WakeNet3-Europe

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

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6.2 Safety Assessment

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6.2.1 Overview

All efforts addressing the safety of flight operations with regard to wake vortex encounter (e.g. wake warning systems) or aiming at increasing the capacity of the air transport system by adjusting wake turbulence separations (e.g. new separation schemes) ultimately aim at reducing the risk of severe wake encounters or must assure that the level of risk is not increased. It is the task of dedicated safety assessments to validate that this risk is either reduced or kept at current levels. Those risk-based safety assessments that consider the possibility of unintentional wake encounter must determine the probability (i.e. frequency) of wake vortex encounters and their associated severity level. Severity assessments concern the determination of the severity of a specified wake vortex encounter. Within such assessments severity criteria correlate objective, measurable quantities with severity descriptions of more general nature and stakeholder-wide understanding. Safety assessments may differ in depth. The most detailed assessments include models of air traffic, weather, wake vortex transport and decay as well as dynamic wake encounter simulations to determine frequency and severity of wake encounters on a statistical basis. Experience shows that a common definition of applicable severity criteria is especially difficult to achieve. This difficulty is due to the fact that many different stakeholders are directly concerned (basically answering the question: “which wake encounter is acceptable?”) but that they have different perspectives, experiences and requirements. While an airline might already be concerned about the number of encounters affecting passenger comfort, a regulator is more likely to be concerned only about encounters leading to incidents.

6.2.2 Current status

6.2.2.1 Absolute safety assessments

Application of ESARR4 is often based on specification of the required safety target of the system in an absolute sense. Such safety target can (but not necessarily has to) be derived from the risk classification scheme as presented in ESARR4. This scheme presents the maximum tolerable probability of the overall ATM contribution to accidents as 1.55×10^{-8} per flight hour. A fraction of this number has to be apportioned to the system in question, representing the overall safety design requirement for the system. Research would be needed to determine a reasonable value for this design requirement. It would comprise an analysis of the contribution of the currently applied separation minima to the overall ATM related accident rate in order to establish a baseline safety requirement. Some of this research has already been conducted in the past, but results have to be verified and agreed to be a valid base for the system design. Further, it is necessary that models are constructed that enable a sufficiently accurate estimate of the actual risk involved in the application of the system. It is of essential importance to the approval process that it can be satisfactorily proven that these models provide trustworthy and valid results, because the results of model simulations factually determine the acceptability of the system in question.

This means that the applicable models will have to be subjected to a rigorous validation process, before they can be accepted as an acceptable means of compliance.

We know the elaborate scale of such validation efforts from -amongst others- aircraft autoland system certification processes. As an illustration it is shown here what is required to be delivered for certification approval of such system (JAR-AWO):

- A specification of the airborne equipment;
- Evidence that the equipment and its installation comply with the applicable standards;
- A failure analysis and an assessment of system safety
- A performance analysis demonstrating compliance with the applicable performance criteria;
- Flight test results including validation of any simulation;
- Limitations on the use of the system and description of crew procedures;
- Evidence that the crew work-load is acceptable;
- Inspection and maintenance procedures shown to be necessary by the system safety assessment

It should be added to this that the performance and safety analysis of a wake vortex advisory system would require a much more complex model than required for auto-land certification. This stems from the fact that simulation of the wake vortex advisory system would have to include the properties of various aircraft types, ground equipment, meteorological conditions and prediction thereof, wake-vortex prediction, and human performance. Development and validation of all these model elements will require a tremendous effort, depending on the required accuracy.

It may even be expected that a complete simulation model of WVAS operation to a similar fidelity as autoland certification simulations might prove to be beyond current technological feasibility. One should think of Monte Carlo type of simulations with a representative number of real (qualified, non-linear, 6 degrees-of-freedom) aircraft models, 3D encounter models, wake vortex measurement and prediction, wind and weather prediction, and human interaction.

Therefore it is clear that simulation models require substantial simplifications. The effects of such simplifications on the accuracy need to be carefully analysed, and it has to be established whether the resulting accuracy will be sufficient for the analysis at hand. Therefore, further research will be needed to establish and validate which model approximations would be acceptable.

6.2.2.2 Relative safety assessments

A possible outcome of mentioned research might be that an absolute estimation of the actual risk cannot be performed with sufficient accuracy, to support approval decisions based on a comparison with a specified (absolute) risk level.

Therefore, alternative methods should be investigated that reduce the effects of model simplifications.

It is known that relative estimates have smaller ranges of uncertainty, and thus are less susceptible to model simplifications. In this respect it should be noted that currently there is not any requirement or standard that would preclude system approval on a relative basis. The basic reasoning is that current ATM procedures and/or systems are each contributing to the currently accepted level of safety (or rather unsafety), as f.i. specified in ESARR4, although the actual quantitative contribution might not be exactly known. If it can be proven that new systems or procedures are at least equally safe as the ones they replace, the overall safety level would not be affected and therefore would satisfy the required target level of safety. The acceptability of such an approach should be further investigated. In particular, agreement should be reached concerning baseline scenarios that would represent current standard practices, and concerning the judgment that these scenarios are considered acceptably safe. Also it would have to be established which model simplifications are allowable in a relative comparison.

6.2.2.3 Introducing new systems

It should be realized that the outcome of any safety assessment (relative or absolute, qualitative or quantitative) will inherently encompass certain levels of uncertainty, due modeling inaccuracies, assumptions and simplifications. Therefore methods should be found that reduce these uncertainties to acceptable levels before the new systems or procedures are fully applied in practical operation. A common procedure is to define a specific introduction phase for the system at hand. A good example of such approach is the autoland system. After the initial approval, based on the safety assessment results, the system is first required to demonstrate a certain number of actual autolands in service before weather limits, under which the system can be operated, are gradually lowered. Clearly such a phased introduction builds confidence in the system and the associated safety assessments. This enables a gradual and controlled transition from the standard operation to the full operational application of the system. In the context of wake vortex advisory systems it is therefore prudent to conduct further research to specify a suitable introduction phase for such systems.

6.2.2.4 Simulation models and validation

Evidently, there is wide array of safety methodologies that can be used for safety assessments, both qualitative and quantitative. It is beyond the scope of the present chapter to address all of these (qualitative and quantitative) methods. However, in light of the anticipated application of ESARR4 requirements for performing risk assessments, simulation models that are able to estimate the risk level in a quantitative (probabilistic) way are of particular interest here.

These models are further addressed in the following.

At present, twelve simulation models that support the assessment of the actual (wake vortex) risk level of flight procedures have been identified:

- WAVIR, developed by NLR-ATSI.
- WakeScene, developed by DLR
- VESA, developed by Airbus
- Airbus A380 wake turbulence minima assessment by Airbus
- Wake Encounter Pilot Model, developed by the TU Berlin (see §4.5)
- RECAT safety assessment method, developed by FAA – EUROCONTROL (see §2.5)
- Wake Vortex Encounter Risk model, developed by DNV
- Wake Vortex Scenario Screening Tool, developed by EUROCONTROL
- Wake Encounter Risk Indicator Simulation package, developed by M3S and UCL
- ASAT, developed by the FAA Flight Procedure Standards Branch
- Probabilistic wake vortex hazard model, developed by the George Mason University
- Recat Step I method, developed by Airbus

These models differ in scope and complexity. Some of the models are actually sub models of others or sub models of a common, larger process.

WAVIR

WAVIR (Wake Vortex Induced Risk) is a stand-alone risk assessment method, based on a modular approach. Risk assessment process employed by WAVIR (Speijker, 2007; Speijker et al., 2004) is depicted in the figure below.

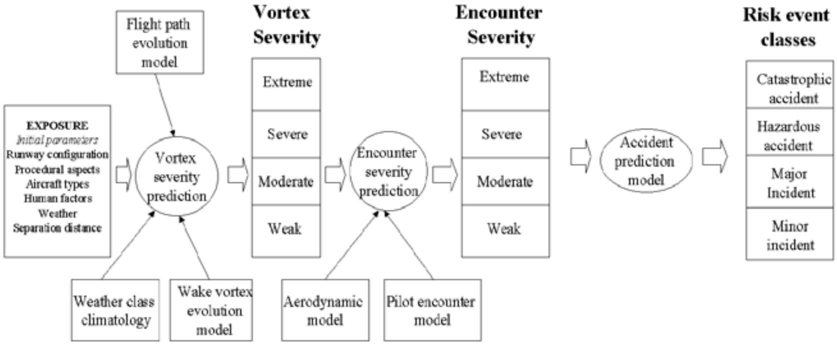

Figure 97: Wake Vortex Induced Risk Assessment (WAVIR).

Basically it is a three step approach. First evolution of the wake vortex generated by a leading aircraft is calculated at a given number of gates along the approach or departure path. The flight path of leader and follower aircraft is specified based on aircraft speed profiles and the nominal trajectory, taking into account uncertainty in speed and position. From this the relative position and strength of the wake vortex can be determined at the time that a following aircraft passes the defined gates. Secondly, the effect of the wake on the passing (i.e. follower) aircraft is determined. Depending on the encounter model used this can be expressed in one or more disturbance parameter (induced roll angle, roll control ratio, loss of height, induced load factor, equivalent roll rate). Finally these disturbances are translated to a certain risk event.

The set-up of the model allows Monte Carlo simulations, using probability distributions for meteorological conditions (stratification, turbulence, wind), aircraft position and speed and other stochastic input parameters. Simulation of a specific scenario, defined in terms of involved aircraft types, flight paths (departure, approach, missed approach, or en-route; interception angle), and the applied separation (horizontal or vertical, distance or time) provides frequency estimates of the risk events in that scenario. This can then be compared with a certain target level of safety in order to establish the anticipated acceptability of the operation.

WAVIR has been used in EC projects (S-Wake, ATC-Wake, I-wake, and Awiator) and supports evaluation of wake vortex safety and required separation distances for:

- Air Traffic Management warning and avoidance procedures (Speijker, September 2006);
- On-board wake detection, warning, avoidance instrumentation (Speijker, October 2006);
- Advanced aircraft wing technology operations (Van Baren, 2007);
- Optimised use of airspace (Van Baren, 2008); and
- New designed high capacity aircraft (Van Baren, 2011).

WakeScene

The WakeScene (Wake Vortex Scenarios Simulation) Package allows assessing the encounter probabilities and the related vortex strengths and can apply different hazard areas behind different wake vortex generating aircraft for different air traffic scenarios (Holzäpfel et al. AST 2009, Holzäpfel et al. JoA 2009). For arrivals the simulation domain extends from the final approach fix to the threshold, for departures it ranges from the runway along different departures routes up to heights of about 3000 ft. Currently, WakeScene is extended to other phases of flight and, in particular, to approaches to closely-spaced parallel runways. In the DLR project ‘Weather & Flying’ it is planned to apply WakeScene for a risk assessment of the WSVBS (WirbelSchleppen Vorhersage und Beobachtungs System, see §4.1.2.2) and for the elaboration of suggestions for a new aircraft separation matrix (re-categorisation, §3.5).

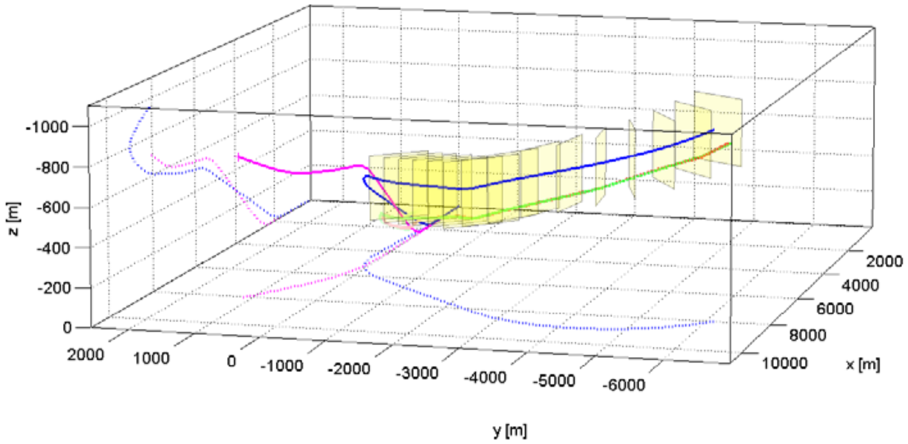

Figure 98: WakeScene simulation of departing aircraft (as analysed in EU project CREDOS, reprinted from Holzäpfel et al. 2009).

The modelling environment supports Monte-Carlo Simulation as well as prescribed parameter variations and generates statistical evaluations. The package consists of elements that model traffic mix, aircraft trajectories, meteorological conditions, wake vortex evolution, and potential hazard area. The Aircraft-Trajectory Model provides time, speed, altitude, mass, and lift of generator and follower aircraft at different gate positions (simulation planes), using point-mass aircraft models or the Advanced Flight Management System (AFMS) based on the BADA database. A large number of environmental- and aircraft specific parameters influence an aircraft trajectory and its deviations from a nominal flight path (see §5.5). The Meteorological Data Base comprises a one-year statistics of realistic meteorological conditions (more than $1.3{\cdot}10^6$ vertical profiles) for the Frankfurt terminal area which were produced with the weather forecast model system NOWVIV (Frech et al. 2007). Based on vertical profiles of environmental conditions and aircraft parameters, the Probabilistic Two-Phase Wake Vortex Decay and Transport Model (P2P, see §5.1.2.2) simulates the development of wake vortex trajectories, circulation, vortex core radius, and attitude of wake vortex axes. The hazard area module defines an area of interest around the wake vortex. When this area of interest is penetrated by the follower aircraft, this is considered to be a “potential wake vortex encounter”. Different options exist for the area of interest definition. A simple circle with 50 m radius around each vortex or the more differentiated approach of “simplified hazard areas” (SHA) (Schwarz and Hahn 2006), which are dynamically adjusted according to vortex strength and aircraft pairing and designed to ensure operationally safe flight outside of the SHA. The SHA are defined by a (conservative) RCR limit that was determined based on pilot ratings in order to ensure that all relevant aircraft upset parameters stay within their typical operational envelope (Hahn and Schwarz 2007). With the aircraft data required for hazard analysis provided by the Simplified Hazard Area Prediction Method (SHAPe), the SHA can be universally applied to any conventional transport aircraft type (Hahn et al. 2004, Schwarz et al. AIAA 2010, Schwarz 2011).

In cases with potential wake encounters all relevant parameters can be provided to VESA (Vortex Encounter Severity Assessment) which may subsequently perform detailed investigations of the encounter severity.

Validation activities have been conducted for the employed submodels of WakeScene (Holzäpfel et al. JoA 2009). For example, the one-year meteorological data base has been validated against a 30-year wind climatology and a 40-days subset has been compared to field measurement data collected at Frankfurt airport (Frech et al. 2007). Validation activities of the P2P wake vortex model (§5.1) have been conducted using data of over 10,000 cases gathered in two US and six European measurement campaigns. Assessments of the wake prediction skill of P2P based on predictions of meteorological conditions with NOWVIV can be found in (Holzäpfel and Robins 2004, Frech and Holzäpfel 2008).

Monte-Carlo Simulations using WakeScene have been used to investigate the wake vortex encounter probabilities for crosswind departure scenarios within the EU-project CREDOS (see §3.1.5). Sensitivity analyses have been conducted regarding the effects of various crosswind scenarios, departure route combinations, flight path adherence, wake vortex modelling, the development of aircraft separations during the departures, the sample size of the Monte Carlo simulations, aircraft type combinations, aircraft take-off weights, meteorological conditions, airport operation times, and a comparison to approach and landing (Holzäpfel and Kladetzke 2011, Holzäpfel and Kladetzke 2009).

VESA (Vortex Encounter Severity Assessment)

The research work performed by Airbus in the last years regarding wake encounter safety assessment built upon different earlier projects that investigated wake encounter hazards. In the EC-funded S-WAKE project (2000-2003) modeling tools were developed that ultimately lead to the wake vortex encounter simulation platform VESA (Vortex Encounter Severity Assessment) (Luckner et al. 2004; Höhne et al. 2004, Kauertz et al. 2012). VESA is able to simulate the effect of wake vortex encounters on an encountering aircraft by adding vortex models to high-fidelity, six degrees-of-freedom flight simulations using dedicated aerodynamic interaction models to couple the wake vortices with the basic aircraft's aerodynamics and flight dynamics. Additional elements included were a model for pilot behavior during wake encounters in approach and hazard criteria to assess the severity of the wake encounter, based on single parameters like bank angle or Roll Control Ratio.

The work in the S-WAKE project focused on the approach phase of flight, and the VESA platform had only limited capabilities to be applied to other flight phases. After S-WAKE the capabilities were continuously extended. Most recently within the CREDOS project (2006-2009) for example the platform was extended to the departure flight phase and existing sub models have been further refined. In particular an advanced severity model was integrated that was developed by TU Berlin using data from extensive piloted simulator tests of wake encounters during departure in the A320 THOR development simulator at Airbus in Hamburg (Amelsberg et al. 2008; Amelsberg, 2009). Pilots taking part in this simulator study also provided subjective hazard ratings for each individual encounter through a dedicated questionnaire. The severity model is based on a multi-parameter envelope approach (Wilborn, 2004; Reinke, 2006) that takes into account the main hazards of a wake encounter on an aircraft, including dynamic aircraft reactions and parameters like load factors, flow angles or aircraft attitude. Advantages of such criteria are that they take into account the actual resistance of the encountering aircraft to the disturbance, and that they can in general be applied to all flight phases and encounter conditions, as all possible hazards caused by the wake are considered. Furthermore a new pilot model was developed by TU Berlin capable of conducting take-off and departure as well as recovery from wake encounters in a way representative of real pilots (Amelsberg, 2006). It is based on a neural net, which has been trained to the recorded pilot reactions from the A320 simulator sessions in CREDOS, simulating wake encounters of varying strengths and types.

The new VESA platform was used within the CREDOS project for an assessment of wake encounter risk during the departure phase, using the Frankfurt/Main International Airport environment as an example. For this assessment the VESA platform was connected to the WakeScene tool developed by DLR (Holzäpfel et al. AST 2009; Holzäpfel et al. JoA 2009), which focuses primarily on the frequency of encounters in the airspace environment. WakeScene identifies potentially significant encounters out of a number of departures, but does not consider any influence of the vortices on the encountering aircraft and thus cannot finally assess the severity of the hazard they pose. The identified potential encounters are instead investigated in detail by VESA. In VESA the encounter conditions in terms of wake intercept angles, vortex characteristics and flight state of the encountering aircraft identified in WakeScene are reconstructed. VESA then allows an estimation of the severity of each identified encounter, using the severity model mentioned above applied to the dynamic response of the aircraft. Both results, the frequency of encounters and their respective severity, allow characterizing the wake encounter risk for the considered scenario. In CREDOS different wake turbulence separation times for Heavy-Medium departures with varying crosswind levels have been compared in a relative way with the goal to find a possible crosswind threshold above which a safe reduction or suspension of wake turbulence specific departure separations is possible.

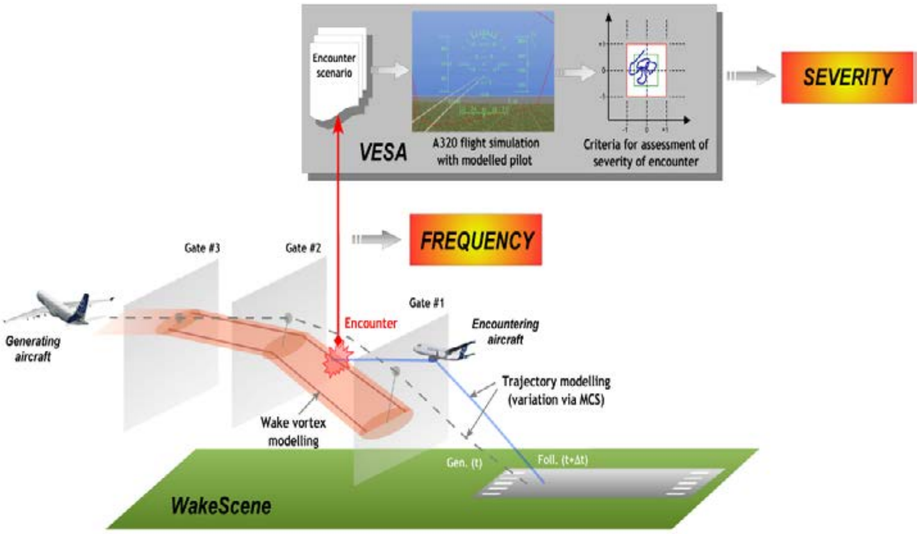

Figure 99: Coupled WakeScene/VESA encounter simulation for departures.

The validation activities undertaken so far for the different sub-models generally show a good quality. The pilot model based on a neural net shows a behaviour representative of real pilots and seems to be a promising approach for this kind of application. It could also be shown that multi-parameter hazard criteria are feasible that correspond reasonably well with pilot judgement of the severity of an encounter (Amelsberg, 2009). Further refinement and validation of the criteria's definition will be necessary however, including expert judgement on which limits are acceptable for the different considered dynamic parameters. Further development in this area will be conducted for example in the frame of SESAR, in which Airbus is involved in several projects concerned with wake vortex topics. WakeNet will be used as a further means to move towards a wider discussion and acceptance of this approach e.g. via dedicated workshops.

Airbus A380 wake vortex safety assessment

In preparation of the Airbus A380 entry into service, Airbus engaged in extensive wake vortex research, measurements, evaluations and analyses. Live trials included ground-based and airborne measurements by LiDAR as well as dedicated wake encounter flight tests involving several different generator and follower aircraft types. Results from these activities are reviewed and evaluated by an international A380 Wake Vortex Steering Group (SG) composed of Airbus, EASA, EUROCONTROL and the FAA as well as ICAO as observer. The A380 Wake Vortex Steering Group has issued its findings from dedicated Safety Assessments to ICAO which in turn has issued several ICAO State Letters to its member states, providing recommendations on safe wake turbulence separations for A380 operations.

The last related ICAO State Letter was issued in July 2008 (ICAO, 2008). In this the A380 radar wake turbulence separation minima for approach have been recommended as follows: no separation requirement for an A380 as follower aircraft, 6 NM for a Heavy following an A380, 7 NM for a Medium and 8 NM for a Light. These recommendations are primarily based on the relative assessment of the A380 wakes' circulations compared to that of other Heavy aircraft already in service. For this, circulation has been measured by ground-based LiDAR. The State Letter does not recommend any special separations for A380 operations in cruise flight – a finding that has been established by direct comparison with existing Heavy aircraft, based on wake encounter flight tests and in-flight LiDAR measurements.

Wake encounter simulations using VESA indicated that the recommendations from the LiDAR-based Safety Assessment for the approach flight phase may still be overly conservative. VESA has shown that vortex circulation is not the only parameter influencing the impact of a wake on an encountering aircraft, but that further characteristics of the wake such as the vortex spacing and core radii play an important role as well. Still, VESA could not be used directly to identify safe A380 separations due to a perceived lack of validation. Given the successful wake encounter tests performed at altitude, Airbus hence engaged in a most extensive wake encounter flight test campaign with the aim to further refine safe separation standards for approach flight conditions. This refinement shall be achieved through evaluation of encounter flight test results that include tests useable for a relative comparison of the wakes behind the A380 and other, reference Heavy aircraft.

Straight-forward comparisons of encounter flight test results already show marginal differences in aircraft responses. To support A380 Wake Vortex SG activities Airbus has developed methods and tools specifically aimed at evaluating wake encounter flight tests by comparing the direct impact of two different wakes on an encountering aircraft. This direct impact is expressed by wake-induced forces and moments acting on the aircraft and can be established from flight testing by comparing the recorded aircraft response with the known aircraft characteristics in calm air. Compared to circulation, direct wake impact established from encounter testing is closer related to relevant operational hazard since wake-aircraft interaction is included. Because the specifics of the encountering aircraft's flight control system are inherently excluded from the evaluated direct wake impact the results obtained can be generalised and the outcome of a relative assessment can be generally applied.

Aiming at objectively documenting flight test conditions as well as showing coherence with ground-based LiDAR measurements, flight test results are furthermore evaluated with regard to the encountered wakes' characteristics and the relative flight path. This is achieved by evaluation of air data recordings in an optimisation process called wake identification.

Despite the promising results, progress towards refined recommendations by the A380 Wake Vortex SG is slower than expected given the scrutiny with which flight test results are analysed and the novelty of the flight test evaluation methods. In the future the Airbus flight test results may be used to further validate VESA as well as other methods and metrics to set safe separation distances, for example in the context of recategorisation.

Airbus method to evaluate potential safety and capacity benefits from static recategorisation (Step I)

At the first major workshop of WakeNet3-Europe, held in January 2009, Airbus presented a study of technical methodology for recategorisation step I ("Recat Step I"), which is defined as a new, static MTOW-based aircraft wake turbulence classification with more than three classes. The goal of the study was to identify if simple recategorisation may deliver safety and capacity gains and to identify potential technical challenges and research requirements. The goal was not to propose a new classification, but mainly a method that has been set-up to evaluate potential safety and capacity benefits from static recategorisation and increased number of categories and to understand potential issues. The methodology presented is depicted in the figure below and can be characterised as follows:

- Representation of all aircraft pairs by the evaluation of a 50x50 matrix of generator / follower aircraft pairs at 10 distinct separation distances ranging from 2.5 to 10 NM.
- Use of generic, probabilistic aircraft models for the generator and the follower aircraft to account for current and future aircraft characteristics and with generalisation achieved through statistical evaluation of up to 161 existing aircraft types.
- Modelling of an operational approach scenario evaluated at a single "gate" along the approach path
- Statistical evaluation of encounter risk through Monte Carlo Simulation of wake generation, wake decay, wake transport and wake encounter as a function of aircraft pairs and separation distance.
- Encounter consequence or severity expressed by wake-induced rolling moment as a function of relative position (distance) between wake vortex and follower aircraft, vortex circulation, spacing and core radius as well as follower aircraft characteristics like speed, span and rolling moment of inertia.
- Modelling of traffic mixes by statistical distributions of aircraft weights representing different airport scenarios.
- Target Level of Safety estimated for current ICAO separations for "Largest individual aircraft risks" as well as for "Average aircraft risks".

- Derivation of minimum pair-wise separation distances based on Target Level of Safety.
- Computation of three different, non-segregated, single runway capacity metrics (average separation between aircraft, number of aircraft operations per hour, payload throughput per hour).
- Establishing of wake turbulence classes or categories based on minimum pair-wise separations with capacity as optimisation goal.

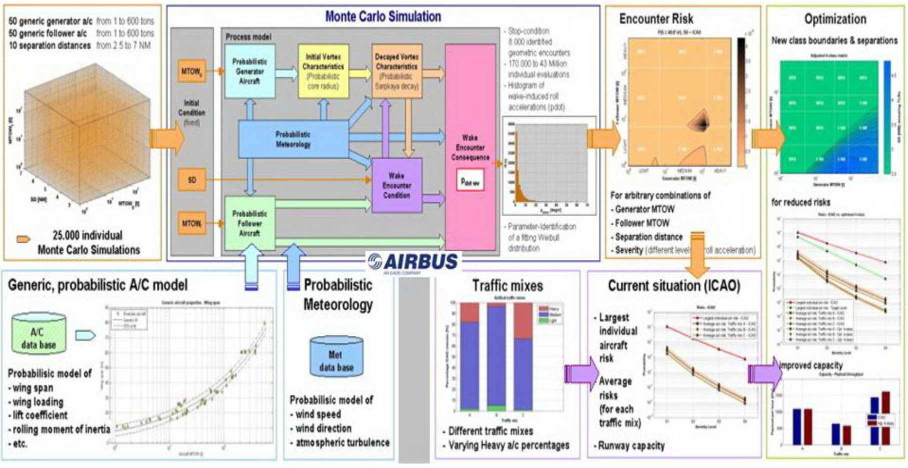

Figure 100: Overview: RECAT method developed by Airbus.

Wake Vortex Scenario Screening Tool

The WV Scenario Screening Tool, available at EUROCONTROL, provides a means of examining and comparing very simple Time-Based Separation and Distance-Based separation scenarios. The WV Scenario Screening tool provides a graphical representation of the positions of the leading and following aircraft in a pair on approach and shows the positions of Wake Vortices generated by the leading aircraft according to a very simple Wake Vortex transport model. The tool also shows the minimum distance from the wake vortices and provides a risk estimate based on an assumed hazard radius for the Wake Vortices, distributions of the vertical and lateral position keeping accuracy of aircraft on an ILS approach.

Wake Encounter Risk Indicator Simulation package

M3S has developed a Wake Vortex Encounter Risk Indicator Simulation package allowing to support the preliminary risk assessment of new concepts of operations (as done for the preliminary safety case of the Time Based Separation concept). This package could also be used to support the development of new concepts of operation or to assess the Wake Vortex Encounter (WVE) risk associated with current real operational situations. The tool is constituted of three separated modules that could be removed and replaced by other ones (provided that the interface with the two other modules is compliant): a) The scenarios definition module, b) The Wake Vortex Simulation module (not developed by M3S, but consisting of the WAKE4D platform developed by UCL), c) The Risk Indicator computation module.

The Scenarios Definition module is used to determine all relevant parameters of the investigated scenario. On the one hand, it allows setting:

- the aircraft characteristics such as the aircraft type, dimensions, weight and lift distribution;
- the aircraft trajectory, i.e. the time evolution of aircraft position (including aircraft navigation errors);
- and the atmospheric conditions such as the wind profile (both head and cross- wind), the atmospheric turbulence and the temperature profile.

On the other hand, it allows describing the application of the new concept of operation by ATCO such as aircraft spacing applied along the flight track or aircraft speed constraints applied.

For prediction of Wake Vortex (WV) behaviour, the WAKE4D platform developed by UCL has been selected and plugged in the risk assessment process. In the WAKE4D the modelling of the aircraft WV behaviour is made using the Deterministic Vortex Model, DVM, or the Probabilistic Vortex Model, PVM (see §5.1). The predictions are conducted in several computational gates along the flight path that move in space with the wind. From the 3-D "gate by gate" DVM (resp. PVM) computations, one obtains the 3-D envelope of the wake. The trajectory can be straight or curved. The computational effort depends on the density of time steps within each gate and the number of gates.

The WAKE4D platform contains also some post-processing routines. The results can be interpolated in a fixed control gate (similar to a LiDAR scanning plane). In PVM mode, one can also count the vortex in a given box as a function of time (useful for potential encounter analyses). For reconstruction of the induced velocity filed a first routine uses a vortex tube segment approach to compute the velocity induced both by the primary and secondary vortices. This approach enables the evaluation of the velocity for complex aircraft trajectory scenarios (e.g., take-off, landing, turns …). A second routine uses the simplified Crow instability model of the WAKE4D, in a vortex filament approach, to compute the 3-D velocity induced by deformed vortices. This evaluation is only applicable to straight aircraft trajectories far from the ground. Both routines evaluate the induced velocity at a hundred of points in real time and can thus be integrated in a flight simulator (as was done in the CREDOS project). The choice of the vortex circulation distribution model is of great importance for encounter analysis.

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. The complete description of the WAKE4D platform is available in (Winckelmans, 2010), which also contains WV prediction results validation against WV measurements performed in the framework of FAR-Wake and CREDOS.

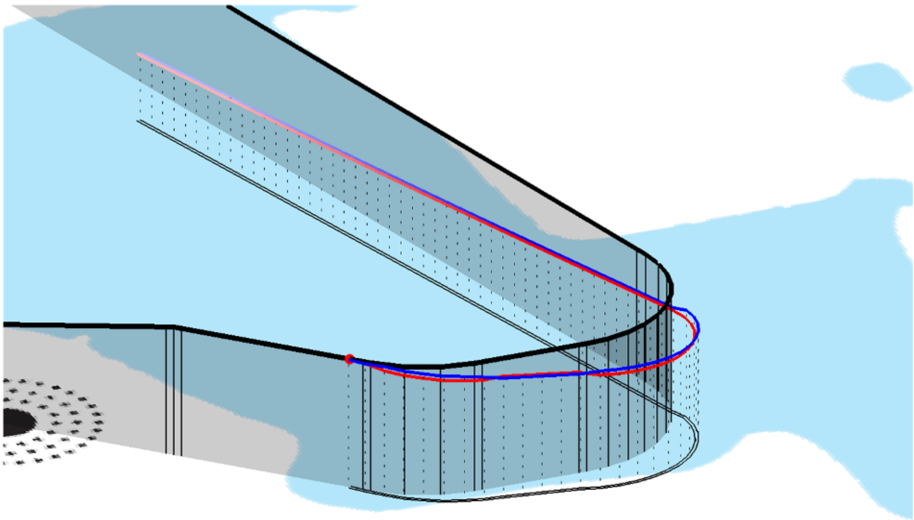

Figure 101: Example of trajectory (thick black line) computed by the pre-processor for an approach to Marseille-Provence airport. A snapshot of the 3-D port (starboard) vortex trajectory is shown in blue (red), the colour intensity being proportional to the vortex circulation.

Based on the Scenario Definition and based on extensive Wake Vortex numerical simulations, the Risk Indicator Computation module allows Wake Vortex Encounter risk assessment through the computation of risk indicator. The risk indicator selected for the study covers the 2 dimensions of wake vortex encounter risk as follows:

the WV Area Encounter probability: the probability for a follower aircraft to penetrate within a wake vortex area defined by geometric considerations and related to the wingspan of leader and follower aircraft; the severity of a potential encounter: the severity is measured through the WV circulation.

Considering the number of factors affecting both aircraft profiles and wake vortex behaviour, including the actual mass of the aircraft, its position with respect to the ground as well as the atmospheric conditions (wind and temperature), the method proposes to follow a relative approach for the risk calculation of potential wake vortex encounter. Relative estimates are felt to have a smaller range of uncertainty and are less susceptible to model simplifications.

ASAT (Airspace Simulation and Analysis for TERPS) is a collection of models and simulations that can be used to analyse safety and risk factors for a large range of aviation scenarios. ASAT is a Monte Carlo Simulation tool that uses statistical input for Aircraft (flight dynamics, propulsion, performance, wake turbulence, on board avionics), Geographical/Geodetic (digital terrain elevation data, obstacles), Environmental (standards atmosphere, non-standards atmosphere, measured wind and temperature gradients data), Navigation ground systems, Surveillance (PRM, ASR-9, ARSR, TCAS, ADS-B), Human factors (pilot, ATC). ASAT can provide answers either in a deterministic or a probabilistic way.

As opposed to WAVIR and WAKESCENE/VESA it has not been specifically designed as a wake vortex risk assessment model. In fact it is a generic simulation package that can be used for many applications, of which wake vortex safety assessment is one.

The heart of the system consists of the high fidelity engineering flight dynamics models of three Boeing aircraft (737, 767, and 747) against which the lesser models normally used in the high speed simulations are frequently checked. Model performance is also driven by empirical data collected in flight simulators and flight tests. In addition to these aircraft simulation models ASAT comprises models of aircraft avionics (FMS, autopilot, etc.) based on real equipment, models of ground navigation aids, etc. In this respect the simulation models resemble the models as for instance used in auto-land certification.

The system also can generate and track wake vortices and identify encounters between wakes and aircraft in the scenario. As such ASAT is regarded as a candidate for wake vortex risk assessments.

Probabilistic wake vortex hazard model

To calculate the Wake Vortex hazard and 'Simultaneous Runway Occupancy' (SRO) risks for a given target wake vortex separation, the George Mason University (GMU) defines a method (Jeddi, 2008; Jeddi et al. 2007; Shortle et al. 2007; Xie et al. 2005) based on probability distribution functions of:

- *Aircraft spacing* in the common landing path when infinitely many aircraft are in the line to land
- Landing Time Intervals (*LTI*) to the runway threshold
- Inter-Arrival Times (*IAT*) at the final approach fix (*FAF*)
- Aircraft Runway Occupancy Times (*ROT*)

These probability distributions are to be calculated from samples extracted from aircraft time-position track data collected by the multilateration surveillance systems in the vicinity of an airport. Imposed separation, corresponding to the first distribution, is not directly observable from aircraft track data and is obtained using distributions of the other variables. Probability distributions for the locations and strengths of wake vortices are using existing wake vortex models such as the Probabilistic Two-Phase (P2P) model, the AVOSS Prediction Algorithm (APA), and the TASS-Driven Algorithm for Wake Prediction (TDAWP). A safe wake vortex separation threshold is assessed with a hybrid simulation methodology using separation probability distributions. The approach is hybrid as part of the simulation is conducted using a data feed of flight-track data, while the other part is obtained by simulation of wake-evolution models. The approach uses a sample of flight tracks to predict the frequency of potential wake alerts, which is defined as event where the trailing aircraft is in a *region* of space where the wake is likely to be.

6.2.3 Research Needs

The simulation models that support wake vortex safety assessment have some generic resemblance, but at the same time they differ essentially at the level of sub-models employed and the calculation processes used.

A comparison and validation of sub-models used within different methods is likely to reveal several differences at sub-model level. For instance wake vortex evolution in ground-effect shows some discrepancies. Also the flight path evolution and wake vortex encounter models in the various risk assessment methods are often modelled differently. It is presently unknown how the various model assumptions and model simplifications in the mentioned models affect the final risk assessment results. However, in light of the anticipated application of the models in future approval processes, it is undesirable if the outcome (in terms of risk estimates) of the various models would differ significantly from each other. Therefore, as part of a future research outlook it is recommended to direct efforts into a comparison of the available models and validation of the employed sub-models. This would provide an indication which simplifications would be allowable, and where the models would be sensitive to the modelling structure and parameters. The outcome of this research could provide a baseline for modelling requirements that would be acceptable as a means of compliance in future approval (or certification) processes. How this research should be mechanized is an issue that still needs to be agreed upon. An effective proposal could be to define a benchmark scenario and apply the various models to conduct a risk assessment for this scenario. This will give an indication of the level of differences between models and will help to identify required accuracies of sub-models to equalize differences to an acceptable level.

The WV behaviour analysis and WVE safety analysis activities are very time consuming and labour intensive and so it takes a long elapsed time before analysis results become available. There is a need for a much more automated and systematic process founded on standard data formats for the wake turbulence measurement data, the correlated aircraft data, and the correlated meteorological data. Automated methods need to be developed for data cleaning which automatically generate an auditable file to support the safety arguments and safety evidence requirements. Automatic methods need to be developed to carry out the safety analysis and generate the safety analysis results. Safety metrics need to be developed against which to assess the safety analysis results. The role of WV behaviour models towards providing safety evidence in support of safety arguments remains an important issue. The challenges associated with the validation of models such that the analysis results can be considered reliable enough to be used as safety evidence remains a research needs challenge. WV behaviour models have the potential to considerably reduce the need for WV behaviour data collection campaigns.

With the deployment of new operational concepts envisaged by SESAR and NextGen, the possibility of encountering wake vortices might increase. Especially 4D-Reference Business Trajectories (RBT) might lead to an increase of crossing, climb and descent through of other aircraft trajectories compared to today. To characterize the impact of these concepts and also the impact of different performance levels of ASAS applications on the Air Traffic System, the following research is recommended:

- Simulation of future air traffic containing estimated traffic mix and 4D-RBT to assess the probability and frequency of wake vortex encounters;
- Assessing the benefit of reduced ASAS Self Separation applications based on airborne Wake Vortex mitigation and alleviation systems;
- In combination with ASAS Self-Separation functions, the need arises to investigate and develop methodologies to mitigate wake vortex encounters en-route.

An innovative method to incorporate the safety benefits of (ground and airborne) wake vortex advisory system in the safety assessment has been developed and applied to two example concepts of operations (Speijker et al., September 2006; Speijker et al., October 2006). Additional research might be directed to further development, verification and validation of such methods, in order to improve the understanding of how the capabilities of these airborne and ground wake vortex systems can properly be taken into account in WV safety assessment and WV safety cases.