results were obtained from linear stability theory and numerical simulations for the optimum forcing of counter-rotating 4-vortex wakes with respect to the long-wavelength Crow modes of the resulting final vortex pair. The optimum forcing location was found to be close to the wake symmetry plane, which has implications for a possible practical exploitation – to be investigated further.

Finally, the effect of background flow turbulence on the long-wavelength instability of a pair of counter-rotating vortices has been investigated experimentally. Turbulence is found to increases vortex meandering and lead to an earlier development of the instability.

In the work package on "Vortex Interactions with Jets and Wakes", the effects of both cold and hot jets (representing engine exhaust) on vortex pairs and merging, and on vortex development and decay were investigated experimentally, and a large amount of data concerning these flows was obtained. In addition, numerical investigations based on the time-dependent Large-Eddy-Simulation approach allowed 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 three-dimensional azimuthal vorticity structures around the jet. A common observation was that a sufficiently strong jet placed sufficiently close to a vortex (e.g., the flap vortex) can have a large effect on the peak vorticity and the core size of the final vortex. The favourable effect can only be exploited by a dedicated design of the engine position in relation to the flap tip.

The interaction of a cold jet with a vortex was investigated under both cruise flight and approach/take-off conditions. A generic wing and jet test set-up was used in a water channel and wind tunnels to obtain a large parametric experimental database (flow visualisation, velocity field measurements) on the effects of jet position, strength and pulsation and on the Reynolds number. Additional experiments using an aircraft model with part-span flaps and two jets in a towing tank showed that the effects of jet-vortex interaction far downstream, after wake rollup, can be either favourable (reduced cross-flow velocities in the vortex) or adverse (increased cross flow), depending on jet position with respect to the vortex core(s). Existing wake data for a realistic high-lift 4-engine aircraft configuration with Turbo-Powered-Simulators at different thrust settings was also evaluated. In agreement with observations from the generic model tests, an important effect of the inner jet on the nearby flap-edge vortex was observed. These data were used to initiate time- and space-developing Large Eddy Simulations, allowing a prediction of the flow further downstream until merging of tip and flap vortices. With a strong jet (thrust for level flight), the co-rotating vortices are predicted to merge 5 wingspans downstream, compared to 15 spans for the case without thrust/jet, and the final core size is roughly twice the one of the merged vortex without jet.

Parametric experimental and numerical studies relevant to isothermal and non-isothermal jets (varying Reynolds number, boundary layer thickness, density ratio, level of turbulence) were carried out. One major outcome is that temperature variations appear not to have an important influence on the wake flow field, but rather behave like passive tracers in the flow.

The lateral spacing of the vorticity centroid behind an aircraft wing is an important parameter for the vortex sink speed and wake decay. Analysis of previous wake experiments showed a significant effect of the wing-body lift carry-over on the lateral position of this centroid. It appears to depend quite strongly on the details of the flow in the wing-body junction and the wake of the fuselage. A major achievement of this project is the numerical and experimental investigation of fuselage wake effects, using exactly the same aircraft geometry. This was made possible by the generation of a numerical Computer-Aided Design model of the aircraft geometry used in previous and the present wind tunnel experiments. The numerical simulations, using Reynolds-Averaged Navier-Stokes methods, showed that the prediction of the correct flow topology in the wake of the fuselage is sensitive to the turbulence model but also to the level of mesh refinement. Final calculation results, obtained after dedicated mesh refinement and adaptation, agree reasonably well with the experimental data. Routine prediction of the lift carry-over effect from wing to fuselage will remain a challenge, because of the large efforts needed in meshing.

Additional simulations have investigated the influence of wind tunnel walls and of the use of half-models in ground-testing facilities, Reynolds-number variations between wind-tunnel and free-flight conditions, and the flow topology behind an isolated landing gear. The wind tunnel measurements behind wing elements focused on the influence of the landing gear for downstream distances up to one wing span. It was found that the landing gear wake introduces a concentrated region of increased turbulence. This region mainly affects the roll-up process in its starting phase, but does not markedly influence the main vortices.

Interesting results were obtained from simulations of wake roll-up with and without simulated velocity defect in the wake of a wing. With velocity defect, longitudinal instabilities develop in the thin wake during the wake roll-up phase, which are subsequently wrapped around the vortex and lead to a reduction in circulation and a modified circulation profile.

In the work package on "Wake Evolution Near the Ground", the effect of ground proximity on the lift of an airfoil was investigated with a vortex panel method, and showed that this effect becomes important only very close to the ground (height less than 50% of airfoil chord). The span loading of wings of various shapes at different heights above the ground was simulated with a modified lifting-line theory. The results from these engineering-type calculations were used to define realistic initial span-loading conditions for wake roll-up studies, as well as interesting test cases for experiments.

Two-dimensional Direct Numerical Simulations showed that the effect of ground proximity on wake roll-up remains small for heights greater than 25% of the final vortex separation distance. Below this limit, simulations at higher Reynolds number predict the formation of high-intensity secondary vortices (emanating from the separating boundary layer at the ground) interacting with the primary vortices. These complex roll-up dynamics are expected to be different in three dimensions.

Detailed information was obtained basic interactions and instabilities of vortex pairs and 4-vortex systems in ground effect, considering idealised spatially uniform or spatially evolving conditions. Vortex pairs generated at large initial height with a given amplitude of a long-wavelength deformation were studied using three-dimensional vortex filament simulations, as well as water tank experiments. Good agreement was found between the two; both show the ground interaction and rebound of the large-scale vortex rings resulting from the Crow instability. Two- and three-dimensional Large Eddy Simulations of a vortex pair created two wingspans above the ground also show a very good correspondence with water tank experiments. They both demonstrate the development of short-wavelength elliptic instabilities on the secondary vortices generated by the ground interaction, and an enhanced decay of the vortex system shortly after reaching the maximum rebound height. These observations are in agreement with results from previous full-scale aircraft wake measurements. Numerical simulations with cross- and head-wind show an even more rapid decay in wind conditions, again in agreement with analysed field measurement data. The numerical results are very helpful for analysing the mechanisms leading to this enhanced decay.

Numerical simulations of a counter rotating 4-vortex system descending into ground effect show a faster decay than observed for a vortex pair, due to the interaction between the inner vortices and the ones separating from the ground, which have the same sign of circulation. Flow visualisations and measurements made in dedicated towing tank experiments of 2- and 4-vortex systems created near the ground revealed the complex interactions between the primary and secondary vortices, leading to an apparent bursting of the main vortex. A very demanding spatial Large Eddy Simulation gave results in good qualitative agreement with these experiments. Compared with time-developing simulations, more complex three-dimensional interactions with the ground and an earlier and more violent transition to turbulence are observed.

Several activities were also dedicated to realistic full-scale aircraft wakes in ground effect. A detailed analysis of a recent data base concerning field measurements made at Frankfurt airport of the wake of a specific aircraft was carried out and yielded valuable results on the effect of crosswind on wake evolution near the ground. These results were then used to improve two existing real-time wake vortex prediction models: the Probabilistic Two-Phase (P2P) model and the Probabilistic Vortex Model (PVM). The parameterization of ground and wind effects in these models has been further developed, based on the field measurement data and additional numerical simulations. The performance of both models has been tested against the Frankfurt field measurement data, showing a significant improvement of wake vortex prediction skills in ground proximity. Both models can be used as a tool for assessing safety for revised dynamic (weather-dependent) aircraft separation strategies.

In the "Synthesis" work package, the applicability of all the above results to real aircraft wakes and the implications for wake vortex safety issues and airport capacity were addressed. A summary was provided of exploitable results that might be used to obtain more benign wakes by aircraft design and/or to allow smaller separation distances between aircraft in certain weather conditions.

Conclusion

This project has generated systematic results and physical understanding concerning previously unresolved issues related to aircraft trailing wakes, including the role of vortex instabilities, the influence of engine jets and fuselage wakes, and ground effects. These results represent a solid knowledge base for future applications aiming at the reduction of wake turbulence hazards. Concerning ground effects, the project has in addition produced improved tools for the real-time prediction of wake vortex behaviour, for potential use in the domain of Air Traffic Management. Due to the mostly fundamental character of the research, the results are also relevant in various other areas of fluid mechanics.

Coordinator contact details

Thomas Leweke

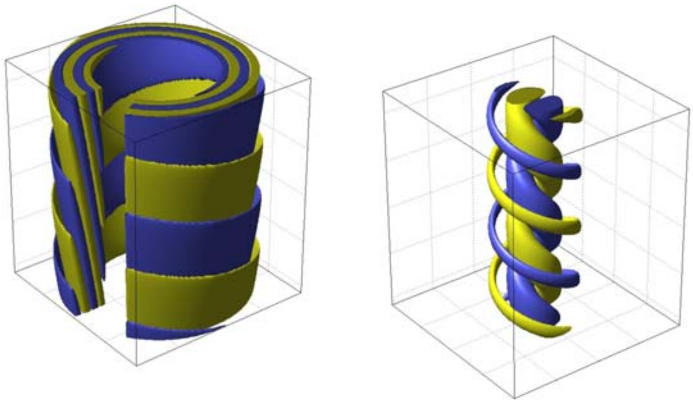
Institut de Recherche sur les Phénomènes Hors Equilibre (IRPHE)
Centre National de la Recherche Scientifique (CNRS)
49, rue Joliot-Curie – BP 146
F-13384 Marseille Cedex 13 – France
Phone: +33 4 96139761
Fax: +33 4 96139709
E-mail: Thomas.Leweke@irphe.univ-mrs.fr

EU Scientific Officer

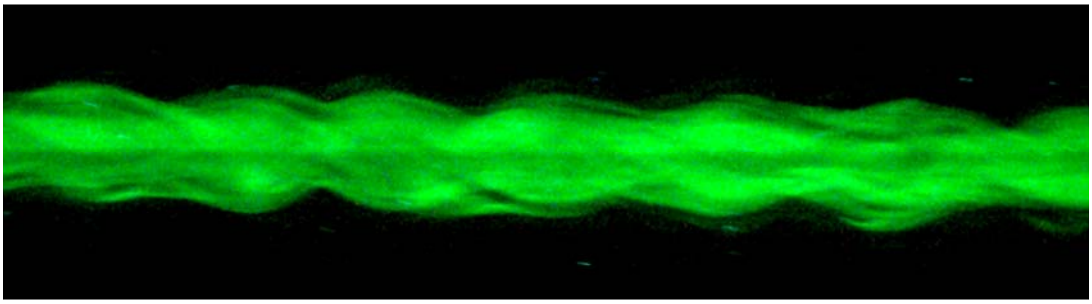
Stephanie Stoltz-Douchet

Directorate General for Research – H.3
European Commission – CDMA 4/138
B-1049 Brussels – Belgium
Phone: +33 2 295 5033
Fax: +33 2 299 6757
E-mail: Stephanie.STOLTZ-DOUCHET@ec.europa.eu

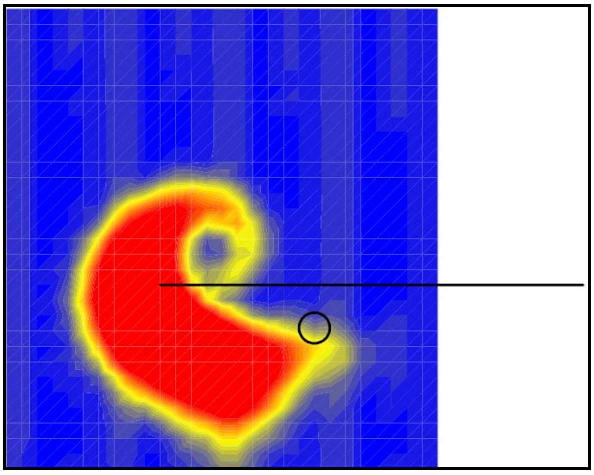
Gallery



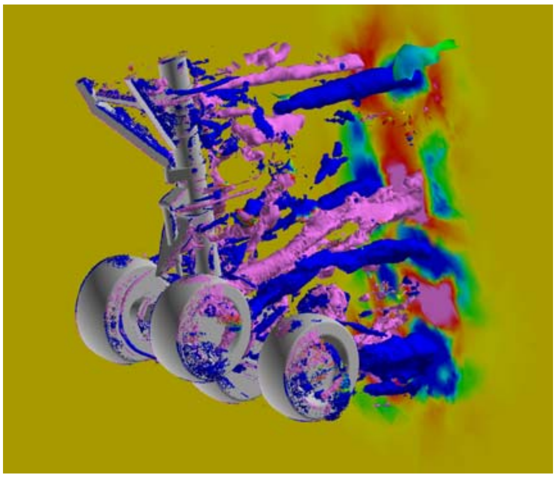
Optimal perturbation for the excitation of vortex core deformations, possibly relevant for understanding vortex meandering. Isosurfaces of axial vorticity at initial and optimal times.



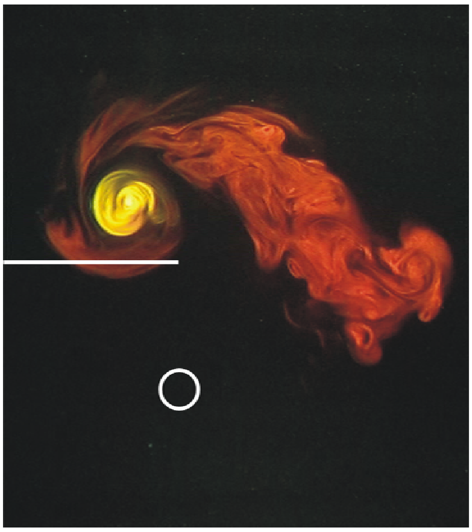
Short-wave instability of a trailing vortex with axial core flow.
Dye visualisation in a water channel.



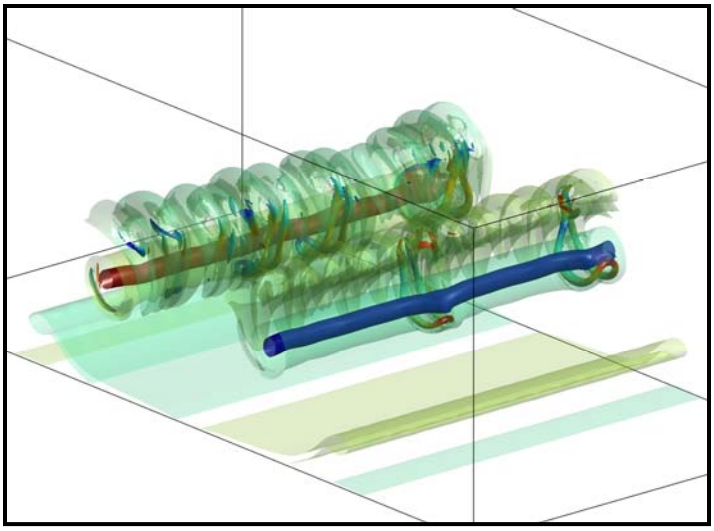
Ingestion of a hot jet into a vortex.
Isoncontous of temperature from
wind tunnel experiments.



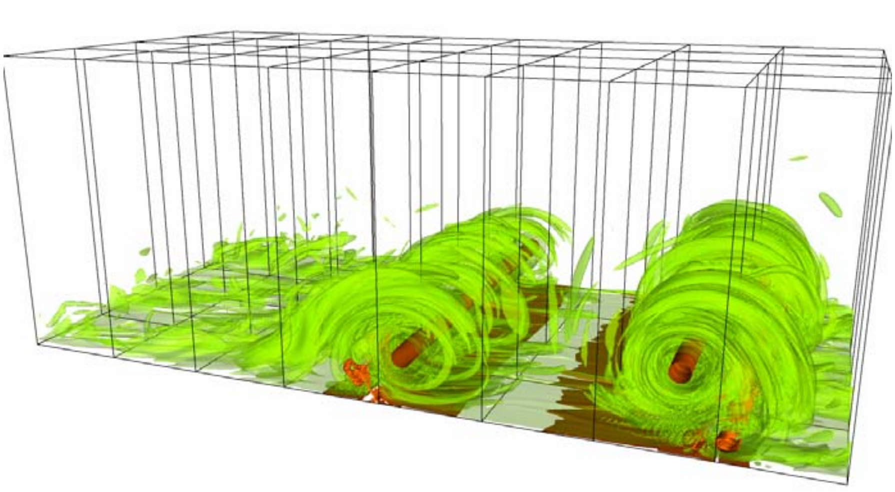
Structure of a landing gear wake.
From RANS calculations.



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



Vortex pair in ground effect: instability of secondary vortices. Results from Direct Numerical Simulation.



Vortex pair in ground effect with turbulent cross-wind. Isosurfaces of vorticity from Large-Eddy Simulations.

Published results

The FAR-Wake project has led to a large number of publications in refereed scientific journals and presentations/papers at international conferences.

Details concerning all publications and presentations made in the framework of this project (i.e., links to summaries of scientific articles, copies of the presentations at the final FAR-Wake Workshop, contact information for each publication/presentation made) are available on the FAR-Wake web site at http://www.far-wake.org/. Most Technical Reports of the project will also be made available on this site.

Below is a complete list of all publications and presentations, grouped according to work packages, and in reverse chronological order.

ARTICLES IN SCIENTIFIC JOURNALS

General

Gerz, T., Holzäpfel, F., Bryant, W., Köpp, F., Frech, M., Tafferner, A., Winckelmans, G.: Research towards a wake-vortex advisory system for optimal aircraft spacing, *Comptes Rendus Physique* **6** (4/5), Special issue on *Aircraft trailing vortices*, 501-523 (2005)

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Vortex Instabilities and Decay

Roy, C., Leweke, T., Thompson, M. C., Hourigan, K.: Experiments on the elliptic instability in vortex pairs with axial core flow, *Journal of Fluid Mechanics* (2009, submitted)

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Frech, M., Holzäpfel, F.: Skill of an aircraft wake-vortex weather prediction and observation, *Journal of Aircraft* **45**, 461-470 (2008)

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