WakeNet3-Europe

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Aircraft Wake Vortex State-of-the-Art & Research Needs

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5.1 Wake Vortex Behaviour Modelling

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5.1.1 Overview

Wake vortex behaviour modelling is the technology relating to the operational (thus necessarily simplified) modelling of aircraft wake vortex behaviour: the transport and the decay of the port and starboard vortices of the two-vortex system formed after complete rollup of the wake behind an aircraft. Those vortices are influenced by various parameters: the characteristics (weight, span, flight speed, attitude, span loading) of the aircraft that generates them, the local meteorological conditions (cross wind and head wind, wind shear, turbulence, stratification) in which they then evolve, and the ground proximity conditions which also affects their transport and decay.

Depending on application, *operational* refers to such software tools being useable for off-line studies or for real-time systems.

The operational models developed are physics-based (hence they are also called "physical models") and aim at predicting the behaviour of the wake vortices in one plane crossing the flight path. The models are expressed, typically, as ordinary differential equations (ODE; with added stochastic components in some cases), and that are integrated in time. Some models also take into account the uncertainty/variability of the impact parameters: they are then denoted probabilistic.

Operational wake vortex models are still being further developed and used essentially in Europe and in the USA. Two platforms have also been developed that use the European models in several gates to rebuild the 3-D wake generated by an aircraft evolving in given meteorological conditions, also enabling analyses relating to potential wake vortex encounter.

For some applications, wake vortex behaviour modelling also refers to modelling the expected topology of the wake vortices (e.g., amplitude of the Crow instability development, topology of the vortex rings formed after reconnection and their decay).

Also the use of velocity field databases in flight simulators, obtained from very detailed large-eddy simulations (LES) of wake vortices in specific conditions, can be considered as some kind of "operational modelling". As such databases can be very large (e.g., 1 GB for one 3-D velocity field at one time), they must be reduced to a smaller set for real-time access in the flight simulator. In some cases (e.g., Crow instability in weak atmospheric turbulence and without or weak stratification), the database itself can be reduced to a simplified mathematical model which fits properly the main vortex 3-D topology; the model can then, in turn, be used to feed the flight simulator with velocity fields computed using an efficient Biot-Savart evaluation.

Finally, this section also describes recent developments achieved with LES and the analysis of field measurement data.

5.1.2 State-of-the-art

There are two European operational wake vortex models:

- the Deterministic/Probabilistic Two-Phase wake vortex decay and transport model (D2P/P2P) of DLR, and
- the Deterministic/Probabilistic wake Vortex Model (DVM/PVM) of UCL

and three US models:

- the AVOSS Prediction Algorithm (APA), a deterministic wake vortex model developed by several groups and researchers,

- the Vortex algorithm Including Parameterized Entrainment Results (VIPER), a deterministic model recently developed by NWRA for the FAA,
- the TASS Driven Algorithm for Wake Prediction (TDAWP), a deterministic model developed by NASA with still limited functionality.

These models forecast, deterministically or probabilistically, the transport and decay of wake vortices generated in one slice across the flight path.

Two platforms have also been developed. Each one uses a European operational model in several gates to rebuild the 3-D wake generated by an aircraft evolving in given met conditions, also enabling potential encounter analysis:

- WakeScene (see §6.2), developed by DLR, that uses the D2P/P2P and
- WAKE4D (see §6.2), developed by UCL, that uses the DVM/PVM.

The European operational models were continuously developed, improved and used, also in the framework of several large-scale projects. The projects in which the models were, and are still, used are listed below.

- Wirbelschleppe I & II (1999-2007) “Fundamental and applied wake vortex research”, DLR Project
- S-Wake (2000-2002): “Assessment of wake vortex safety”, FP5
- C-Wake (2000-2003): “Wake vortex characterization and control”, FP5
- I-Wake (2002-2005): “Instrumentation systems for on-board WAKE-vortex and other hazards detection, warning and avoidance”, FP5
- ATC-Wake (2002-2005): “Integrated Air Traffic Control WAKE vortex safety and capacity optimization system”, FP5
- AWIATOR (2002-2007): “Aircraft WIng with Advanced Technology Operation”, FP5
- FAR-Wake (2005-2008): “Fundamental Research on Aircraft Wake Phenomena”, FP6
- FLYSAFE (2005-2009): “Airborne Integrated Systems for Safety Improvement, Flight Hazard Protection and All Weather Operations”, FP6
- CREDOS (2006-2010): “Crosswind Reduced Separations for Departure Operations”, FP6

  In the EU project CREDOS the D2P and DVM models have been used within the WakeScene-D package to estimate the probability to encounter wake vortices during departures in different traffic and crosswind scenarios. Comprehensive sensitivity analyses have been conducted and crosswind scenarios for reduced separations have been evaluated (see §3.1).
- TBS (2006-2008): EUROCONTROL “Time-Based Separation project”

  The WAKE4D-DVM/PVM was used in the first phase of the EUROCONTROL project “Aircraft Wake Vortex Modelling in support to Time-Based Separations on Final Approach''. This work was a partnership between UCL and M3Systems. The WAKE4D platform was used for a comparative risk analysis. The wakes generated by various aircraft in various wind conditions were simulated. A risk metric using the highest possible circulation of the potentially encountered vortices was also computed and was used to compare applying the current distance-based separations in still air conditions to applying the time-based separation (Desenfans 2010).
- Green-Wake (2008-2012): “Demonstration of LiDAR based wake vortex Detection System incorporating an Atmospheric Hazard map”, FP7
- WIDAO (2007-2010): “Wake-Independent Departure and Arrival Operations (WIDAO) at Paris CDG airport”, EUROCONTROL and DSNA project

The WAKE4D-PVM was also used for a fast-time study that aims to quantify the impact on landing medium aircraft safety of wake turbulence generated by heavy aircraft departing on parallel runways. Different scenarios of departure were investigated and the impact on the wake frequency/severity curves of the potentially encountered vortices was studied. The curves correspond to the complementary cumulative density function (CCDF) of the circulation. This study was performed for the CDG airport in the framework of the EUROCONTROL and DSNA WIDAO project. The purpose of the project was first to quantify the increase of frequency and severity of potential wake vortex encounter (WVE) by medium landing aircraft if the departing heavy aircraft are lined up shifted ahead of the currently used runway entry. It also aimed to compare the results with the frequency/severity curve of potential WVE at ICAO separation in trail behind a heavy aircraft. In that project, more than 4000 departing aircraft were considered in about 2000 different wind conditions and for two pairs of runways.

- RECAT (started in 2008): “Re-categorization of the Wake Turbulence Separation Minima”, Joint EUROCONTROL-FAA project

  In the framework of the joint EUROCONTROL-FAA RECAT project (see §3.5), Phases II and III, DLR and UCL (Gerz et al. 2011, Winckelmans 2011) proposed that the operational models should be used, in addition to the very simplified model (fitted on measurements close to the ground) with assumed linear decay which was used in Phase I.

- Wetter & Fliegen (2008 - 2012): “Airport and aircraft wake vortex, thunderstorm, and winter weather systems”, DLR Project

- SESAR P6.8.1 (started in 2010): “Wake vortex data analysis and modelling”, led by EUROCONTROL

  In the framework of SESAR P6.8.1, described in Sections 3.1 and 3.4, and in collaboration with EUROCONTROL, it is planned that UCL will also compare the results of their models (DVM/PVM in WAKE4D) to those of large-scale measurement campaigns (e.g., the Heathrow campaign).

- SESAR P12.2.2 (started in 2011): “Runway Wake Vortex Detection, Prediction and Decision Support Tool”, led by Thales

  As subcontractors to Thales, UCL and DLR integrate their wake vortex prediction platforms (WAKE4D and WakeScene) into the WVDSS platform described in §6.2.2.4. In the framework of the project, the predictor will also be benchmarked and validated. The final platform will also integrate the concept and system defined, also with EUROCONTROL, in the project P6.8.1.

- SESAR P9.11: “Aircraft Systems for Wake Encounter Alleviation” and P9.30:” Weather Hazards / Wake Vortex Sensor”, led by Airbus and started in 2011

  As subcontractors to Airbus, UCL and DLR bring their probabilistic models (PVM and P2P) of wake vortex behaviour in and out of ground effect, and adapt them to the requirements of a real-time, airborne warning system WEPS-P (Wake Encounter Prevention System based on Prediction, see §4.2). The models will also be verified against wake measurements.

- WSVBS

  The P2P model has been applied for performance tests of the WSVBS (see §4.1.2.2) at Frankfurt airport in winter 2006/07 and at Munich Airport in summer 2010 and spring 2011 for landings on single runways as well as closely-spaced parallel runways either for aircraft weight class combinations or dynamic pairwise separations.

- Wake vortex encounters in cruise flight

  In a cooperation between DLR and NCAR (National Center for Atmospheric Research) funded by FAA the probability to encounter wake vortices en route will be estimated employing the P2P and the WaVoP (Wake Vortex Prediction) model. WaVoP is an adaptation of CoCiP (Contrail Cirrus Prediction Tool, Schumann 2011) which supports the identification and quantification of potential encounters employing air traffic density and weather data bases.

5.1.2.1 Deterministic and Probabilistic wake Vortex Model (DVM / PVM)

UCL's Deterministic wake Vortex Model (DVM) is a deterministic model based on the method of discrete "vortex particles" that models the primary wake vortices (generated by an aircraft) as well as the "secondary" vortices (generated when the vortex comes into ground effect, IGE). The DVM takes into account the influence of the generating aircraft characteristics (position, aircraft configuration, span, weight, and airspeed), the atmospheric conditions (the vertical profiles of head-, crosswind, wind shear turbulence and temperature stratification, see also §5.1.2.7), and the ground proximity (see §5.1.2.5). A simplified model of the Crow instability growth is also included and was also validated using LES results (see §5.1.2.7). The wake vortex evolution (i.e. transport and decay) is computed, using simplified physical models, in a plane ("computational gate") that is perpendicular to the trajectory. Results are the time evolution of the vortex position and strength. Two initialization options are available in the DVM. Either a vortex sheet (with a certain circulation distribution model) is discretised using vortex particles, or a chosen circulation distribution model (i.e., one-scale models: the low-order algebraic model (Burnham-Hallock) or the high-order algebraic model; or even the more complex, two-scale model of Proctor-Winckelmans) of rolled up vortices is used and is itself discretised. The model has been improved, calibrated, assessed and validated against data of US and EU measurement campaigns and results of Large Eddy Simulations (LES), also in the framework of EC funded projects. Figure 25 provides an example of comparison between DVM predictions and measurements (form the EDDF-1 database) for a NGE/IGE case.

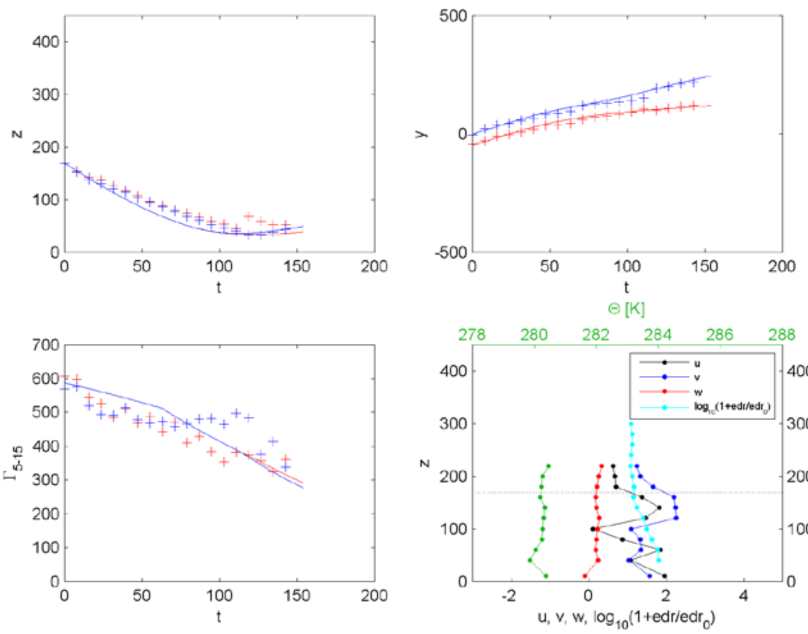

Figure 25: Example of comparison between EDDF-1 measurement data (crosses) and DVM prediction (solid). Red and blue colours are used respectively for the starboard and the port vortices. The measured met data are also provided ($edr_0 = 10^{-5}$ m^2/s^3).

The Probabilistic wake Vortex Model (PVM) uses the DVM as sub-tool in a Monte Carlo approach with variations of the impact parameters (inputs, i.e. aircraft characteristics and weather profiles, and model coefficients). Those parameters are varied depending on their natural variations (for the met data), their uncertainty (for the met and aircraft data) and their calibration (for the coefficients of the physical models). So each PVM run uses many DVM runs. The total number of DVM runs used is large, yet is not directly related to the number of varied input parameters. This enables to obtain the statistics of the results (vortex positions and circulation) in one computational gate. The PVM also uses the bootstrap resampling technique that enables to obtain conservative statistical results while limiting the number of DVM runs.

The WAKE4D, and its subcomponents DVM and PVM, have been used in fast-time and real-time simulations of WVEs as well as a vortex forecast function in experimental detection, warning and avoidance systems in aircraft and on ground. A Graphical User Interface (GUI) was also developed for easy use of the DVM/PVM. This GUI is also useful for demonstration or training purposes. These developments were aimed at allowing more easily a transfer of the simulation tools to other users. The WAKE4D and its subcomponents DVM and PVM are described in detail in (Winckelmans et al. 2010, De Visscher et al. 2010 and Winckelmans et al. 2011)

5.1.2.2 Deterministic and Probabilistic 2-Phase Model (D2P/P2P)

DLR's Deterministic 2-Phase model (D2P) computes the transport and decay of the wake vortex pair in a 2D plane (gate). It takes into account the aircraft characteristics: weight, wing span, flight speed, position, height above ground, flight path angle, and bank angle. The model considers the vertical profiles of the meteorological quantities: head wind, cross wind, wind shear, turbulence (TKE, EDR), and temperature stratification (gradient of potential temperature). All parameters are normalized based on initial vortex separation, b_0, and initial circulation, Γ_0. The probabilistic version P2P is based on the uncertainties of wake vortex evolution found in LES and field experiment data. Uncertainty allowances are modelled by conducting three model runs with different fixed and dynamic uncertainty parameters. Finally, the probabilistic envelopes for vortex position and strength are calibrated employing field measurement data. The model has been validated against data of over 10,000 cases gathered in two US and six EU measurement campaigns. With a computation time below 0.01 s on a standard personal computer, P2P is suited for fast-time simulations. The D2P and P2P have been used in fast-time and real-time simulations of WVEs and in risk analysis tools (see §5.5) as well as in airborne and ground based experimental wake vortex prediction and avoidance systems (see sections 4.2 and 3.4). The model design and applications to field measurement data are described in detail in (Holzäpfel 2003, Holzäpfel and Robins 2004, Holzäpfel 2006, Holzäpfel and Steen 2007, Frech and Holzäpfel 2008, Holzäpfel 2011).

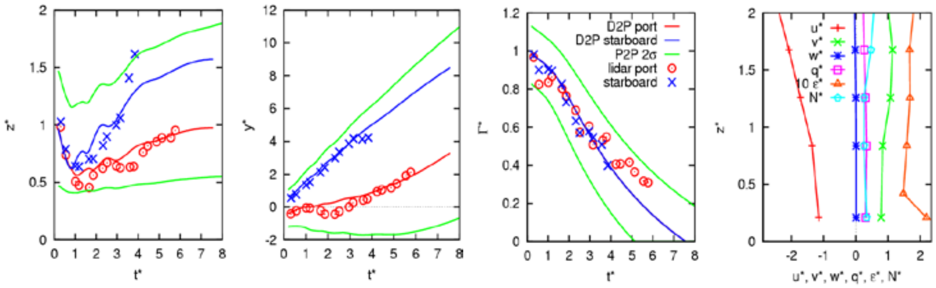

Figure 26: P2P prediction of wake vortex behaviour in ground proximity. Measured (symbols) and predicted (lines) evolution of normalized vertical and lateral positions and circulation. Red and blue lines denote deterministic predictions; green lines are envelopes for 95.4% probability. Right: Vertical profiles of normalized environmental data.

Figure 26 left shows exemplarily the asymmetric rebound of the wake vortices in a crosswind situation close to the ground. Also the measured vortex divergence (second from left) and the circulation decay (third from left) are well predicted by the D2P. One LiDAR measurement point of vertical position is situated outside of the predicted probabilistic envelopes (2σ corresponding to 95.4%) of wake vortex behaviour.

Currently, the vortex model is further improved. The Probabilistic 3-Phase (P3P) wake vortex model is based on core elements of the P2P model and improves vortex position and circulation prediction in particular in the late stages of the vortex life (far field of the wake) where vortex rings are forming. The P3P model combines the circulation evolution phases of gradual diffusion, rapid decay and ring diffusion.

5.1.2.3 Description of the US operational models

The APA 3.2 model predicts wake vortex trajectories and circulation within a plane perpendicular to the path of the generating aircraft (Sarpkaya et al. 2001, Robins and Delisi, 2002). Atmospheric inputs include vertical profiles of the ambient crosswind, temperature, and turbulence intensity (represented by EDR). The initial wake is represented as two vortices whose initial strength and position are dependent upon input conditions.

If the wake is out of ground effect, the APA model utilizes a decay and transport model, such as developed by Sarpkaya (Sarpkaya 2000). For in ground effect, APA utilizes image vortices to represent the effect of an impenetrable ground, and the introduction of secondary vortices that cause wake vortex rebound. The method for vortex decay while in ground effect depends on a formula derived from a TASS LES study (Proctor et al. 2000). The latest APA version, Suite 4.0, is similar to APA 3.2, but allows the option of using Sarpkaya, TDAWP, or D2P as the OGE module.

The TDAWP model is a deterministic wake vortex model. It has separate prognostic equations for vortex descent rate and 5-15 m average circulation, and it applies these separately to both the port and starboard vortices (Proctor et al. 2006). The formulation is driven by parametric studies from LES using TASS (Proctor and Switzer 2000). The TDAWP formulation includes the effects of crosswind shear on vortex descent rate, thus allowing the prediction of vortex tilt and the change in lateral separation due to crosswind. Ground effect is not yet included in the model.

The VIPER model is being developed for the FAA by NWRA (Delisi 2011). It will be used to predict the evolution of aircraft-generated wake vortices under a variety of atmospheric conditions and aircraft flight regimes for evaluating new, proposed operational procedures. It is based on control-volume analyses and the fluid laws for conservation of mass, momentum, and angular momentum. An IGE model is currently being developed to be combined with the OGE model.

5.1.2.4 Multi-Model Ensemble

In a recent study the prediction skills of several deterministic wake vortex models have been compared (Pruis and Delisi 2010, Pruis 2011). It is found that the models are generally pretty good. However, a “best” fast-time numerical wake vortex model cannot be determined due to uncertainties in accuracy of the input environmental and aircraft conditions. As a consequence, it is suggested to utilize multiple fast-time wake vortex models and to determine the probabilistic estimates of wake vortex behaviour using the model ensemble. Such multi-model ensembles have proven to be successful for probabilistic weather prediction (see § 5.3). The finding that the uncertainties and variability of the initial and environmental conditions have a dominant impact on wake vortex prediction skill is well known; see e.g. (Holzäpfel 2009, Winckelmans et al. 2009, Winckelmans and Bourgeois 2010).

5.1.2.5 Wake vortex interacting with the ground and the wind: simulations and modelling

In the FAR-Wake project, significant researches were achieved on wake vortex physics and operational modelling NGE/IGE, also for cross-wind or headwind (Holzäpfel et al. 2008). They were supported by the results of Large Eddy Simulations (LES) performed in the framework of the project (Giovannini et al. 2007) and by the data of the WakeFRA 2004 measurement campaign (Holzäpfel & Steen 2007). In addition, complementary studies were performed to analyse the result sensitivity to the crosswind amplitude and to the generation altitude. The IGE models of the DVM and of the D2P have then been further improved.

LES studies of wake vortices IGE: sensitivity analysis to the crosswind amplitude and to the generation altitude

In addition to the work performed in the FAR-Wake project (Giovannini et al. 2007), further wall-resolved LES investigations of wake vortices IGE and with realistic turbulent crosswind were carried out by UCL, in collaboration work with Airbus, using an improved subgrid-scale model (Bricteux et al. 2009), valid for both vortex flows and wall-bounded. Four cases were considered with various wind amplitudes and release altitudes. A visualization of the flow field for the case with the strongest investigated wind is provided in Figure 27. DLR has also conducted wall-resolved and wall-modelling LES of wake vortex evolution in ground proximity with and without wind. Figure 28 left shows the interaction of the primary wake vortices with the turbulent structures generated by some crosswind at the ground surface.

In Figure 27 and 21 left, one observes the vorticity sheet, generated at the ground, by the presence of the primary vortices that detaches from the ground and starts rotating around the primary vortices. Triggered by crosswind streaks those secondary vorticity sheet transforms into so-called omega loops wrapping around the primary vortices and initiating vortex decay.

UCL performed detailed analyses of the wake vortex transport and decay. In particular, the circulation distribution, $\Gamma(r)$, of the longitudinally averaged vortex (flow averaged over the computational plane of the longitudinal direction) was evaluated as a function of time, enabling to obtain both $\Gamma_{5\text{-}15}$ and Γ_{tot} of each "mean vortex". In addition, the circulation distribution was also measured in each computational plane which enables also deriving the statistics of $\Gamma_{5\text{-}15}$ and Γ_{tot}. The results allow the estimation of the spread that can be expected in LiDAR measurements derived values of $\Gamma_{5\text{-}15}$ or Γ_{tot} (as a LiDAR measurement scans a plane, not a mean vortex). Further, the results were used to calibrate the DVM/PVM transport and decay parameterizations (see below). The report by UCL to Airbus (Bricteux et al. 2009) will be used to produce a publication. Some of this work was also presented at an ASME conference (Bricteux et al. 2009).

DLR further investigated the influence of the introduction of obstacles at the ground surface (see Figure 28 right, Stephan et al. 2012). It can be seen that the obstacle may substantially accelerate vortex decay in the critical area close to the threshold where most vortex encounters occur. Such a setup specifically exploits properties of vortex dynamics to accelerate wake vortex decay in ground proximity with the following characteristics: (i) early detachment of strong omega-shaped secondary vortices, (ii) omega shape causes self-induced fast approach to the primary vortex, (iii) after the secondary vortex has looped around the primary vortex, it separates and travels both ways along the primary vortex, again driven by self-induction, (iv) the artificially generated secondary vortex connects to the regular ground effect vortex and thus obtains continued supply of energy, (v) the highly intense interaction of primary and secondary vortices leads to rapid wake vortex decay independent from natural external disturbances.

Good agreement with towing tank experiments has demonstrated another proof of concept (Geisler & Konrath 2012). In a next step the obstacles have been optimized with respect to size and shape. LES indicate that plate lines cause even slightly stronger effects than much more massive block-shaped obstacles (Stephan et al. 2012). The beneficial effects are robust with respect to headwind and crosswind. The time for decay to 50% of the initial vortex strength can be halved by the introduction of the barriers.

In summary the introduction of plate lines at the ground supports the selective generation of secondary vortices and enables a smart utilization of vortex properties in order to generate fast approaching and rapidly spreading disturbances leading to premature vortex decay in ground proximity. The installation of suitable obstacles at runway tails may improve safety by reducing the number of wake encounters and increase the efficiency of wake vortex advisory systems. A respective patent entitled "Surface Structure on a Ground Surface for Accelerating Decay of Wake Turbulence in the Short Final of an Approach to a Runway" has been filed under number DE 10 2011 010 147. Flight experiments will be conducted at Oberpfaffenhofen airport (Germany) in order to demonstrate the real-life functionality of plate lines for the release of premature wake vortex decay in the most critical flight phase prior to touchdown.

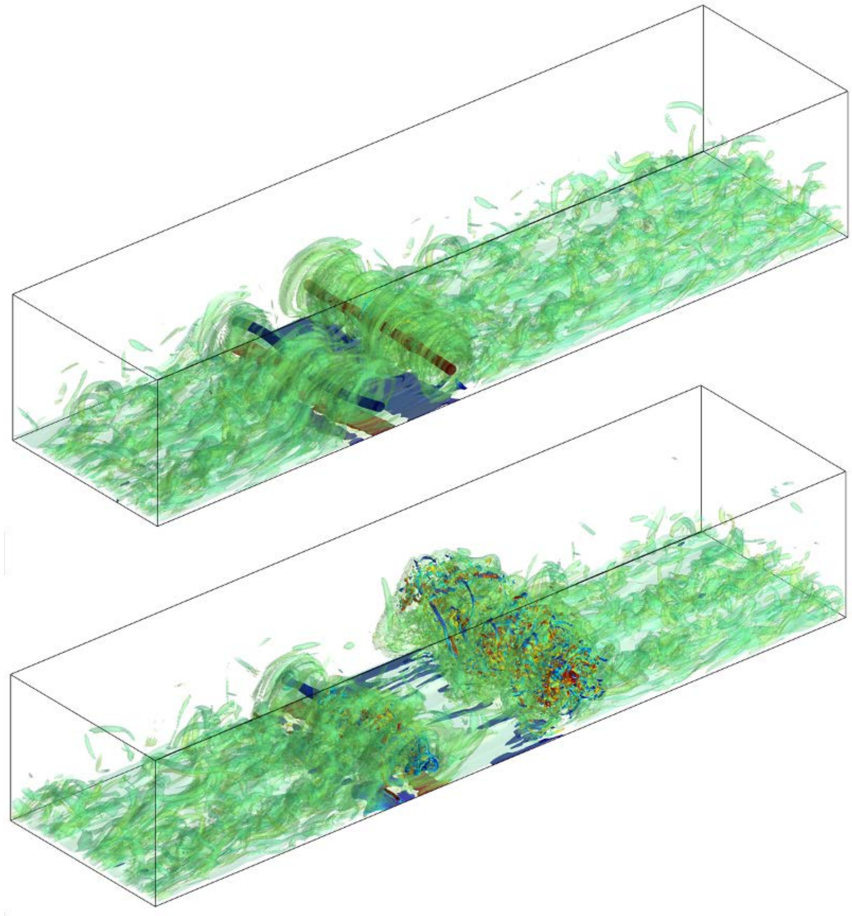

Figure 27: Wake vortices IGE and with turbulent cross-wind $v(h_0) = 2\ V_0$ and with $h_0=b_0$: Iso-surfaces of vorticity norm coloured by the axial vorticity ω_x at time $t/t_0 = 1.0$ (top) and $t/t_0 = 2.0$ (bottom; by that time, the downwind vortex has already much decayed and lost coherence).

Modelling of ground effects on wake vortex behaviour

UCL developed and validated an improved model for wake vortex behaviour In-Ground Effect. It models the flow dynamics using vortex particles both for the primary and secondary ground-generated vorticity. It is able to dynamically reproduce the combined effects, on the wake vortex behaviour, of the ground proximity and of the wind (both head- and crosswind components). The agglomeration of secondary separated vortex particles limits the number of used particles (and hence the computational time) while maintaining a sufficiently good representation of the flow dynamics. The further reorganization of the secondary particles, after the primary vortex rebound, also permits to mimic the turbulent reorganization of the secondary vorticity around the primary vortices at those times and its interaction with those, leading to a much enhanced decay IGE. The DVM, and in particular the IGE model, was calibrated and assessed based on LES results and on measurement data from the WakeFRA 2004 campaign. It was found to properly reproduce the wake vortex behaviour both in terms of transport and circulation decay for times up to t/t_0 = 4-5, the typical times of interest for operational applications (for large aircraft, t/t_0 = 4 corresponds roughly to 120 s). As the model is based on physical concepts, one expects it to be also valid for conditions different from those tested here. Further details on the model and its validation are found in (De Visscher et al. 2011, De Visscher 2012).

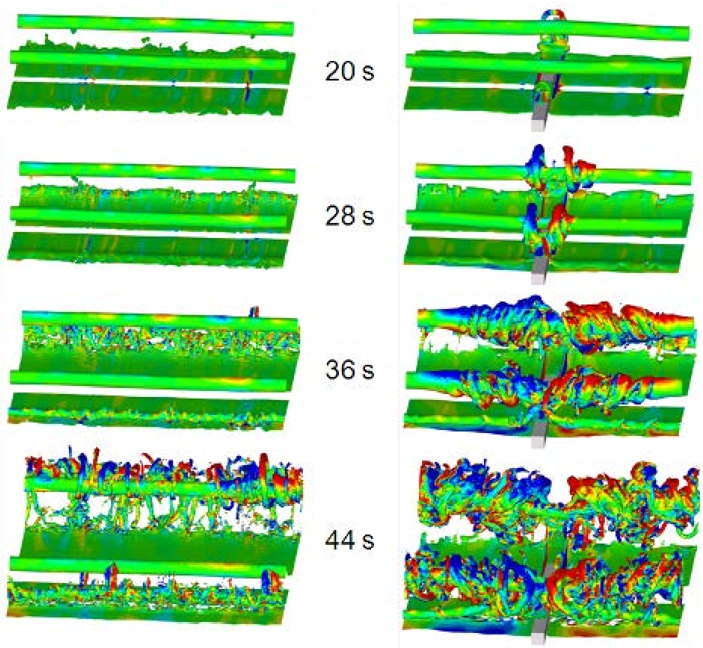

Figure 28: Wall resolving LES of wake vortex evolution in ground proximity with turbulent crosswind of 0.85 of initial vortex descent speed at initial vortex altitude of b_0 and vortex time scale t_0 = 26.3 s (wind direction points into image plane). Left without and right with obstacle at the ground surface (square profile with side length 0.19 b_0).

5.1.2.6 Wake vortex transport and decay depending on the cross-wind, also combined with ground effects

These investigations were performed in the framework of the FP6 CREDOS project than ran from 2006-2010. The involved partners were DLR, UCL and Airbus.

Use of the EDDF-1 and EDDF-2 databases

In the framework of the CREDOS project, two measurement campaigns of wake vortices generating by departing aircraft were performed: EDDF-1 and EDDF-2. The databases were analysed and used to assess the performance of the operational prediction models (DVM/PVM and D2P/P2P). The use of the two measurement campaign databases is described in (CREDOS deliverable D2-5 by De Visscher et al. 2009). Selected highlights of the results are reported in the following.

The EDDF-2 database contains about 10,000 wake vortex cases generated by heavy and medium aircraft at various height (up to 150 m) and in a large range of meteorological conditions. This hence enables to perform well-converged statistical analyses. The wake vortex lateral transport was statistically correlated with the crosswind, using different (operational or not) “crosswind definitions”.

For each crosswind definition, the envelopes containing the wake vortices with various probability levels were built at different times. An example of the obtained envelopes is shown in Figure 29. A simple mathematical model was proposed and calibrated for the evolution, as a function of the crosswind, of the envelope containing the vortices (with a certain probability level). Finally, an analysis of the wake vortex circulation decay, depending on the wind amplitude, was also performed: those results can also be related to the recent Large-Eddy Simulation (LES) studies carried out by UCL on wake vortices IGE and with different crosswinds (see details above).

The prediction models DVM/PVM were also assessed employing both the EDDF-1 and the EDDF-2 databases. The simulations were run using inputs as close as possible to the measurement conditions, and also using the “declared” measurement uncertainties. The results were compared with the provided experimental data, and quantified comparisons on the wake vortex positions and circulations were provided and discussed, using statistical means. The difference between the LiDAR processed $\Gamma_{5\text{-}15}$ circulation (as provided in the EDDF-1 database) and the LiDAR processed total circulation Γ_{tot} (as provided in the EDDF-2 database) was also highlighted. An example of comparison between EDDF-1 measurement data and DVM prediction is shown in Figure 25. Also studied was the influence, on the DVM results, of the extrapolation of the met data, when not available. Due to the high variability of the met and wake vortex data in both databases the obtained differences between the measurements and the model predictions were found to be higher than those obtained with the WakeFRA 2004 data and results of LES. Considering the quite high variability of the present data, the agreement between the DVM predictions and the measurements data was considered as quite good. For the PVM it appeared that the predicted envelopes, obtained using the declared measurement uncertainties, were reliable. In order to obtain “better" predicted results, yet of course larger envelopes, one should rerun the PVM using input uncertainties which better reflect the true uncertainty of the provided data.

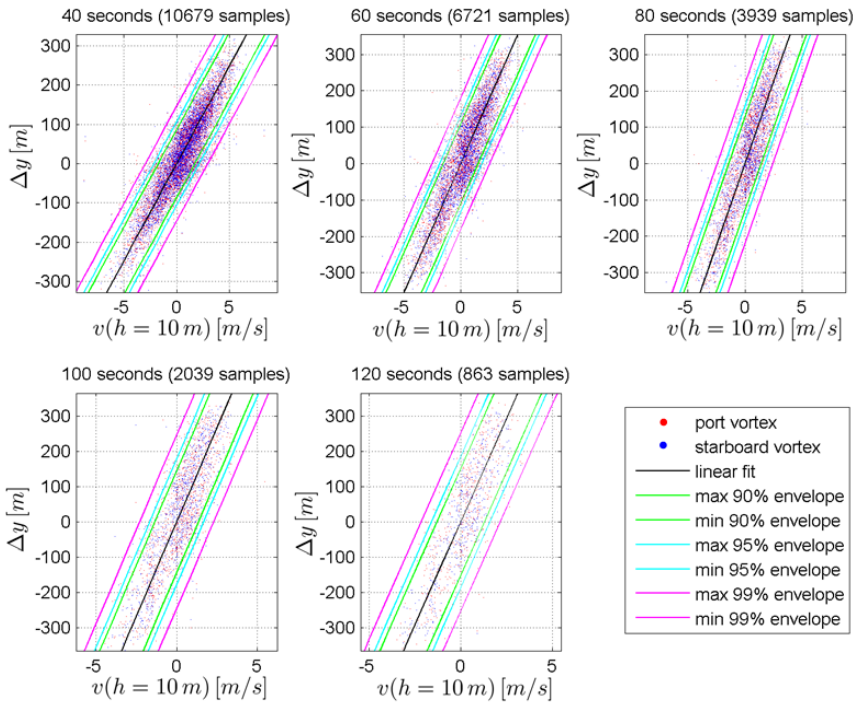

Figure 29: Evolution of the vortex net lateral displacement as a function of the crosswind (at 10 m height) at different vortex ages. Linear fits (black) show the mean evolution whereas coloured envelopes delimit 90% (green), 95% (cyan) and 99% (magenta) of the examined vortices.

Different parameterizations and inputs of the D2P/P2P model were tested to investigate the effects of the onset of ground induced rapid decay, the headwind/tailwind modelling, the crosswind shear model, the vortex decay models, the input wind profile (SODAR/RASS or WTR/RASS). A scoring procedure was used to compare the obtained results. The comparison of scoring results indicated on average better model performance for EDDF-1 than for EDDF-2, although wake vortex prediction OGE is subjected to larger uncertainties than IGE and although the measurement conditions during EDDF-1 were complicated by very strong winds. With the WakeFRA data significantly higher prediction skill was achieved (Holzäpfel & Steen 2007). The scoring results also confirmed that crosswinds measured by LiDAR yield superior prediction skill of lateral transport compared to WTR/RASS measured crosswinds; this is as expected.

Then the two deterministic models DVM and D2P were compared in a “benchmarking exercise”, based on a small subset of the EDDF-1 database. For the benchmark, Airbus selected 16 cases representing different crosswind and headwind classes. Both wake vortex models were run from identical initial conditions specified by Airbus and based on aircraft and LiDAR data. The predicted vortex characteristics (lateral and vertical positions and circulation) of both models were confronted to the LiDAR measurements, comparing the running average of vortex characteristics (predicted by both models and “measured”) and computing the rms deviation between the predictions and the measurements. An assessment depending on crosswind and headwind categories was also performed. It was noted that the sample size is not sufficient for robust conclusion. However, for both models, the vortex predicted characteristics were in the range of the scatter of the LiDAR data. It was concluded that both models represent well the wake vortex transport and decay. It is indicated that the models could indeed be used for the prediction of vortex trajectories under cross wind conditions, together with the appropriate probabilistic versions (PVM and P2P) or using an appropriate safety margin to be defined and applied.

DFS, DLR, and UCL employed different approaches in order to estimate crosswind threshold values supporting vortex-free corridors for departing aircraft (Dengler et al. 2010). Although several competing effects as wake vortex transport in and out of ground effect, temporal and spatial wind variability, and the spreading of aircraft trajectories after take-off complicate the analyses, all three approaches lead to similar crosswind thresholds. Employing standard instrumentation at 10 m height a minimum crosswind threshold of 3.9 – 5.0 ms^{-1} has been identified to clear a safety corridor of 200 m width from wake vortices with a 95% probability within 60 seconds. Crosswind thresholds can be reduced if the wind is measured close to the air mass in which the vortices evolve. A definite crosswind threshold for operational use cannot be deduced solely from this study since critical factors like risk and safety assessment have not yet been taken into account.

Monte-Carlo simulations of departure under crosswind conditions

Another contribution of CREDOS was the use of both D2P and DVM modules in the WakeScene-D software package of DLR, as part of the work in CREDOS on "Risk Modelling and Risk Assessment" (CREDOS deliverable D3-9 by Holzäpfel and Kladetzke 2009, Holzäpfel et al. 2009). This used the updated and validated wake vortex behaviour models to realistically simulate takeoff scenarios with complex flight path, involving wake vortex evolution and decay in and out of ground effects. A description of WakeScene is given in §6.2.

The Monte Carlo simulations of the departure scenarios showed that the use of different wake vortex models (P2P or PVM) did not change the conclusions with respect to the suggested crosswind thresholds. This indicates that, on one hand, the models have reached a valuable level of maturity and that, on the other hand, the results of relative safety assessments could be quite robust with respect to peculiarities of the employed submodules.

Measured vortex tracks of about 10,000 departures from runway 25R of Frankfurt airport have been compared with WakeScene-D simulations. For lateral vortex transport, which for crosswind departures constitutes the most important quantity, good agreement between the characteristics of measurement and simulation has been achieved. This indicates that WakeScene-D with its wake vortex models allows investigating realistic wake vortex behaviour in domains and height ranges that are far out of reach of measurements.

5.1.2.7 Wake vortex behaviour depending on combined turbulence and stable stratification: simulations and modelling

LES investigations of wake vortices evolving in stably stratified and weakly turbulent atmospheres were conducted by UCL (De Visscher et al. 2009, De Visscher and Winckelmans 2010, De Visscher 2012). Those simulations aim to be as realistic as possible (very high Reynolds number, tight vortex cores $r_c/b_0 = 0.050$). Different stratification cases were investigated, from neutral to very high and with weak to very weak ambient turbulence levels. In order to best represent the combined atmospheric conditions, the stratified and turbulent realistic fields are obtained using LES of forced turbulence, evolving until it reaches a statistically converged equilibrium state. The computational domains were $(4\ b_0)^3$ and $(8\ b_0)^3$, thus also defining different integral length scale L_0 of the turbulence. An example of the flow field is provided in Figure 30 for a case with turbulence and low stratification level in a computational domain allowing the development of the Crow instability.

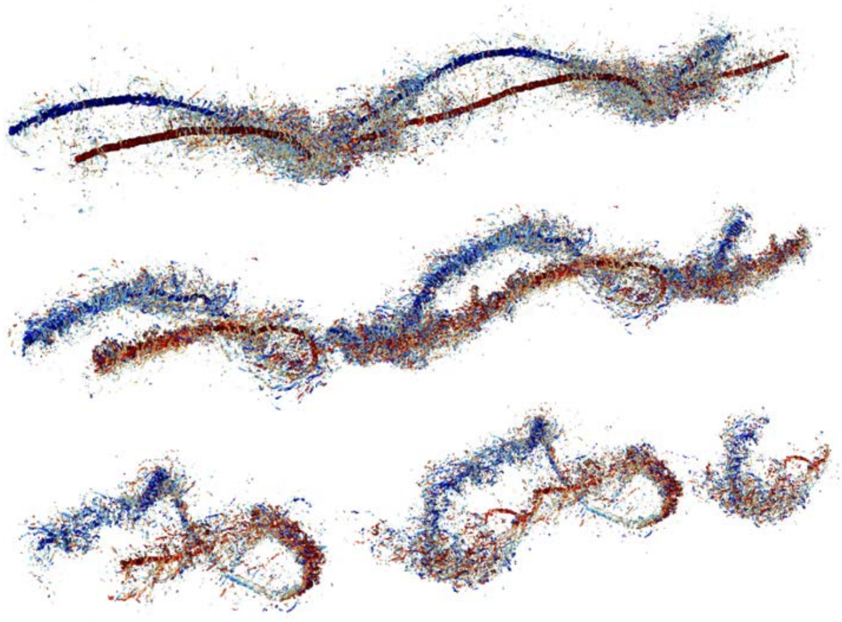

Figure 30: Case of weakly turbulent and stratified atmosphere with N*=0.35: iso-surfaces of λ_2 coloured by the axial vorticity ω_x at times t/t0= 3.0 (top), t/t0=4.0 (middle), and t/t0=5.0 (bottom).

When the stratification level is from medium to high (N* > 0.75), the instabilities have short to medium wavelengths and the turbulence integral scale has a weak impact. When the stratification is absent or low (e.g., N* <= 0.75), the long wavelength Crow type instabilities are also triggered and this leads to vortex linking.

The influence of solely turbulence on wake vortex behaviour (transport, decay and topology) was then also investigated by UCL using LES (De Visscher 2012). The vortices were observed to link and form vortex rings only in weak turbulence cases, whereas, in moderate to strong turbulence, smaller wavelength instabilities also significantly develop and prevent the vortices from linking.

Stratification, turbulence and the Crow linking process all significantly influence the vortex decay. In weak stratification and weak turbulence, the decay is very slow until the time of vortex reconnection. The Crow linking then induces a decay that is much non uniform along the vortex and it must be measured and characterized in various cross-planes (e.g., measure the circulation distribution, $\Gamma(r)$, perpendicular to the detected deformed vortex core line in each cross-plane, and thus obtain local values of $\Gamma_{5\text{-}15}$ and Γ_{tot}): some planes exhibit a very fast second phase decay whereas others only see a slight increase of their circulation decay rate. For higher stratification levels, the strong interactions of the turbulent baroclinic vorticity structures with the wake vortices induce a fast decay of their circulation, which is much uniform along the vortices. For cases with moderate to strong turbulence, the smaller wavelength instabilities also induce an additional decay all along the vortex tubes. This quantification of the circulation decay is very important from an operational point of view. The mean circulation evolution is indeed a relevant measure of the vortex strength (and hence of the related hazard) only for cases of moderate to strong turbulence and/or moderate to strong stratification. For vortices evolving in calm and weakly stratified (or neutral) atmospheres, the use of the complete circulation decay envelope (i.e., as obtained in all cross-planes) is required for any potential encounter analysis. Examples of circulation decay for a case with low and high stratification levels are shown in Figure 31.

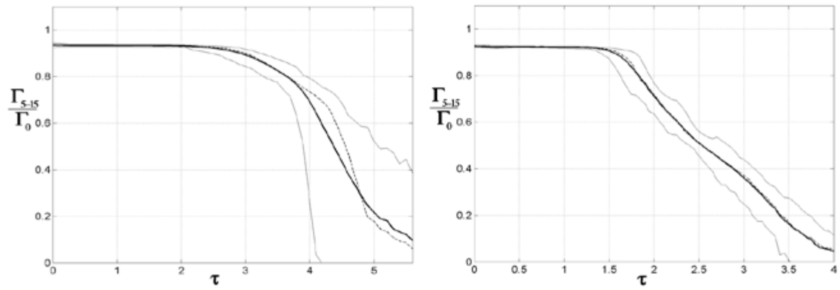

Figure 31: Comparison of the circulation decay of WV evolving in a weakly turbulent (ε* = 2.4·10^-4) and stratified atmosphere for N*=0.35 (left) and N*=1.0 (right). The mean (solid line), the median (dash line) and the 95% envelope (thin lines) are computed using the circulation evaluated in several cross-planes.

The results of these studies were compared and used to propose improvements of the DVM stratification transport model. The comparison between LES results and DVM results are provided in Figure 31. Note that ε* is defined as $\varepsilon^* = \varepsilon \cdot b_0/V_0^3$.

Two models were also proposed for the effects of combined stratification and turbulence on the circulation decay. The first model is valid for cases of weak turbulence and for all the investigated stratification levels. It represents the decay of the longitudinally-averaged circulation. In case of Crow linking, it then represents the mean decay of the circulation evaluated in all cross-planes (those who cut the vortex ring and those who don't and hence have a zero circulation). The second proposed model only represents the circulation decay of the parts of the vortices that are still alive, thus providing the upper bound. Examples of comparison between LES and DVM (using the first decay model) results are provided in Figure 32: .

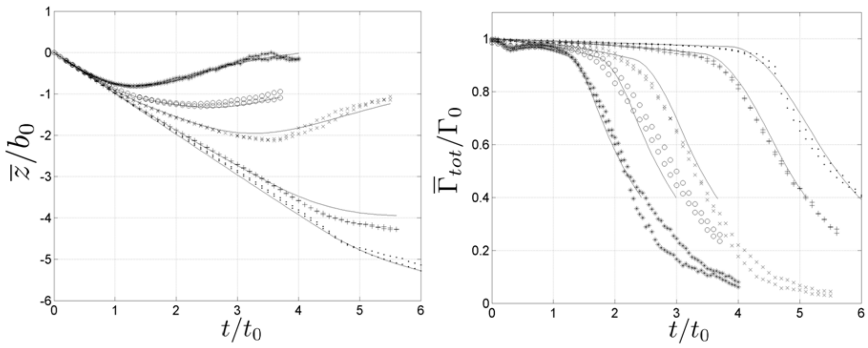

Figure 32: Average vertical displacement (left) and average total circulation (right) for cases with $\varepsilon^* = 2.4\ 10^{-4}$ and N*=0 (.), 0.35 (+), 0.75 (x), 1.0 (o) and 1.4 (+). The DVM results are also displayed (solid).

For the PVM model, a decay pdf and decay envelopes will be used for the strong decay phase, and containing the characterization results obtained from the different cross-planes. For the medium to high stratification levels and/or moderate to strong turbulence levels, those envelopes are found to be tight (confirming the longitudinal uniformity of the decay) while they are quite spread for the low stratification and weak turbulence levels.

It is also important to stress that the resulting detailed velocity fields of such LES correspond to wake vortices in specific and realistic conditions. As such, they can also be stored and used as input in “fast time velocity field evaluation” routines for flight simulator encounter studies (see §5.5, and (De Visscher and Winckelmans 2010, Vechtel 2010, Vechtel 2011, Bieniek and Luckner 2011)). Such LES fields have also been used with good success as databases for LiDAR simulator studies (Brousmiche et al. 2009, Brousmiche 2010, Lugan et al. 2010, Holzäpfel et al. 2003) and also for radar simulator studies (Vanhoenacker-Janvier et al. 2010).

DLR has also conducted LES of wake vortex evolution in environments with various degrees of atmospheric turbulence and stable stratification (Hennemann and Holzäpfel 2009, Hennemann 2010, Holzäpfel et al. 2010, Hennemann and Holzäpfel 2011, Misaka et al. 2012). Prior to the inset of the counter-rotating vortex pair the atmospheric turbulence was allowed to develop a state with a distinct inertial subrange and a constant eddy dissipation rate, ε*. Different size distributions of turbulent eddies leading to different turbulent integral length scales, L_t, result from the initialisation of turbulence energy spectra with different peak wave numbers.

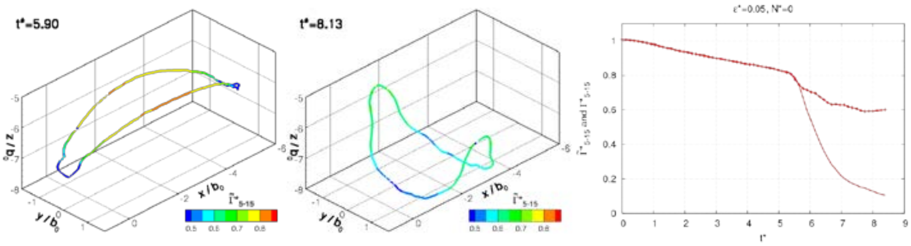

Figure 33: Wake vortex topology with colour-coded circulation in a neutrally stratified environment with weak to moderate turbulence (ε* = 0.05, L_t/b_0 = 0.41) shortly after linking (left) and in vortex ring regime (centre). Corresponding temporal circulation evolution (right) averaged over “cross-planes” (line) and along vortex tubes (symbols).

A post processing method has been developed that is capable to identify the vortices even in progressed states of vortex decay where the coherent vortex structure is getting lost. In a next step this method allows determining circulation along the vortex centre lines (see Figure 33, left). In contrast to the two-phase circulation decay characteristics as obtained from the “cross-plane view and characterization”, the vortex circulation estimated perpendicular to the detected deformed vortex core line may reveal a three-phase decay sequence (see Figure 33, right). The initial phase of gradual decay termed “diffusion phase” is followed by a “rapid decay phase” which typically commences at the time when the vortices link. In neutrally stratified environments long-living vortex rings are observed with gradual vortex decay. This third phase may be termed “ring diffusion phase”. The evolution of the vortex topology from the initial sinusoidal oscillations, the subsequent vortex linking and vortex ring formation up to the axial contraction and the lateral spreading of the vortex ring can be explained phenomenological by mutual velocity induction.

Concerning the operational characterization of the decay in the case with low or without stratification (i.e., neutrally stratified), one can adopt different views. If one switches from a “cross-plane view and characterization” (thus with min and max second phase circulation decay depending on the plane considered) during the phase of linking to a “vortex ring view and characterization” after, then one finds that the decay is again fairly uniform, and again quite weak, along each vortex ring, corresponding to a third “ring diffusion phase”. If one remains in the “cross-plane view and characterization”, then there is no clear third phase, as in Figure 31. Both view points are of interest to the operational modelling.

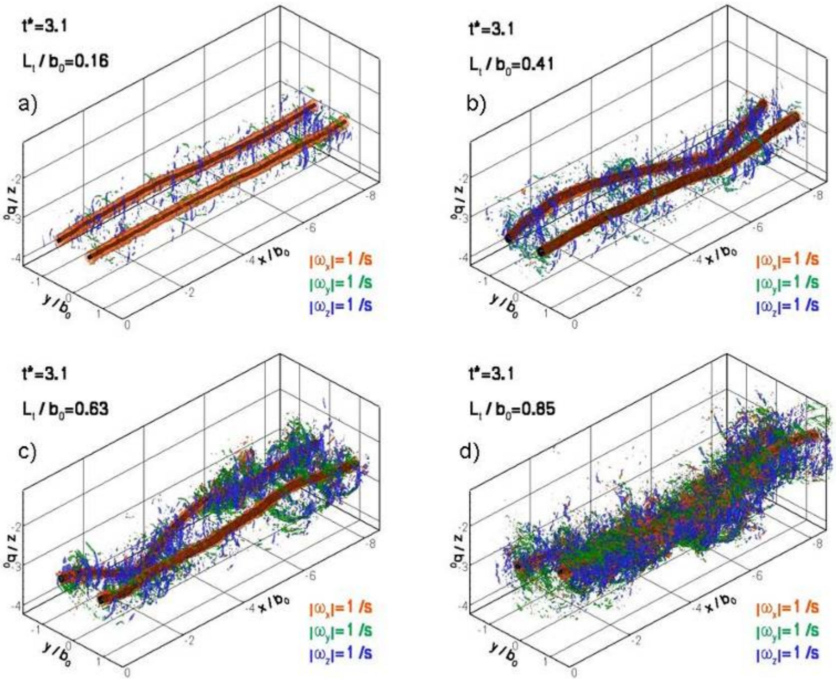

Figure 34: Vortex topology and secondary vorticity for different integral turbulence length scales prior to onset of rapid decay ($\varepsilon^* = 0.23$, $N^* = 0$, reprinted from Hennemann & Holzäpfel 2011).

The ratio of the integral length scale of turbulence and initial vortex separation, L_t/b_0, may have a strong effect on vortex decay characteristics and vortex topology. With increasing L_t/b_0 ratios the decay rate already in the diffusion phase is increased and the vortex topology is becoming more complex. Figure 34 shows that increasing L_t/b_0 ratios increase the amount of secondary vorticity generated from environmental eddies which in turn reduces the energy of the primary vortices. DLR has also been working on subgrid-scale models and has found that the Lagrangian Dynamic Model (Meneveau et al. 1996) is well suited to predict sustained tight vortex cores in turbulent environments.

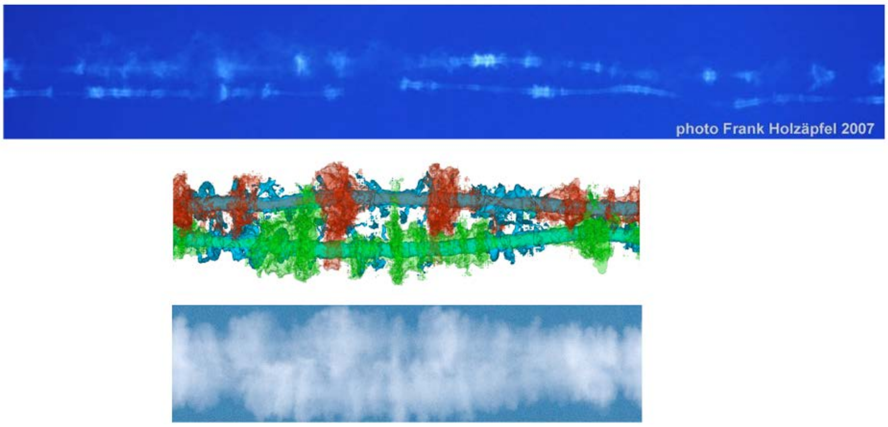

Figure 35: Vortex bursting phenomenon. Top: photograph; centre: LES, isosurfaces of vorticity magnitude (blue) and of passive tracer distributions (red and green) ($t^* = 4.6$, $\varepsilon^* = 0.01$, $N^* = 0.35$, $L_t/b_0 = 0.95$, reprinted from Misaka et al. 2012); below: visualisation based on radiative transfer simulation with libRadtran/MYSTIC (Tobias Zinner, Moritz Schönegg, MIM, LM Universität München).

Turbulent exchange processes of passive tracers within the descending vortex oval and between the oval and its environment have been investigated (Holzäpfel et al. 2010). The dispersion of the ice crystals during the vortex descent is an important parameter in order to quantify the vertical extent, optical thickness, and lifetime of the contrails produced during cruise. Currently, it is not yet clear how strong the contribution of contrails to global warming might be.

Figure 35 shows a photo (top) and simulations of the apparent axial redistribution of ice crystals along the vortex tubes, a phenomenon termed vortex bursting, puffs or pancake vortices (Spalart 1998). In Holzäpfel et al. 2010 and Misaka et al. 2012 it is revealed that the mechanism of vortex bursting is related to collisions of secondary vorticity structures propagating along the vortex lines and that vortex bursting is not related to local vortex decay. Also the formation of vortex funnels can be explained by these propagating coherent secondary vorticity structures (Misaka et al. 2012).

From LiDAR observations it is known that wake vortices may frequently live much longer than anticipated by the aircraft separations that have to be obeyed during approach and landing or during departures. One potential reason why flying is safe nevertheless is the fact that the vortices do not remain straight but are rapidly deformed by the relatively strong turbulence prevailing in the atmospheric boundary layer. The deformation of vortex segments may reduce the impact time of adverse forces and moments experienced by an encountering aircraft and thus may alleviate the severity of the encounter (see §5.5).

The vortex deformation found in LES with various degrees of turbulence and stratification was characterized in terms of curvature radii (Hennemann and Holzäpfel 2011). At a late stage of vortex evolution the established statistics indicate a predominance of curvature radii on the order of one initial vortex separation, b_0, for a variety of environmental conditions. It still has to be investigated thoroughly whether such strongly deformed vortex segments may still pose a risk to follower aircraft. Encounter flights of the DLR research aircraft Falcon behind an A380 indicate that already pronounced sinusoidal oscillations prior to vortex linking might significantly reduce the severity of encounters.

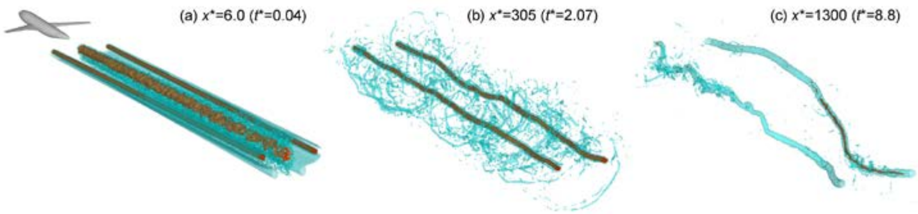

Figure 36: Evolution of aircraft near wake and the resulting wake vortex pair at cruise conditions. Two different levels of vorticity magnitude are shown by red and blue transparent surfaces.

Wake vortex evolution depends not only on environmental conditions but also on the specific aircraft geometry and the configurations for cruise, take-off or landing. A novel wake initialization approach is developed by DLR where a realistic aircraft wake is generated in a LES domain by sweeping a high-fidelity RANS flow field through the domain. This also requires new developments for the boundary conditions supporting spatial LES throughout wake vortex lifetime. Using this approach simulations have been performed from the roll-up until final vortex decay for long range aircraft models in clean and high-lift configuration (Misaka et al. 2012).

Figure 36 shows the wake roll-up and the subsequent evolution of a vortex pair behind the DLR-F6 wing-body model in weak ambient turbulence. Wingtip vortices and fuselage wake have high vorticity magnitudes in the beginning. The fuselage wake with its pronounced axial velocities decays relatively quickly while the wingtip vortices preserve the high vorticity. The decayed fuselage wake and the vorticity from the inboard wing wrap around the wingtip vortices adding disturbances around them. Remarkably, this leads to an increased circulation decay rate in the early diffusion phase as it is observed in LiDAR measurements. A stable vortex pair appears at t*=2.1 and at t* = 8.8 the vortex pair is highly disturbed and almost decayed.

5.1.3 Research Needs

5.1.3.1 “Validation” of the wake vortex models

A large number of questions regarding wake vortex modelling have been raised again and again and so far no answer is in sight that would be considered appropriate by a majority of stakeholders: Are the wake vortex models mature enough to be applied in a wake vortex advisory system? Have the wake vortex models been sufficiently validated? How and when can this be achieved? What is the necessary number of data against which the models need to be validated? How can it be assured that the models are capable to predict wake vortex behaviour under unusual meteorological conditions and all flight phases? Are they applicable to cruise conditions? It appears very difficult to answer these questions.

It is thus of primary importance to define, with stakeholders, the required validation level and the appropriate metric to be used to compare predictions and measurements. Finally, and most important, a correct validation, can only be performed with high quality, experimental and/or numerical (LES), databases.

- Define the required “validation level”

  So an inversion of the questions might be useful. One could prescribe alternatively the wake vortex prediction accuracy needed for a particular concept, system or safety assessment. Then the models would have to prove whether or not they are capable to achieve the required accuracy. This approach would correspond not only to the validation of the wake vortex models themselves but to that of the complete set-up, i.e. including inputs of meteo and aircraft parameters.

- Define a proper metric of comparison

  Different metrics have been developed and used to compare experimental or LES results to those of operational models. For instance, one can perform a comparison case by case. In cases for which long wave (e.g., Crow type) instabilities also occur, one can then also consider the distribution of the circulation decay (or at least the envelopes) along the direction of flight, as various parts of the vortices do not decay at the same rate.

  Alternatively, one can compare the statistics (mean, median, envelopes) of an experimental database to those of the model-predicted database. This last measurement is indeed less sensitive to the individual measurement errors but rather shows the general ability of the model to represent the wake vortex behaviour in various conditions.

- Need of high quality measurement databases

  Any validation exercise requires a high quality measurement database, both for the vortex characteristics (position and circulation) and the meteorological data. Ideally, each measurement is provided together with an estimate of its measurement error.

5.1.3.2 Vortex models and wake vortex encounter studies

The results of LES and of simplified operational models should be used in encounter studies. This can be done in flight simulators and compared to the results of flight experiments. Finally, encounter simulation studies can only be performed if the core radius size, the topology, and the velocity distribution of the wake vortices are known with sufficient precision.

- Wake vortex models in flight simulators

  Promote the operational use of the LES methodologies and available LES databases in flight simulator studies, also in support to severity characterization of wake vortex encounters, new operational concepts, and also in support to new/improved LiDAR system and/or LiDAR signal processing developments. The induced velocity fields obtained from the results of the prediction platform WakeScene or WAKE4D can also be used. The resulting encounter could then be compared when using either the LES or the wake vortex model results.

- Flight experiments

  Flight experiments should be conducted where wake vortex characteristics are estimated simultaneously from (i) in situ measurement (nose booms), from (ii) the aircraft reaction during the encounter, and (iii) from remote sensing with airborne LiDAR. Simultaneous video recordings of the visualized wake (contrail or smoke) from the encountering aircraft and from larger distance would provide information on the prevailing vortex topology. Complementarily, the particular wake vortex evolution under the prevailing meteorological conditions could be investigated with LES. The application of all these key technologies to identical wake vortex segments could enable comprehensive and substantial insights into physical wake vortex parameters, accuracies of the respective measurement instrumentations and encounter modelling (aerodynamic interaction model, wake parameter identification). This would further be a valuable method for validation and/or improvement of the participating methods.

- Determine vortex core sizes and tangential velocity distributions for real aircraft in cruise and high-lift conditions.

  This is an important question for the characterization of the encounter hazard also in context with the A380 wake vortex separations (see, e.g., Bieniek and Luckner 2011, Winckelmans and Chatelain 2011). Different methods could be employed: (i) highly resolving simulations considering the flow around the aircraft and the roll-up process, (ii) dedicated remote sensing measurements with e.g. LiDAR or (iii) with aircraft in-situ measurements employing a nose boom rake or (iv) tower fly by measurements with dedicated sensors.

  This could also be done by pursuing the simulations of far wake vortex systems in turbulent equilibrium and on fine grids, also taking into account Reynolds number effects: to determine r_c "as determined by the fluid mechanics in the far wake and also based on energy arguments (themselves related to induced drag)", and hence participate to resolving the discussion on this important issue. Use the results for operational modelling of r_c and for support to wake vortex encounter studies (evaluation of induced rolling moment, flight simulator studies using improved wake vortex models).

5.1.3.3 Further improvement of the wake vortex behaviour modelling

The wake vortex models are already quite mature. They can hence be used as such. However, some further studies would enable a better characterisation and hence a better modelling of the wake vortex behaviour. These studies should include the further characterisation of the vortex behaviour OGE in turbulent, stratified (stable or unstable) and sheared atmospheres and of the vortex behaviour IGE with head- and crosswind.

- Effects of stable stratification and turbulence on wake vortex behaviour OGE

  The enhanced characterization (from LES results on various sizes of periodic domains) and operational modelling (in DVM/PVM and D2P/P2P) of wake vortex transport, topology and decay should be finalized for cases with and without stable stratification and submitted to various turbulence levels, and also to various integral length scales (yet always limited by the size of the simulation box). For significant stratification the long wavelength Crow-type instability does not develop and the decay is essentially uniform along the vortex, as the result of short and medium wavelength instabilities. For low stratification the long wavelength Crow-type instability does develop, resulting into vortex linking and subsequent non-uniform decay along the vortex. For relatively weak turbulence long-lived vortex rings may form yielding a third phase of decay. It should also be investigated whether for large integral turbulence length scales ($L_t/b_0 > 1$) the effect of turbulence can be characterized solely by eddy dissipation rate.

- Effects of convective boundary layer on wake vortex behaviour OGE

  Further work would also be needed on the characterization and operational probabilistic modelling (in PVM and P2P) of wake vortices submitted to a highly unstable and buoyant atmosphere.

- Further improvement of the modelling of wake vortex behaviour NGE/IGE

  Further work on the enhanced characterization (from LES results) and operational modelling (in DVM/PVM and D2P/P2P) of wake vortices submitted to wind NGE/IGE: cross-wind cases of various strengths, head wind cases of various strengths and combined cases.

5.1.3.4 Modelling of the Near-wake behaviour

- Further improve the operational modelling (in DVM/PVM and D2P/P2P) of the wake generated by aircraft in approach and takeoff configuration.

The merging of the outer flap vortices and the tip wing vortices form the "primary outer two-vortex system" (Γ_1 and b_1) which typically survives in the extended near wake and in the far wake. The HTP vortices, possibly combined with the inner flap vortices, form the "secondary inner two-vortex system" (Γ_2 and b_2) which may not survive as it quickly moves upward as a dipole which is fast dissipated. The transport and decay of the surviving two-vortex system (Γ_1 and b_1) is then what needs to be modelled by the operational models. In particular, the effective spacing factor, $s = b_1/b$, can then, on some aircraft, be larger than that corresponding to cruise conditions.

5.1.3.5 Miscellaneous

- It should be investigated in which limits the classical normalization of wake vortex parameters based on initial vortex separation, b_0, and on initial circulation, Γ_0, is valid. The question arises in particular when considering wakes generated near the ground.
- The LES methodology considering the effects of peculiarities of specific aircraft designs on the resulting wake vortex characteristics in the far field should be further developed. The method should be capable to simulate the flow around specific aircraft geometries (including fuselage, tail plane, jet engines, flaps, slats, landing gear, …) and also consider different flight manoeuvres. This would be helpful to answer questions regarding the proper normalization (see above), merging or separation of individual vortices, appropriate real-time modelling, entrainment of jet exhaust, vortex core sizes and resulting tangential velocity profiles, and circulation evolution in the early diffusion phase. This refined method for initialization of wake vortices certainly requires careful validation.
- Further characterize, from LES, the difference between the averaged vortex (e.g., by removing the meandering) and the instantaneous vortex: effect on r_c and on $\Gamma(r)$.
- Further discuss and study the cost (also computational) and the related benefits of operational probabilistic envelopes for wake vortex transport and decay: pdf, mean, percentiles at various levels (e.g., 95% and 99%), etc. This, of course, is highly related to each application.
- Further study the benefit of parallel computing in operational models, using either CPU or GPU or both. This can become important for real-time application of models that use a Monte Carlo approach, even with a re-sampling procedure (such as the PVM).