



Aeronautics and Space



AST4-CT-2005-012238

## ***FAR-Wake***

**Fundamental Research on Aircraft Wake Phenomena**

**Specific Targeted Research Project**

**Start: 01 February 2005**

**Duration: 40 months**

# ***Publishable Final Activity Report***

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## Fundamental Research on Aircraft Wake Phenomena

EC Specific Targeted Research Project no. AST4-CT-2005-012238

[www.FAR-Wake.org](http://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

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Centre de Recherche en Aéronautique, ASBL .....	BE
Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique ...	FR
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Stichting Nationaal Lucht- en Ruimtevaartlaboratorium (NLR) .....	NL
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## **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 increase 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 generate 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.

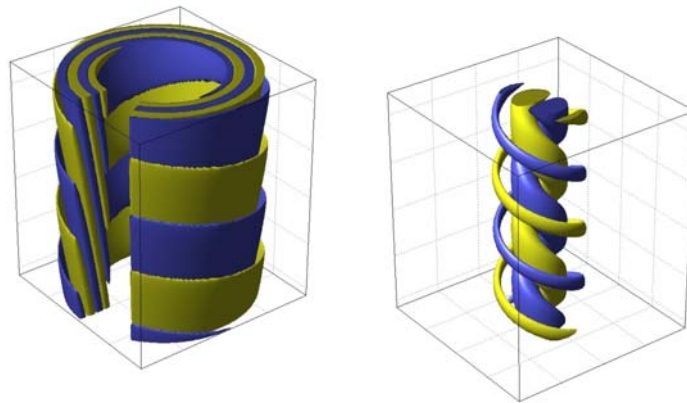
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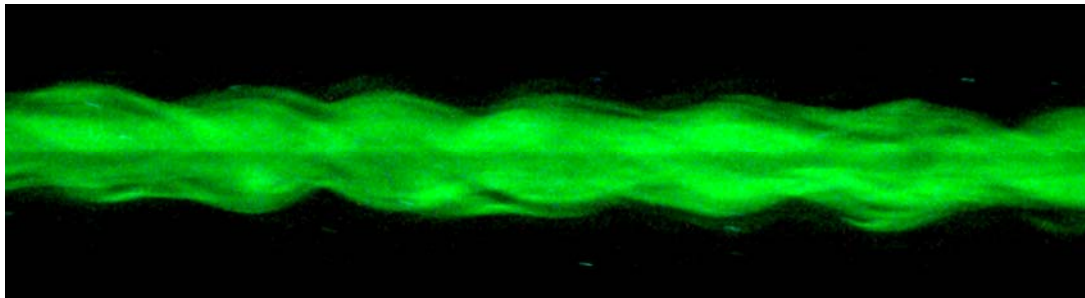
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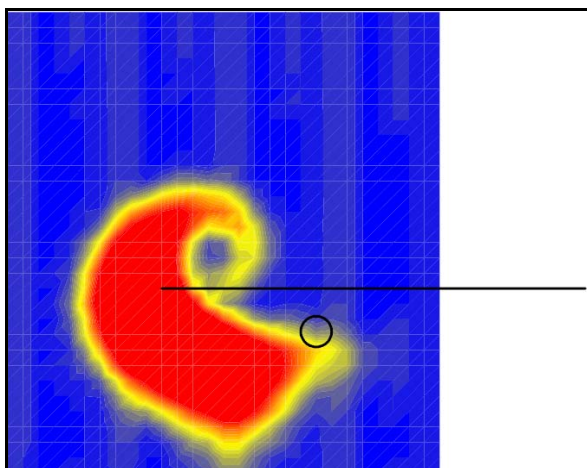
**Gallery**



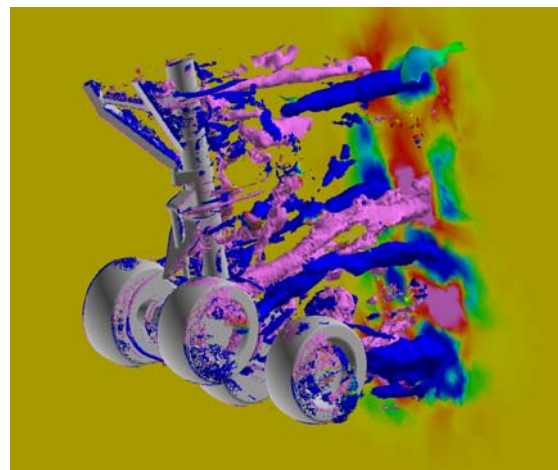
Optimal perturbation for the excitation of vortex core deformations, possibly relevant for understanding vortex meandering. Isosurfaces of axial vorticity at initial and optimal times.



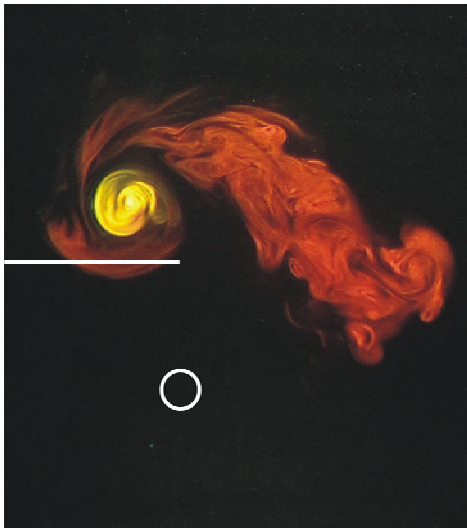
Short-wave instability of a trailing vortex with axial core flow.  
Dye visualisation in a water channel.



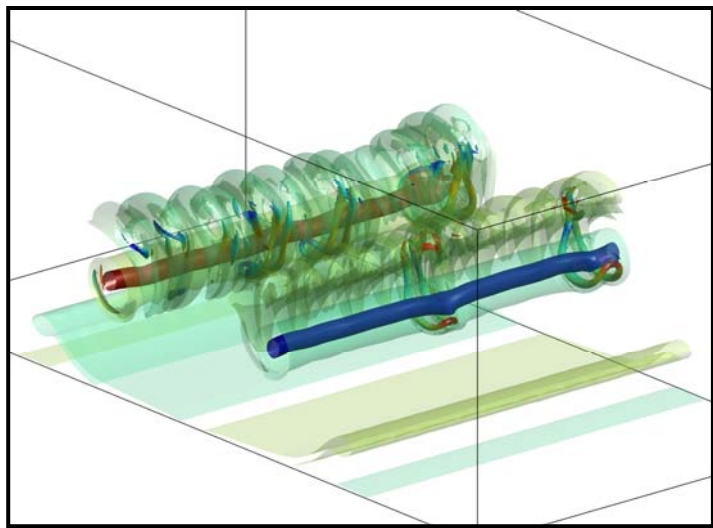
Ingestion of a hot jet into a vortex.  
Isoncontous of temperature from  
wind tunnel experiments.



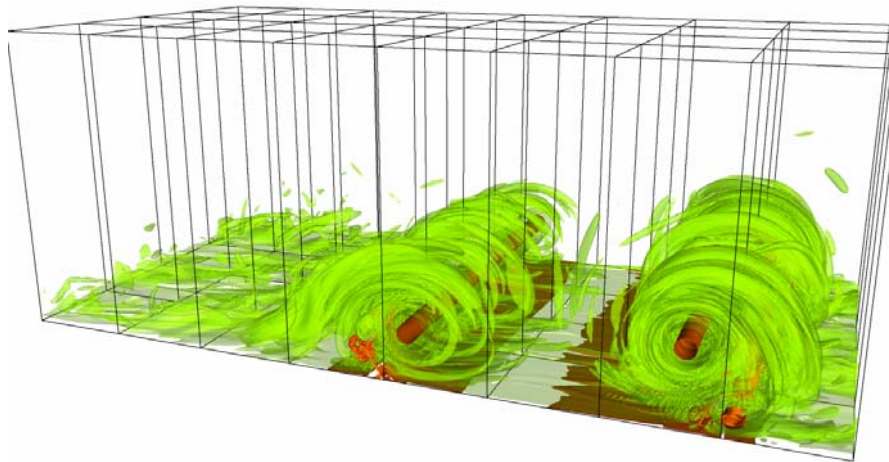
Structure of a landing gear wake.  
From RANS calculations.



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., Tafferger, A., Winkelmanns, 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)

Winkelmanns, G., Cocle, R., Dufresne, L., Capart, R.: Vortex methods and their application to trailing wake vortex simulations, *Comptes Rendus Physique* **6** (4/5), Special issue on *Aircraft trailing vortices*, 467-486 (2005)

### 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* (2008, submitted)

Deniau, H., Nybelen, L.: Strategy for spatial simulation of co-rotating vortices, *International Journal for Numerical Methods in Fluids* (2008, submitted)

Nybelen, L., Paoli, R.: Direct and large-eddy simulations of merging in co-rotating vortex system: *AIAA Journal* (2008, submitted)

Schaeffer, N., Le Dizès, S.: Nonlinear dynamics of the elliptic instability, *Physical Review Letters* (2008, submitted)

del Pino, C., Parras, L., Fernández-Feria, R.: Non-parallel spatial stability of Batchelor vortex, *Physics of Fluids* (2008, submitted)

Allen, A., Breitsamter, C.: Experimental investigation of counter-rotating four vortex aircraft wake, *Aerospace Science and Technology* (2008, in press)

González, L. M., Gómez-Blanco, R., Theofilis, V.: Eigenmodes of a co-rotating vortex dipole, *AIAA Journal* **46**, 2796-2805 (2008)

Roy, C., Schaeffer, N., Le Dizès, S., Thompson, M.: Stability of a pair of Co-rotating vortices with axial flow, *Physics of Fluids* **20**, 094101 (2008)

Fontane, J., Brancher, P., Fabre, D.: Stochastic forcing of the Lamb-Oseen vortex, *Journal of Fluid Mechanics* **613**, 233-254 (2008)

Abid, M. Nonlinear mode selection in a model of trailing line vortices, *Journal of Fluid Mechanics* **605**, 19-45 (2008)

Fabre, D., Le Dizès, S.: Viscous and inviscid centre modes in the linear stability of vortices: the vicinity of the neutral curves, *Journal of Fluid Mechanics* **603**, 1-38 (2008)

Brion, V., Sipp, D., Jacquin, L.: Optimal amplification of the Crow instability, *Physics of Fluids* **19**, 111703 (2008)

- von Carmer, C. F., Konrath, R., Schröder, A., Monnier, J.-C.: Identification of vortex pairs in aircraft wakes from sectional velocity data, *Experiments in Fluids* **44**, 367-380 (2008)
- Le Dizès, S., Fabre, D.: Large-Reynolds-number asymptotic analysis of viscous centre modes in vortices, *Journal of Fluid Mechanics* **585**, 153-180 (2007)
- Parras, L., Fernández-Feria, R.: Spatial stability and the onset of absolute instability of Batchelor's vortex for high swirl numbers, *Journal of Fluid Mechanics* **583**, 27-43 (2007)
- Antkowiak, A., Brancher, P.: On vortex rings around vortices: an optimal mechanism, *Journal of Fluid Mechanics* **578**, 295-304 (2007)
- González, L. M., Theofilis, V., Gómez-Blanco, R.: Finite-element numerical methods for viscous incompressible BiGlobal linear instability analysis on unstructured meshes, *AIAA Journal* **45** (4), 840-854 (2007)
- Lacaze, L., Ryan, K., Le Dizès, S.: Elliptic instability in a strained Batchelor vortex, *Journal of Fluid Mechanics* **577**, 341-361 (2007)
- Cocle, R., Dufresne, L., Winckelmans, G.: Investigation of multiscale subgrid scale models for LES of instabilities and turbulence in wake vortex systems, in "Complex Effects in Large Eddy Simulations" (eds. S. C. Kassinos, C. A. Langer, G. Iaccarino, P. Moin), *Lecture Notes in Computational Science and Engineering* **56**, 141-159 (2007)
- Fabre, D., Sipp, D., Jacquin, L.: Kelvin waves and the singular modes of the Lamb-Oseen vortex, *Journal of Fluid Mechanics* **551**, 235-274 (2006)
- Moet, H., Laporte, F., Chevalier, G., Poinso, T.: Wave propagation in vortices and vortex bursting, *Physics of Fluids* **17**, 054109 (2005)
- Le Dizès, S., Lacaze, L.: An asymptotic description of vortex Kelvin modes, *Journal of Fluid Mechanics* **542**, 69-96 (2005)

### **Vortex Interactions with Jets and Wakes**

- Allen, A., Breitsamter, C.: Landing gear influence on the wake vortex of a large transport aircraft, *Journal of Aircraft* **45**, 1367-1372 (2008)
- Margaris, P., Marles, D., Gursul, I.: Experiments on jet/vortex interaction, *Experiments in Fluids* **44**, 261-278 (2008)
- Marles, D., Gursul, I.: Effect of an axial jet on vortex merging, *Physics of Fluids* **20**, 047101 (2008)
- Sipp, D., Fabre, D., Michelin, S., Jacquin, L.: Stability of a vortex with a heavy core, *Journal of Fluid Mechanics* **526**, 67-76 (2005)
- Coquart, L., Sipp, D., Jacquin, L.: Mixing induced by Rayleigh-Taylor instability in a vortex, *Physics of Fluids* **17**, 021703 (2005)

### **Wake Evolution Near the Ground**

- Duponcheel, M., Cottin, C., Daeninck, G., Winckelmans, G., Leweke, T.: Three-dimensional dynamics of vortex pairs in ground effect, *Physics of Fluids* (2008, in preparation)
- Frech, M., Holzäpfel, F.: Skill of an aircraft wake-vortex weather prediction and observation, *Journal of Aircraft* **45**, 461-470 (2008)
- Holzäpfel, F., Steen, M.: Aircraft wake-vortex evolution in ground proximity: analysis and parametrization, *AIAA Journal* **45** (1), 218-227 (2007)

## **PRESENTATIONS/PAPERS AT SCIENTIFIC CONFERENCES**

### **General**

- Leweke, T.: FAR-Wake: Fundamental Research on Aircraft Wake Phenomena, 1st WakeNet3-Europe Workshop on "Wake Turbulence Safety in Future Aircraft Operations", 8-9 January 2009, Paris-Versailles, France
- Leweke, T.: Vortex pairs, IUTAM Symposium "150 Years of Vortex Dynamics", 12-16 October 2008, Lyngby, Denmark
- De Bruin, A. C., Nybelen, L., Winckelmans, G., Giovannini, A., Georges, L., Melber, S.: CFD simulations of wake flows in the FAR-Wake project, 5th European Congress on Computational Methods in Applied Sciences and Engineering, 30 June - 4 July 2008, Venice, Italy
- Jacquin, L., Leweke, T.: Fundamental Research on Aircraft Wake Phenomena - EU Project FAR-Wake, 4th AIAA Flow Control Conference, 23-26 June 2008, Seattle (WA), USA
- de Bruin, A.: A summary of exploitable results for enhanced safety and/or airport capacity - results from the FAR-Wake synthesis activity, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Laporte, F.: A380 wake vortex status, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Winckelmans, G.: Wake vortex simulations using the vortex-in-cell (VIC) method, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Schönfeld, T., Bousuge, J.-F., Le Dizès, S., Leweke, T.: Fundamental vortex phenomena: instabilities and interactions with jets and wakes (EU project FAR-Wake), First CEAS European Air and Space Conference - Century Perspectives, 10-13 September 2007, Berlin, Germany - Paper CEAS-2007-007
- Winckelmans, G., Cocle, R., Lonfils, T., Cottin, C., Daeninck, G., Thirifay, F., Ploumhans, P.: Vortex Particle and Vortex-in-cell methods, 3rd European SCAT (Scientific Computing Advanced Training) Workshop and Summer School, 4-10 June 2007, Porquerolles, France
- Leweke, T.: Fundamental Research on Aircraft Wake Phenomena - Project FAR-Wake, Wakenet Europe Workshop 2007: "Wake Vortex Operational Concepts Implementation - What are the research and validation needs?", 5-7 February 2007, Brussels, Belgium
- Winckelmans, G., Cocle, R., Dufresne, L., Capart, R., Bricteux, L., Daeninck, G., Lonfils, T., Duponcheel, M., Desenfans, O., Georges, L.: Direct numerical simulation and large-eddy simulation of wake vortices: going from laboratory conditions to flight conditions, European Conference on Computational Fluid Dynamics (ECCOMAS CFD 2006), 5-8 September 2006, Egmond aan Zee, The Netherlands
- Leweke, T.: Fundamental Research on Aircraft Wake Phenomena - Project FAR-Wake, Fifth Community Aeronautical Days, 19-21 June 2006, Vienna, Austria, Book of Abstracts, p. 97

### **Vortex Instabilities and Decay**

- Le Dizès, S., Fabre, D.: Viscous ring modes in vortices with jet, IUTAM Symposium "150 Years of Vortex Dynamics", 12-16 October 2008, Lyngby, Denmark
- Roy, C., Leweke, T., Thompson, M. C., Hourigan, K.: Experiments on the elliptic instability in vortex pairs with axial core flow, XXII International Congress of Theoretical and Applied Mechanics, 24-29 August 2008, Adelaide, Australia - Abstracts Book, p. 134
- Moldoveanu, C., Giovannini, A., Boisson, H.C.: Turbulence receptivity of longitudinal-vortex-dominated flows, International Conference on Boundary and Interior Layers - Computational & Asymptotic Methods, 28 July - 1 August 2008, Limerick, Ireland

- Deniau, H., Nybelen, L.: Spatial simulation of a co-rotating vortex merging process in unstable conditions, 5th European Congress on Computational Methods in Applied Sciences and Engineering, 30 June - 4 July 2008, Venice, Italy
- Abid, M.: Nonlinear mode selection in a model of trailing line vortices, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Coustols, E., Labbé, O., Moens, F., Molton, P., Jacquin, L.: Status of ONERA research on wake vortex evolution and alleviation in the framework of national activities and European collaboration, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Fabre, D.: Waves on vortices, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Fontane, J., Brancher, P., Antkowiak, A., Fabre, D.: Nonmodal stability analysis of the Lamb-Oseen vortex, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- González, L. M., Theofilis, V.: Temporal instability analysis of two- and four-vortex systems, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Jacquin, L.: Destabilizing trailing wake vortices, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Konrath, R., von Carmer, C. F.: Validation experiment with 4-vortex wake in large tow tank, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Nybelen, L., Deniau H.: Spatial simulation of a co-rotating vortex merging process in unstable conditions, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Parras, L., del Pino, C., Fernandez-Feria, R.: Spatial stability of q-vortex and Batchelor vortex for high swirl numbers, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Roy, C., Leweke, T.: Experiments on vortex meandering, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Roy, C., Leweke, T., Thompson, M. C., Hourigan, K., Schaeffer, N., Le Dizès, S., Lacaze, L.: Elliptic instability in a pair of vortices with axial jet, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Schaeffer, N., Le Dizès, S.: Nonlinear dynamics of the short-wavelength elliptic instability, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Vandernoot, F.-X., Barricau, P., Bézard, H., Boisson, H.-C.: Mean and turbulence measurements in wake vortices. Wandering effects, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- van Jaarsveld, J. P. J., Holten, A. P. C., Elsenaar, A., Trieling, R. R., van Heijst, G. J. F.: Wind tunnel experiments on wake-vortex decay in external turbulence, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Voß, G., Konrath, R., von Carmer, C. F.: Wake vortex alleviation by differential and oscillating flap setting: an experimental study, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Vandernoot, F.-X., Barricau, P., Boisson, H.-C.: Tourbillons de sillage quadripolaires, 43ème Colloque d'Aérodynamique Appliquée, 10-12 March 2008, Poitiers, France

- Fabre, D., Le Dizès, S.: Viscous and inviscid centre modes in vortices: the vicinity of the neutral curves, 60th Annual Meeting of the Division of Fluid Dynamics - American Physical Society, 18-20 November 2007, Salt Lake City (UT), USA, *Bulletin of the American Physical Society* **52** (12) (2007)
- Le Dizès, S.: Waves on vortices, EUROMECH Colloquium 491: "Vortex dynamics from quantum to geophysical scales", 11-14 September 2007, Exeter, UK
- Allen, A., Breitsamter, C.: Investigation of four vortex system wake characteristics, First CEAS European Air and Space Conference - Century Perspectives, 10-13 September 2007, Berlin, Germany - Paper CEAS-2007-181
- Voss, G., Carmer, C. v., Konrath, R., Stumpf, E., Krückeberg, C.-P., Meyer, H., Mattner, H.: Wake vortex alleviation by differential and oscillating flap setting: a comparative numerical and experimental study, First CEAS European Air and Space Conference - Century Perspectives, 10-13 September 2007, Berlin, Germany - Paper CEAS-2007-006
- Roy, C., Thompson, M. C., Leweke, T., Hourigan, K.: Etude numérique de l'instabilité elliptique dans une paire de vortex co-rotatifs avec écoulement axial, 18e Congrès Français de Mécanique, 27-31 August 2007, Grenoble, France - Paper CFM2007-0599
- Thomas, O., Sipp, D., Jacquin, L., Serval, P., Fabre, D., Sagaut, P.: Etude de l'éclatement tourbillonnaire dans les sillages des avions de transport, 18e Congrès Français de Mécanique, 27-31 August 2007, Grenoble, France - Paper CFM2007-0926
- Brion, V., Sipp, D., Jacquin, L.: Optimal perturbation of a counter-rotating vortex pair, 18e Congrès Français de Mécanique, 27-31 August 2007, Grenoble, France - Paper CFM2007-1060
- Fabre, D., Jacquin, L.: Dynamique linéaire d'un tourbillon de Lamb-Oseen, 18e Congrès Français de Mécanique, 27-31 August 2007, Grenoble, France - Paper CFM2007-0903
- Fontane, J., Brancher, P., Fabre, D.: Forçage stochastique du tourbillon de Lamb-Oseen, 18e Congrès Français de Mécanique, 27-31 August 2007, Grenoble, France - Paper CFM2007-0937
- Schaeffer, N., Le Dizès, S.: Influence of an elliptic instability on the merging of a co-rotating vortex pair, 18e Congrès Français de Mécanique, 27-31 August 2007, Grenoble, France - Paper CFM2007-1038
- Theofilis, V., González, L. M.: Finite-element numerical methods for BiGlobal linear instability analysis of vortical flows, 37th AIAA Fluid Dynamics Conference and Exhibit, 25-28 June 2007, Miami (FL), USA, AIAA Paper 2007-4359
- Roy, C., Leweke, T., Thompson, M. C., Hourigan, K.: Elliptic instability in a pair of vortices with axial jet, 3rd European SCAT (Scientific Computing Advanced Training) Workshop and Summer School, 4-10 June 2007, Porquerolles, France
- González, L., de Vicente, J., Theofilis, V.: Finite-element numerical methods for BiGlobal linear instability analysis of vortical flows, 3rd European SCAT (Scientific Computing Advanced Training) Workshop and Summer School, 4-10 June 2007, Porquerolles, France
- Brancher, P., Antkowiak, A., Fontane, J., Fabre, D., Adjovi, J., Corbett, P.: Transient growth in vortices, 3rd European SCAT (Scientific Computing Advanced Training) Workshop and Summer School, 4-10 June 2007, Porquerolles, France
- Le Dizès, S.: 1. Kelvin vortex waves - 2. Elliptic instability, 3rd European SCAT (Scientific Computing Advanced Training) Workshop and Summer School, 4-10 June 2007, Porquerolles, France
- Del Pino, C., Parras, L., Fernández-Feria, R.: Non-parallel spatial stability of Batchelor vortex, 59th Annual Meeting of the Division of Fluid Dynamics - American Physical Society, 19-21 November 2006, Tampa (FL), USA, *Bulletin of the American Physical Society* **51** (9), 159 (2006)
- Brion, V., Sipp, D., Jacquin, L.: Influence of axial flow and aspect ratio on the stability of vortex pairs, 59th Annual Meeting of the Division of Fluid Dynamics - American Physical Society, 19-21 November 2006, Tampa (FL), USA, *Bulletin of the American Physical Society* **51** (9), 91 (2006)
- Le Dizès, S.: Dynamics and instabilities of aircraft vortices, 2nd European SCAT (Scientific Computing Advanced Training) Workshop, 25-29 September 2006, Paris, France
-

- Theofilis, V., de Vicente, J., Valero, E., Abdessemed, N., Sherwin, S.: Recent advances in the computation of BiGlobal linear instability of flows over complex configurations, 6th EUROMECH Fluid Mechanics Conference, 26-30 June 2006, Stockholm, Sweden, EFMC6 Abstracts - Volume 2, p. 357
- Fabre, D., Sipp, D., Jacquin, L.: The Kelvin waves and the singular modes of the Lamb-Oseen vortex, 6th EUROMECH Fluid Mechanics Conference, 26-30 June 2006, Stockholm, Sweden, EFMC6 Abstracts - Volume 1, p. 113
- Ren, M., Elsenaar, A., van Heijst, G. J. F., Kuczajy, A. K., Geurts, B. J.: Decay or collapse: aircraft wake vortices in grid turbulence, 6th EUROMECH Fluid Mechanics Conference, 26-30 June 2006, Stockholm, Sweden, EFMC6 Abstracts - Volume 1, p. 167
- Schaeffer, N., Lacaze, L., Le Dizès, S.: Instabilities in co-rotating vortices with axial flow, 6th EUROMECH Fluid Mechanics Conference, 26-30 June 2006, Stockholm, Sweden, EFMC6 Abstracts - Volume 1, p. 198
- von Carmer, C. F., Konrath, R., Schröder, A., Monnier, J.-C.: Identification and visualisations of parallel vortex pairs in aircraft wakes from PIV data, 12th International Symposium on Flow Visualization, 10-14 September 2006, Göttingen, Germany, Paper ISFV12-5.3
- Parras, L., Fernández-Feria, R.: Spatial stability and the onset of absolute instability of Batchelor vortex for high swirl numbers, 58th Annual Meeting of the Division of Fluid Dynamics - American Physical Society, 20-22 November 2005, Chicago (IL), USA, *Bulletin of the American Physical Society* **50** (9), 195 (2005)
- Cocle, R., Dufresne, L., Winckelmans, G.: LES of multiscale instabilities in wake vortex systems, International Symposium on Complex Effects in Large Eddy Simulations, 20-24 September 2005, Limassol, Cyprus
- Le Dizes, S., Lacaze, L., Ryan, K.: Elliptical instabilities in vortices with axial flow, International Conference on High Reynolds Number Vortex Interactions, 29-31 August 2005, Toulouse, France
- Roy, C., Leweke, T.: Experiments on the dynamics and stability of vortex pairs with axial core flow at high Reynolds numbers, International Conference on High Reynolds Number Vortex Interactions, 29-31 August 2005, Toulouse, France
- Dufresne, L., Winckelmans, G.: LES of the interaction and partial reconnection of unequal strength vortices, International Conference on High Reynolds Number Vortex Interactions, 29-31 August 2005, Toulouse, France

### **Vortex Interactions with Jets and Wakes**

- Veldhuis, L. L. M., de Kat, R.: Vortex wake Investigation behind a wing-flap model with jet simulation 26th Congress of the International Council of the Aeronautical Sciences, 14-19 September 2008, Anchorage (AK), USA
- Coustols, E., Labbé, O., Moens, F., Molton, P., Jacquin, L.: Status of ONERA research on wake vortex evolution and alleviation in the framework of national activities and European collaboration, 5th European Congress on Computational Methods in Applied Sciences and Engineering, 30 June - 4 July 2008, Venice, Italy
- Tyliszczak, A., Boguslawski, A., Drobniak, S.: LES predictions of isothermal and hot round jet, 7th International ERCOFTAC Symposium on Engineering Turbulence Modelling and Measurements (ETMM7), 4-6 June 2008, Limassol, Cyprus
- Boguslawski, A., Tyliszczak, A., Drobniak, S.: LES predictions of round isothermal and heated jets, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Cottin, C., Lonfils, T., Cocle, R., Winckelmans, G.: Roll-up of wing and propelled-wing wakes: time- and space-developing LES including comparisons to experiments, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France

- Jacquín, L., Molton, P., Loiret, P., Coustols, E.: An experiment on jet-wake vortex interaction, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Jung, U., Breitsamter, C.: Vortex interactions with wakes: wing elements, fuselage, and landing gear, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Louagie, T., Georges, L., Geuzaine, P., Melber-Wilkending, S., Allen, A., Breitsamter, C.: Wake vortices generated by an aircraft fuselage: comparison of wind tunnel measurements on the TAK model with RANS and RANS-LES simulations, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Marles, D., Margaris, P., Gursul, I.: Effect of an axial jet on aircraft wake vortices, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Veldhuis, L. L. M., de Kat, R., Elsinga, G. E.: Towing tank experiments of cold jet-vortex interaction on a generic wing-flap model, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Coustols, E., Labbé, O., Moens, F., Molton, P., Jacquín, L.: Status of ONERA research on wake vortex evolution and alleviation in the framework of national activities and European collaboration, 43ème Colloque d'Aérodynamique Appliquée, 10-12 March 2008, Poitiers, France
- Tyliszczak, A., Boguslawski, A.: Quality of LES predictions of isothermal and hot round jet, Workshop on Quality and Reliability of Large-Eddy Simulations, 24-26 October 2007, Leuven, Belgium
- Melber-Wilkending, S., Allen, A., Breitsamter, C.: A comparison between CFD and wind tunnel measurements for wake vortex prediction, First CEAS European Air and Space Conference - Century Perspectives, 10-13 September 2007, Berlin, Germany - Paper CEAS-2007-182
- Marles, D., Gursul, I.: Effect of a jet on vortex merging, 37th AIAA Fluid Dynamics Conference and Exhibit, 25-28 June 2007, Miami (FL), USA, AIAA Paper 2007-4364
- Jacquín, L., Molton, P., Loiret, P., Coustols, E.: An experiment on jet-wake vortex interaction, 37th AIAA Fluid Dynamics Conference and Exhibit, 25-28 June 2007, Miami (FL), USA, AIAA Paper 2007-4363
- Margaris, P., Marles, D., Gursul, I.: Experiments on interaction of a jet with a trailing vortex, 45th AIAA Aerospace Sciences Meeting and Exhibit, 8-11 January 2007, Reno (NV), USA, AIAA Paper 2007-1123
- Tyliszczak, A., Boguslawski, A.: Modelling of bifurcating jet using LES method, XVIIth Biennial National Polish Conference on Fluid Mechanics, 17-21 September 2006, Belchatów, Poland
- Tyliszczak, A., Boguslawski, A.: Parametric study of the jet in variable density conditions, International Symposium on Complex Effects in Large Eddy Simulations, 20-24 September 2005, Limassol, Cyprus
- Tyliszczak, A., Boguslawski, A.: LES of the jet in low Mach variable density conditions, 6th ERCOFTAC Workshop Direct and Large Eddy Simulations (DLES-6), 12-14 September 2005, Poitiers, France

### **Wake Evolution Near the Ground**

- De Visscher, I., Lonfils, T., Winckelmans, G.: Improvement of the Deterministic/Probabilistic wake Vortex Models (DVM/PVM) for the combined effects of ground and meteorology, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Georges, L., Geuzaine, P., Bricteux, L., Duponcheel, M., Lonfils, T., Winckelmans, G.: LES of wake vortices in ground effect without and with wind (comparing different multiscale subgrid models), International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France

- Giovannini, A., Boisson, H.-C.: Dynamic Mixed Large Eddy Simulation of a vortex pair in a turbulent channel, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Holzäpfel, F., de Bruin, A.: Aircraft wake-vortex evolution in ground proximity: analysis of field measurement data and parameterization, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Konrath, R., von Carmer, C. F.: Towing tank investigations on 2- and 4-vortex systems in ground effect using PIV, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Pereira, J. C. F., Sereno, J.: Uncertainty quantification of a 2D vortex pair in ground effect, International Workshop on Fundamental Issues Related to Aircraft Wakes (FAR-Wake Workshop), 27-29 May 2008, Marseille, France
- Louagie, T., Georges, L., Geuzaine, P., Bricteux, L., Duponcheel, M., Lonfils, T., Winckelmans, G.: Numerical simulation of wake vortex flows: RANS-LES of a fuselage wake and LES of wake vortices in ground effect with and without wind, 43<sup>ème</sup> Colloque d'Aérodynamique Appliquée, 10-12 March 2008, Poitiers, France
- Holzäpfel, F., Gerz, T., Frech, M., Tafferner, A., Köpp, F., Smalikho, I., Rahm, S., Hahn, K.-U., Schwarz, C.: The wake vortex prediction and monitoring system WSVBS - Part I: Design, First CEAS European Air and Space Conference - Century Perspectives, 10-13 September 2007, Berlin, Germany - Paper CEAS-2007-177
- Duponcheel, M., Cottin, C., Daeninck, G., Leweke, T., Winckelmans, G.: Experimental and numerical study of counter-rotating vortex pair dynamics in ground effect, 18<sup>e</sup> Congrès Français de Mécanique, 27-31 August 2007, Grenoble, France - Paper CFM2007-1131
- Bricteux, L., Cocle, R., Duponcheel, M., Georges, L., Winckelmans, G.: Assessment of multiscale models for LES: spectral behaviour in very high Reynolds number turbulence and cases with aircraft wakes vortices, Proc. 5th International Symposium on Turbulence and Shear Flow Phenomena (TSFP-5), 27-29 August 2007, Garching, Germany, vol. 1, pp. 327-331
- Moldoveanu, C., Giovannini, A., Boisson, H., Moraru, F.: Numerical simulation of longitudinal counter-rotating vortices pair in interaction with the ground, 5th IASME / WSEAS International Conference on Fluid Mechanics and Aerodynamics, 25-27 August 2007, Athens, Greece
- Louagie, T., Georges, L., Thomas, J.-F., Hillewaert, K., Geuzaine, P.: Towards DES and advanced LES in complex geometries: development, validation and application to wake vortex dynamics, 2nd European Conference for Aero-Space Sciences (EUCASS), 1-6 July 2007, Brussels, Belgium
- Duponcheel, M., Lonfils, T., Bricteux, L., Georges, L., Cocle, R., Daeninck, G., Cottin, C., Desenfans, O., De Visscher, I., Winckelmans, G.: Investigation of wake vortices in ground effect: DNS, LES, towing tank experiments, real-time operational modelling, Annual Seminar of the Belgian ERCOFTAC Pilot Centre, 8 December 2006, Louvain-la-Neuve, Belgium
- Cottin, C., Leweke, T.: Experiments on vortex pair dynamics in ground effect, 6th EUROMECH Fluid Mechanics Conference, 26-30 June 2006, Stockholm, Sweden, EFMC6 Abstracts - Volume 1, p. 199
- Duponcheel, M., Lonfils, T., Bricteux, L., Winckelmans, G.: Simulation of three-dimensional wake vortices in ground effect using a fourth order incompressible code, 7th National Congress on Theoretical and Applied Mechanics (NCTAM2006), 29-30 May 2006, Mons, Belgium
- Frech, M., Holzäpfel, F.: Skill of an aircraft wake-vortex transport and decay model using short-term weather prediction and observation, AMS 12th Conference on Aviation Range and Aerospace Meteorology, 30 January-2 February 2006, Atlanta (GA), USA, Paper 6.8
- Holzäpfel, F., Steen, M.: Aircraft wake-vortex evolution in ground proximity: analysis and parameterization, 44th AIAA Aerospace Sciences Meeting and Exhibit, 9-12 January 2006, Reno (NV), USA, AIAA Paper 2006-1077
-