Report of the

WakeNet3-Europe Specific Workshop on Models and Methods for Wake Vortex Encounter Simulations

1st and 2nd June 2010
Technical University of Berlin
Flight Mechanics, Flight Control and Aeroelasticity
Berlin, Germany

Prepared by Robert Luckner, Swantje Amelsberg, TU Berlin

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1 INTRODUCTION

Wake vortices are one of the major constraints on separations between aircraft pairs, as wake vortex encounters (WVEs) can be harmful to other aircraft during any phase of flight. The vortex flow field disturbs the encountering aircraft affecting pilot workload, comfort and safety of passengers and crewmembers and has an impact on structural loads. It also perturbs aircraft's attitude and flight path, which increases pilot workload for compensation. The level of tolerable disturbances depends on the flight phase.

Current ICAO wake turbulence separation rules are safe but conservative under many conditions. To cope with increasing air traffic demand, they shall be revised using better knowledge about the wake vortex encounter mechanism that means from vortex generation to encounter hazard. Fig. 1 shows how this complex physical process can be modelled by linking several sub-models. The overall model can be used to determine the conditions for which modified separation minima are safe and eventually for risk assessments that are needed to revise separation standards. Parts of the complete process can be used for other applications, such as development of vortex detection, warning and avoidance (DWA) systems.

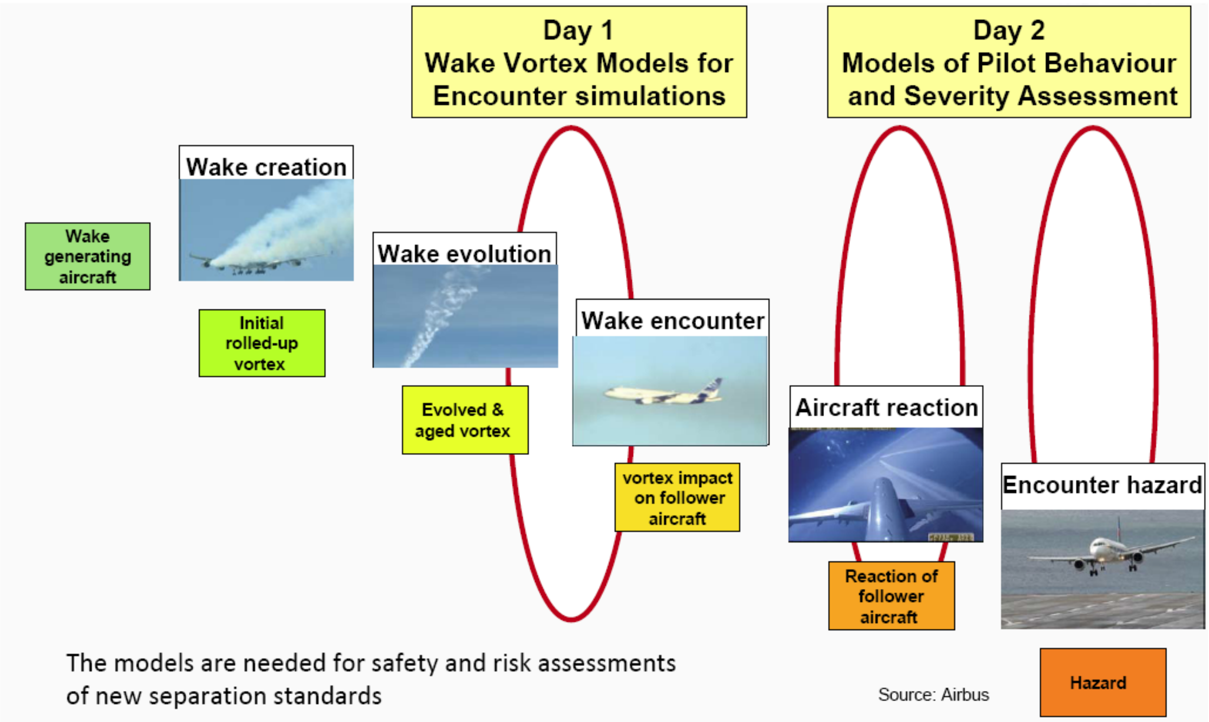

Fig. 1: A model of wake vortex encounter physics from vortex generation to encounter hazard

For some sub-processes well-established, validated sub-models exist, for others, sub-models are under development but are not validated yet. The WakeNet3-Europe specific workshop "*Models and Methods for Wake Vortex Encounter Simulations*", hosted by TU Berlin, addresses the following three sub-processes that are essential for WVE risk assessments:

- wake vortex models,
- models of pilot control behaviour and
- models for severity assessment.

They are indicated in Fig. 1 by red ellipses.

2 OBJECTIVES OF THIS WORKSHOP

The workshop had the objective to make a survey on existing sub-models, to summarize the state-of-the-art, new developments and the research needs in the following three domains:

1. Wake vortex models for encounter simulations,
2. Pilot control behaviour models for wake vortex encounter simulations,
3. Severity assessment models that determine the consequences of a wake vortex encounter on aircraft, crew and passengers.

The models shall be applicable

- for encounter simulations in real-time piloted simulator tests (real-time models) or
- for fast-time Monte Carlo simulations for risk assessment (fast-time models)

This report gives an overview on the presentations, on the state-of-the-art of existing models, on the requirements from the authorities for models that shall be used in the rule making process; it describes the discussion on model quality and maturity, and gives directions for future research. Starting point were the recommendations given by the National Research Council in [1] and by WakeNet2-Europe in [2].

Organisation:

Robert Luckner, Swantje Amelsberg, TU Berlin

Participants:

The following, invited international specialists from Air Navigation Service Providers, Regulators, Industry, Research Centres and Universities participated (in alphabetical order):

Swantje	Amelsberg	Technical University of Berlin
David	Bieniek	Technical University of Berlin
Wayne	Bryant	Federal Aviation Administration (FAA), USA
Jeffrey	Crouch	Boeing, Seattle
Herman	Damveld	Delft University of Technology
Ivan	de Visscher	Université Catholique de Louvain
Jorg	Entzinger	University of Tokyo
George	Greene	Federal Aviation Administration (FAA), USA
Richard	Greenhaw	Federal Aviation Administration (FAA), USA
Ingo	Hennemann	DLR, Institute of Atmospheric Physics, Oberpfaffenhofen
Ronald	Hess	University of California
Sebastian	Kauertz	AIRBUS Operations SAS, Toulouse
Jan	Kladetzke	DLR, Institute of Robotics and Mechatronics, Oberpfaffenhofen
Steven	Lang	Federal Aviation Administration (FAA), USA
Robert	Luckner	Technical University of Berlin
Jean-Pierre	Nicolaon	Federal Aviation Administration
Andreas	Reinke	AIRBUS Operations SAS, Toulouse
Andreas	Schneider	Technical University of Berlin
Andrej	Schönfeld	Technical University of Berlin
Carsten	Schwarz	DLR, Institute of Flight Systems, Braunschweig
Graham	Spence	University of Sheffield
Meiko	Steen	Technical University of Braunschweig
Olaf	Stroosma	Delft University of Technology
Jeffrey	Tittsworth	Federal Aviation Administration (FAA), USA
Peter	van der Geest	NLR, Amsterdam
Dennis	Vechtel	DLR, Institute of Flight Systems, Braunschweig

3 AGENDA

1st day: Wake vortex models for real-time and fast-time encounter simulations

Part 1: Chairman: Robert Luckner

10:00 **Welcome & Introduction**
Robert Luckner, Vice Dean Faculty Mechanical Engineering and Transport Systems, TU Berlin, Professor Flight Mechanics, Flight Control and Aeroelasticity

10:00 **Overview of existing wake vortex models used in flight simulator studies**
Robert Luckner / Technical University Berlin

10:30 **Wake vortex models, and the associated 3-D velocity fields, for real-time and fast-time WVE simulations**
Ivan de Visscher / Université Catholique de Louvain

11:00 **Aircraft wake vortex curvature and resulting risk potential for following aircraft**
Ingo Hennemann / DLR Oberpfaffenhofen

11:30 **Wake vortex models for real-time flight simulations based on large eddy simulations**
Graham Spence / University of Sheffield

12:00 **Aircraft wake vortex evolution in ground proximity: analysis and parameterization**
Meiko Steen / Technical University Braunschweig, Frank Holzäpfel / DLR Oberpfaffenhofen

12:30 Lunch

Part 2: Chairman: Sebastian Kauertz

13:30 **Curved wake vortices encounter simulation with pilots-in-the-loop**
Dennis Vechtel / DLR Braunschweig

14:00 **Flight-simulator study of airplane encounters with perturbed trailing vortices**
Jeffrey Crouch / Boeing

14:30 **Lessons learned: WakeScene-D, results of quantitative (Monte Carlo) simulation studies**
Jan Kladetzke / DLR Oberpfaffenhofen

15:00 Coffee break

Part 3: Chairman: Jean-Pierre Nicolaon

15:15 **Application of wake vortex models in real-time and fast-time wake encounter simulation**
Sebastian Kauertz / Airbus Toulouse

15:45 **Re-categorisation Phase II and III requirements (wake vortex models)**
Jeffrey Tittsworth / FAA

16:15 **Workshop wrap-up**
Discussion about the workshop outcome, a state-of-the-art summary of existing wake vortex models: 1) that are useful for flight simulator investigations (real-time models); 2) that are applicable for Monte Carlo simulations (fast-time models)

17:00 Simulator Session

Visiting and flying of the SEPHIR Simulator (VFW-614-ATD) and THYRAS (Transall). Demonstration of different implemented wake vortex models

2nd day: Models of pilot behaviour for real-time and fast-time wake vortex encounter simulations

Part 1: Chairman: Robert Luckner

09:00 **Overview of existing pilot behaviour models used in flight simulator studies**
Robert Luckner / Technical University Berlin

09:30 **Multi-axis pilot modeling**
Ronald Hess / University of California

10:00 **Pilot model for take-off and departure and wake vortex recovery**
Swantje Amelsberg / Technical University Berlin

10:30 Coffee break

Part 2: Chairman: Peter van der Geest

10:45 **Analysis of visual cues during landing phase using neural networks**
Jorg Entzinger / University of Tokyo

11:15 **Identifying human control behaviour in the SIMONA research simulator**
Herman Damveld / Delft University of Technology

11:45 **Probabilistic pilot model approach for wake vortex encounter simulations**
David Bieniek / Technical University Berlin

12:15 Lunch

Part 3: Chairman: Jeffrey Crouch

13:15 **Characterizing wake vortex encounters for hazard analysis/ safety management system purpose**
Richard Greenhaw / FAA

13:45 **Wake vortex severity criteria developed by NLR**
Peter van der Geest / NLR

14:15 **Wake vortex severity criteria for departure**
Swantje Amelsberg / Technical University Berlin

14:45 Coffee break

Part 4: Chairman: Andreas Reinke

15:00 **Modified optimal control model and wake vortex encounter**
Andrej Schönfeld / Technical University Berlin

15:30 **Re- categorisation Phase II and III requirement (pilot models)**
Jeffrey Tittsworth / FAA

16:00 **Workshop wrap-up**
Discussion about the workshop outcome, a the state-of-the-art summary of existing pilot behaviour models for tracking tasks and high dynamic recovery tasks in real- and fast time flight simulations

17:00 End of the workshop

4 WAKE VORTEX MODELS

4.1 STATE-OF-THE-ART

A vortex-induced flow field consists of wind velocity vectors (three components) that are a function of space and time. The temporal evolution depends on characteristics of the generating aircraft and on atmospheric conditions. Wake vortex models (WVM) compute the temporal-spatial distribution with different levels of fidelity. Large Eddy Simulation (LES) models cover the vortex and its complex flow structure over the whole life-time while in most simulations the roll-up of the vortex system is not explicitly modelled. They require extremely high computational effort. However, they can be used to validate simplified models that are better suited for real-time and fast-time simulations.

Simplified models that describe the vortex flow field characteristics are needed for risk assessments (fast-time simulations) and for real-time flight simulations. They have to model

- the position of the vortex pair,
- vortex-induced velocities at the position of the encountering aircraft.

Such models exist and they are used in both types of application: real-time and fast-time simulations.

WVE risk assessments are performed by a two step approach:

1) **Encounter probability**: First, the encounter probability is determined. This is achieved by assessing the minimum distance between the vortex pair of a leading aircraft with the trajectory of a follower. If the distance falls below a certain limit, this is counted as an encounter.
2) **Encounter severity**: Second, if an encounter is discovered, the influence of the vortex-induced flow field on the encountering aircraft has to be simulated, taking the encounter geometry and initial conditions into account. The resulting aircraft reaction is evaluated which leads to the encounter severity.

The encounter probability computation requires a wake vortex evolution model that computes vortex transport and vortex strength taking the decay into account, whereas the encounter severity computation requires the 3D vortex flow field around the encountering aircraft. Currently, the flow field is simplified as a frozen 2D flow field that can be defined either by a parameterized analytical model (circulation, vortex separation, core radius, straight or curved vortex axes and an analytical velocity distribution model) or by a numerical model.

Existing tools that compute encounter probabilities are: WakeScene (DLR/Airbus), WAKE-4D (UCL), WIDAT™/ASAT (ATSI/FAA), WAVIR (NLR).

An overview on the state-of-the-art for wake vortex models and their applications was given by [R. Luckner].

4.2 RECENT DEVELOPMENTS

Recent developments of improved WVMs for real-time and for fast-time flight simulations were presented. They are summarised below.

- **The Deterministic and Probabilistic wake Vortex Model (DVM/PVM) and the WAKE4D platform developed by G. Winckelmans, UCL** (See [Ivan de Visscher]).

  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 (positions, aircraft configuration, span, weight, and airspeed), the atmospheric conditions (head- and crosswind, turbulence, wind shear, temperature stratification), and the ground proximity. A simplified model of the Crow instability growth is also included. 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. 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 E-C funded projects. Each vortex particle, used in the DVM, has a certain circulation distribution profile (choice between the "one-scale" Low-Order Algebraic and High-Order Algebraic models, or the "two-scales" Proctor-Winckelmans model).

  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). This enables to obtain the statistics of the results (vortex positions and circulation) in one computational gate. So each PVM run uses many DVM runs.

  The *WAKE4D* is a « 3-D space + time » wake vortex prediction platform software. It takes as input the aircraft trajectory and the atmospheric conditions. The WAKE4D-DVM (resp. WAKE4D-PVM) simulates the 3-D wake vortex behaviour using the DVM (resp. the PVM) in several computational gates along the flight path. The gates are Lagrangian, they thus move in space also with the wind. From the 3-D "gate by gate" DVM (resp. PVM) computations, one obtains the 3-D wake (resp. 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 then be interpolated in a fixed control gate (similar to a LIDAR scanning plane). In PVM mode, one can also count the vortex present in a given box as a function of time (useful for potential encounter analyses).

  Using the WAKE4D-DVM results, the 3-D velocity field induced by the vortices can also be evaluated as post-processing. 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 than 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.

A complete description of the WAKE4D platform is given in [4].

- **The Deterministic and Probabilistic 2-Phase Model (D2P/P2P) developed by F. Holzäpfel, DLR**

  DLR's Deterministic 2-Phase model (D2P) is a simplified physical model that computes the transport and decay of the wake vortex pair in 2D gates. It takes into account aircraft characteristics, head wind, cross wind, wind shear, turbulence, temperature stratification and ground proximity. The probabilistic version P2P [5] is based on the uncertainties of wake vortex evolution found in LES and field experiment data. Uncertainty allowances are modelled by conducting 3 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 2 US and 6 EU measurement campaigns. With a computation time below 0.01 s, P2P is suited for fast-time simulations.

  The gates move in space depending on head or crosswind. A linear interpolation between the gates is assumed. The impact of Crow instability on decay is considered in each gate, but not the deformation of wake vortex axes (linear interpolation between the gates).

  The P2P ground effect model was developed employing LIDAR and SODAR/RASS data from a measurement campaign at Frankfurt in 2004, in which vortices of 288 aircraft (mostly B744, A343, A346) were measured in heights between 10 m and 100 m [6]. In ground proximity the impact of turbulence and crosswind on wake–vortex decay proves to be weak, whereas already light crosswind turns out to be sufficient to cause pronounced asymmetric rebound characteristics. Comparison to wake predictions out of ground effect indicates that in ground effect 1) the rapid-decay phase progresses slower, 2) wake–vortex evolution can be predicted with improved accuracy, and 3) fair prediction skill requires only limited environmental data. [M. Steen]

  LES have been performed in order to investigate three-dimensional vortex decay. Therefore a predictor-corrector algorithm was developed which determines vortex positions in more detail and which reveals that vortex ring formation is common. In that state circulation decay is slow, so instead of a two-phase decay a three-phase decay is observed (diffusion phase, phase of rapid decay, ring diffusion phase), especially in neutral or weakly stable temperature stratification. Based on those results, ideas for a new real-time model called Probabilistic 3 Phase wake vortex model (P3P) have been presented. The P3P 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 evolution phases of gradual diffusion, rapid decay and ring diffusion. Vortex decay is parameterized depending on turbulent eddy dissipation rate ε^*, integral turbulence length scale L_t^*, and Brunt-Väisälä-Frequency N^*, see [I. Hennemann].

New developments in vortex models for real-time simulations

University of Sheffield presented an approach to use high quality vortex data in real-time flight simulation. The vortex data is generated by CFD LES methods, compressed and reorganised for real-time access. The aim is to capture evolving short and long wave instabilities (e.g. Crow instabilities). The LES methods require high resolution meshes to reproduce vortex decay (spatial and temporal). One wavy wake vortex segment was calculated in 3-D boxes and linked to a vortex trajectory. Each segment contains a vortex state dependent on the time behind the wake generating aircraft. See presentation given by [G. Spence].

UCL also presented recent results of Large Eddy Simulations (LES). Those simulations are performed in realistic conditions (very high Reynolds number, tight vortex cores, and realistic background atmospheric conditions). Those LES results are used for real-time model improvement and validation. The resulting detailed velocity fields correspond to wake vortices in specific and realistic conditions. As such, they can also be stored and used operationally as input in a fast "velocity field evaluation" routine for flight simulator encounter studies. Three examples were shown: vortices OGE evolving in a weakly turbulent atmosphere leading to the development of the Crow instability, also with reconnection and further decay, vortices OGE evolving in a stratified and weakly turbulent atmosphere, vortices evolving in ground proximity (IGE) and with crosswind. See presentation given by Ivan de Visscher.

DLR presented results of a simulator campaign conducted to evaluate the influence of vortex curvature on encounter hazard. DLR analysed the influence of vortex curvature on the interaction between pilot and aircraft for controlled augmented aircraft. A method to expose the aircraft to a wake vortex upset is to use pre-recorded or computed time-series of induced forces and moments and insert these in the simulation instead of calculating them in real-time depending on relative position to the vortex. The flow-fields of the curved vortices were generated by means of Large-Eddy-Simulations (LES). The vortex-induced forces and moments were pre-computed for different predefined tracks through the vortex flow-field using an aerodynamic interaction model.

The analysis of the simulation results revealed that curved vortices result in shorter encounter duration and thus much smaller absolute integral forces and moments. Nevertheless aircraft response is similar compared to encounters with straight vortices, as are the pilot ratings. The simulator campaign also revealed an increased risk of pilot-induced-oscillations (PIOs) when encountering curved vortices in comparison to straight vortices. See presentation given by [D. Vechtel].

Vortex models for fast-time simulations

Boeing has conducted a 737-300 autopilot offline simulator campaign to determine the role of vortex strength versus distortion on encountering aircraft upsets. Encounters in three different states of vortices were investigated: straight vortices (analytical solution for velocities), wavy vortices (numerical integration for velocities) and ring vortices (numerical integration for velocities). Whereas all vortex states were modelled by vortex filaments frozen in space and time to be fast-time capable. Results show a significant reduction in maximum bank angle upset experienced by an encountering airplane, due to vortex distortion and break-up. Findings are that a large number of simulations are required to assess potential upset severity (fast-time simulations) and the potential upset maybe linked to vortex characteristics using simple measure. See presentation given by J. Crouch [J. Crouch]

Airbus presented three successfully implemented vortex models in the Airbus VESA tool:

- Simple straight vortices of infinite length were used to investigate the influence of parameters (vortex strength, position, intercept angles, etc.) on encounter severity.
- Simulated parameterized wavy and ring vortices, useful for investigating influence of vortex waviness and break-up into vortex rings on encounter severity.
- Curved, segmented vortices, increasing realism of vortex representation along a flight path without undue computational effort (developed within CREDOS)

The approaches are in general applicable to all flight phases and have been successfully applied already for specific investigations (e.g. S-WAKE, CREDOS). The maturity of the models is assumed to be good and adequate for the application, especially for the OGE case. A combination of the different models into one (e.g. curved vortices + waviness) is not envisaged, see [S. Kauertz].

DLR presented the WakeScene (Wake Vortex Scenarios Simulation) Package which allows assessing the encounter probabilities and the related vortex strengths behind different wake vortex generating aircraft for different air traffic scenarios [13]. 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.

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 aircraft parameters at different gate positions (simulation planes) using point-mass aircraft models or the Advanced Flight Management System (AFMS) based on the BADA database. The Meteorological Data Base comprises a one-year statistics of realistic meteorological conditions (more than 1.3 10^6 vertical profiles) for the Frankfurt terminal area which was produced with the weather forecast model system NOWVIV. The deterministic and fast-time capable wake vortex models D2P and DVM have been implemented in WakeScene-D in the EU-project CREDOS. Wake vortex evolution is modelled in gates that move in space depending on headwind. A linear interpolation between the gates is assumed. The impact of Crow instability on decay is considered in each gate, but not the deformation of wake vortex axes (linear interpolation between the gates). When an area of interest is penetrated by the follower aircraft, this is considered to be a 'potential wake vortex encounter'. In cases with potential wake encounters all relevant parameters can be provided to VESA (see above) which may subsequently perform detailed investigations of the encounter severity.

Monte-Carlo Simulations using WakeScene have been used to investigate the wake vortex encounter probabilities for crosswind departure scenarios within the EU-project CREDOS. Comprehensive sensitivity analyses have been conducted [13]. In particular, it was found that the use of different wake vortex models (D2P or DVM) or the deactivation of flight path deviations 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 sub-modules, see [J. Kladetzke].

4.3 DISCUSSION AND CONCLUSIONS

The discussion was stimulated with three questions:

a. What are the strengths and the weaknesses of current Vortex Models for risk assessment?

b. Is the achieved fidelity sufficient or is further research required?
c. How can validation and credibility of models be achieved?

In addition to that, FAA/Eurocontrol gave an overview on the Joint Eurocontrol/FAA Wake Turbulence Re-Categorization Effort, see [J. Tittsworth]. Requirements for wake vortex models and encounter models, which shall be used in Re-Cat Phase II and III, were presented and the following questions were raised for discussion:

- What else should be included?
- Is it necessary to consider WVEs with a wake system (pair) or is it sufficient to model only a single vortex?
- Should we consider WV models with perturbed vortices?

All participants agreed that significant and visible progress in model fidelity has been achieved over the last 5 years. The following improved wake vortex models have been developed and have been used for WVE simulations that address:

- curved trajectories and curved vortex axis,
- wavy vortex pairs and ring vortices,
- impact of atmospheric conditions on vortex decay,
- impact of atmospheric conditions on vortex transport,
- vortex behaviour in ground effect,
- efficient code for fast-time computations.

It can be stated that the steep gradient of the learning curve has been left. The number of the parameters has increased significantly and it becomes necessary to distinguish between primary and secondary aspects. The models of higher complexity could be used to identify models that are more simple – but good enough for the task. Uncertainties still exist regarding the size of the core radius and its evolution in time.

For operational use of the models, as envisaged in SESAR and NextGen, the main problem is to correctly measure and predict input data for the models (e.g. turbulence, temperatures and wind velocities at multiple locations in space).

Current models are capable to capture many real-life features. The models can be used in fast-time simulations for parameter sensitivity studies or to compute statistics of vortex characteristics.

As a full validation is impossible, confidence has to be built, that models and simulations are correct. How can this be achieved? Simple models should be – and have been - validated by comparison with LES results and flight test data. Ultimate validation should focus on flight test results. In cooperation with the regulators, a validation plan should be developed that defines the validation requirements, and determines data that are available and data that needs to be generated. This may become a repetitive activity. Such a process is described in [9].

5 PILOT BEHAVIOUR MODELS

5.1 STATE-OF-THE-ART

Systematic research in modelling the control behaviour of a human pilot controlling an aircraft began in the 1950s. The objective of the models was “*to summarize behavioral data, to provide a basis for rationalization and understanding of pilot control actions, and, most important of all, to be used in conjunction with vehicle dynamics in forming predictions or in explaining behavior of pilot-vehicle systems*” [8].

Models of pilot control behaviour can be classified into two main categories:

- *Behavioural models* that describe the intentional pilot action during (compensatory) tracking tasks.
- *Biomechanical models* that simulate those involuntary control inputs that are caused by the pilot acting as a passive biodynamic element within the pilot-aircraft system.

Biomechanical models have been successfully applied to describe phenomena that are caused by unconscious pilot control inputs at Frequencies above 2Hz such as “roll ratcheting”. For tasks at lower frequencies and that require conscious pilot commands, behavioural pilot models are better suited. They are typically used to describe pilot control behaviour when they compensate vortex induced disturbances or recover from vortex encounters. A brief overview on existing behavioural pilot models was given by [R. Luckner]. It is summarized below.

The analytical theory of manual control of vehicles that has been developed in the 1950s and 60s has emerged as a useful engineering tool. It became part of handling quality criteria and was used for aircraft and flight control law design. An essential feature of this theory is the use of quasi-linear analytical models for the human pilot wherein the models' form and parameters are adapted to the task variables involved in the particular pilot-vehicle situation [8].

An important class of situations for which pilot vehicle models are useful are closed-loop *compensatory tracking* tasks, in which the pilot acts on the displayed error between a desired command input and the comparable vehicle output motion to produce a control action. A fundamental finding of McRuer and Krendel was that the human pilot adapts his behaviour in such a way that dynamic deficiencies of the controlled aircraft are compensated, essentially leading to similar open-loop behaviour of the pilot-aircraft system near the crossover frequency[1], see [7]. Based on this finding, they proposed the simple four parameter *Crossover model*. It is the most commonly used pilot model. Further research expanded the model and resulted in more complex models such as:

- *Precision model*: An extension to the Crossover model considering a representation of the human neuromuscular system.
- *Structural pilot model*: An explicit description of the human signal processing including sub-models for the human central nervous and neuromuscular system. In comparison to other models it focuses on the human processing of proprioceptive feedbacks in addition to visual or vestibular cues.

[1] The crossover frequency is the frequency for which the open-loop describing function of the pilot aircraft system passes the 0db line and it determines the bandwidth of the system.

- *Descriptive model*: A detailed model of the human operator information processing. It includes several sub-models for the dynamics of visual and vestibular channels.

Those quasi-linear models were also expanded from a single axis to the multi-axis control case. Furthermore several other approaches for pilot modelling exist, e.g. models that are based on optimal control theory, such as the Optimal Control Model (OCM), and models using alternative concepts such as Fuzzy Logic or Artificial Neural Networks.

In a *tracking task*, pilots follow a target command, whereas in a *disturbance suppression task* they have to maintain the current flight condition while the aircraft is exposed to disturbances. Developing pilot models for either task can build on the available vast experience. This is especially true for pilot models for recovery from wake vortex encounters.

Three presentations gave an introduction into the field of pilot modelling, its state-of-the-art and current research topics.

- **Identifying Human Control Behaviour**

  H. Damveld gave an overview on how pilot behaviour is identified at TU Delft from flight or flight simulator tests [H. Damveld]. He described the methods that were used in three different applications.

  1. For evaluation of aircraft handling qualities the "Experimental Behaviour Measurement Method" is used in which multiple forcing functions on the head-up display force the pilot to adopt a high-frequency control strategy. This allows measuring Crossover-regression frequency as a measure for handling qualities.
  2. Another application is the use of pilot models to improve flight simulator fidelity. A pilot model that has been identified in flight tests is used as reference to tune the filter parameters of the simulator motion system. The methodology makes use of the effect that a human pilot can compensate missing information in the vestibular channel by information in the visual system. It requires a second forcing function that perturbs the elevator of the aircraft to identify the contributions of the visual and vestibular systems separately. The tuning of the motion system is optimal, when describing functions of pilot-aircraft dynamics in flight simulator are the same as in flight test.
  3. To improve the model of the neuromuscular system and estimate its parameters, a third forcing function that adds force perturbations to the control inceptor is required to identify the admittance of the spinal neuro-muskuloskeletal dynamics as well as the combined physical interaction.

- **Multi-axis Pilot Model**

  R. Hess presented a multi-axis pilot model that is based on a simplified pursuit model and how it can be applied to WVE simulations [R. Hess]. The model incorporates visual, vestibular and proprioceptive sensory information and is typically used to simulate tracking tasks of fighter or rotary aircraft. The model accounts for task interference in multi-axis tasks (reductions in tracking performance) and considers different levels of pilot "aggressiveness". Hypothesis is that the pilot closes multiple loops in each axis. So the structure is based upon serial loop closures with crossover frequency separation. Pilot model parameters for each loop are defined by using Bode plots. The model is suited for time domain simulations but has not been adapted to wake vortex encounters yet. R. Hess mentioned that an area of concern is the ability of a vortex encounter to create a "triggering event" for a pilot-induced-oscillation (PIO). This may not be addressed by this type of pilot model.

- **Analysis of visual cues during the landing phase**
  J. Entzinger presented the status of his investigations on the visual cues that a pilot uses during a landing approach especially to maintain the glide path and for flare before touch-down. The objective is to improve training of new pilots and to gain understanding and recognition of visual illusions and thus increase air safety. The model shall be flexible, general and transparent to pilots and instructors (easy to explain) and above all, the model shall be based on information that the pilot is concerned with: especially visual cues. The approach uses a neuro-fuzzy network with a gamma operator. Experiments were conducted in fixed base and full flight simulators (ANA Boeing 767) as well as in real flight (Citation V, Boeing 767-300)

A WVE is a single unexpected event, in which the aircraft's flight condition can be severely disturbed. The pilot is typically surprised and his reaction is not necessarily optimal. This is in contrast to disturbances from atmospheric turbulence that typically last for a while and the pilot can adapt his control behaviour.

The target applications for WVE pilot models are risk assessments that can discriminate safe, tolerable or unacceptable encounters. As the results shall be used to perform the safety of regulatory changes (e.g. minimum wake separations) or modified ATC procedures (e.g. approaches to closely spaced parallel runways) the validation requirements are more stringent.

For WVE risk assessment pilot models are needed that simulate pilot control commands during a WVE. They have to be validated with results from WVE in flight tests or simulator tests.

Pilot models have been developed in the EC funded projects S-WAKE and CREDOS by Airbus, DLR and TU Berlin starting in 2001. The first models were Crossover models and addressed roll control. Pilot model parameters are adapted by means of numerical optimization in the time domain to achieve a match between simulated and recorded control commands. Applicability of the models is limited to the flight phase and aircraft type for which the model parameters have been validated. For the VFW614-ATD a roll control behaviour pilot model has been successfully used in the Airbus VESA fast-time simulation tool [12].

5.2 RECENT DEVELOPMENTS

Recent work on WVE pilot models at TU Berlin has extended the structure and the scope of models. The status of the research was presented by three authors.

- **Pilot model for take-off, departure and wake vortex recovery**
  TUB has developed a deterministic pilot model for vortex encounter simulation during departure in the European project CREDOS (Crosswind-Reduced Separations for Departure Operations), see [S. Amelsberg]. The model controls the aircraft throughout the complete departure that includes the following flight phases: take-off run, rotation, tracking of Standard Instrument Departure (SID) routes and vortex encounter. For each flight phase a specific sub-model has been developed based on recorded data from piloted A320 and A330 flight simulator tests with commercial airline pilots.
  The sub-model for vortex upset recovery consists of two artificial *static feed-forward neural networks* that simulate pilot side-stick commands in roll and pitch during the WVE. Flight director commands, angular rates and angular accelerations in both axes are inputs to the

pilot model. The neural networks were trained for the time interval, in which the encounter occurred, using the recorded pilot side-stick commands as reference.

To validate the model, identical encounter scenarios as used during the piloted tests were simulated with the pilot model controlling the aircraft. The results show a very good agreement between pilot and pilot model control behaviour, especially in the roll axis. Additionally, the largest vortex induced aircraft upsets (peaks) have been used as validation criteria. In most of the cases, pilot model outputs lie within the standard deviation of results with human pilot simulator tests.

The pilot model was successfully integrated into Airbus' VESA tool to perform Monte Carlo simulations for risk assessment within the CREDOS project.

- **Probabilistic pilot model approach for WVE simulations**

  D. Bieniek presented an approach that addresses the statistical variations in pilot behaviour, see [D. Bieniek]. Recorded pilot control inputs from flight simulator tests show a significant scatter in pilot behaviour for identical encounter scenarios. Pilot control commands during the vortex encounter affect the magnitude of resulting aircraft upsets. These upsets contribute to the pilot's perception of the hazard and are used as metrics in current severity assessment models. To account for the variation in pilot control behaviour probabilistic pilot models are needed.

  TUB has proposed a methodology to set up a probabilistic pilot roll control model based on the Crossover model. For two of the four model parameters statistical distributions (rather than fixed values) are identified from piloted simulator tests. The other two parameters are kept constant to account for correlations in-between model parameters. Only data from special "fixed" encounter simulations is used, where identical vortex encounters are repeated multiple times. This eliminates effects of varying encounter conditions on the pilot behaviour.

  The methodology was applied on available data from piloted A330 and A320 vortex encounter simulations (e.g. S-WAKE, CREDOS). Static tests with recorded aircraft upsets indicate how the probabilistic pilot model responses scatter around the deterministic model. Dynamic fast-time simulations with the probabilistic pilot model have to be carried out to evaluate the effect on the scatter of aircraft upsets.

- **Application of Modified Optimal Control Model (MOCM) for WVEs**

  A. Schönfeld presented the results of a research work that he had performed during his diploma thesis at the Moscow Aviation Institute, see [A. Schönfeld]. The Modified Optimal Control Model is based upon the assumption that well-trained and motivated human controllers behave optimally in a certain sense that is subject to their inherent psycho-physical limitations. The model can be applied to model multi-axis and multi-loop tasks and it also allows considering fractional attention of the pilot.

  To evaluate the applicability of the model for vortex encounter simulation, piloted tests (no licensed pilots) with a simplified aircraft model and a representative vortex disturbance were performed. At first the human operators had to correct upsets from atmospheric turbulence before being confronted with the vortex disturbance. The pilot model was also tuned using the turbulence tracking task, and was then applied to compensate vortex induced upsets.

  Results showed a correspondence to the piloted experiments for the first couple seconds of the encounter. As the operator was trained to flight in turbulent conditions he was surprised by the WVE but adjusted his behaviour after a certain time delay leading to differences between recorded inputs and model results.

5.3 DISCUSSION AND CONCLUSIONS

The discussion was stimulated by the following questions that were distributed before the presentations:

1. Is the performance of current Pilot Models (control behaviour) satisfying for WVE risk assessment?
2. Is there further research required? In which area?
3. How can validation and credibility of models be achieved?

Further questions were raised during the meeting:

4. What is required to make a development and validation process for pilot models (in particular the validation criteria) acceptable for authorities?
5. What is the necessary level of model fidelity?
6. Is a probabilistic pilot model necessary for risk assessment or are deterministic models sufficient?
7. How well does the pilot control behaviour in flight simulator tests reflect the pilot reactions in real life WVEs? What about the missing surprise effect and the training effect when simulated WVEs are repeated?

FAA raised some additional questions related to RECAT Phase II and III, see [J. Tittsworth, page 16 to 18]:

8. Why should pilot response models be included in the analysis for Phase II or Phase III?
9. Should pilot or auto-pilot response be included in the analysis of wake encounters? If so, how complex does it have to be?
10. How is the reference pilot behaviour defined and which deviations from this behaviour should be considered?
11. What kind of pilot response model should be included and how?

Not all questions could be answered during the workshop.

In summary it can be stated: recent research improved the knowledge on pilot behaviour during WVEs and how to model it significantly. Improvements have been achieved concerning:

- Pilot models that address all flight phases,
- Alternative approaches for WVE pilot models have been investigated with the objective to improve model fidelity,
- Techniques for assessing variations in pilot control behaviour,
- Knowledge about the variation (scatter) in pilot response to a WVE,
- Methods to consider probabilistic pilot behaviour during WVEs,
- Validation requirements and validation techniques.

However, there is still a gap between the pilot models that have been developed by research and validated pilot models that can be used for risk assessments of new regulations.

Risk assessments have been performed without pilot models using parameters like maximum takeoff weight of the vortex generator aircraft, vortex strength (circulation) or induced rolling moment. But those parameters do not cover essential aspects of the complete encounter mechanism, as shown in Fig. 1.

It was generally agreed that an accurate relative (as well as a quantitative, absolute) WVE risk assessment, i.e. from WV creation to encounter hazard (as shown in fig1), requires a representation of the pilot. The pilot model needs to be “conservative”. In order to investigate the achievable fidelity, developing more complex models may be necessary. However, the model that is used for risk assessment should be as simple as possible.

For future research activities it is essential to define criteria for pilot model validation that are agreed by all stakeholders. A possible way ahead is the risk analysis process of FAA’s Flight Systems Laboratory. It is used to produce safety studies related to flight procedure design and is described in [9]. This process requires defining and agreeing on validation requirements as well as on reference data for models that are used in risk assessments. The process needs to be a joint activity of model developers and authorities.

The pilot model affects aircraft response in a WVE and aircraft response relates to encounter severity, that means the the pilot model has a direct impact on the severity criteria. Therefore, the validation criteria for WVE pilot behaviour models should take this aspect into account.

6 SEVERITY ASSESSMENT MODELS

6.1 STATE-OF-THE-ART

Models that can be used to assess the severity of a WVE are based on *severity criteria* (hazard criteria) that relate pilots' hazard assessment to objective, measurable flight data.

Development of severity criteria for WVEs started in the 1970ties. The first criteria were single-parameter criteria addressing the roll axis. An often cited result is the dependence between the maximum bank angle excursion that was acceptable for pilots during a WVE in landing approach and the encounter altitude; see Fig. 2.

But also other parameters that represent aircraft reaction in the roll axis were investigated as hazard metrics: roll acceleration, combinations of bank angle, roll rate and roll acceleration, as well as the so called *Roll Control Ratio* (RCR). The RCR relates vortex-induced roll moment to the roll moment that the pilot is able to command (roll control power).

Those criteria address the roll axis only and are not sufficient to describe the overall hazard. So, more complex criteria with multiple metrics from the longitudinal and the lateral motion were investigated. In Europe, research on severity criteria was performed by Airbus NLR and TU Berlin in the in the S-WAKE project. Various criteria were developed and optimized using results from flight simulator tests (Airbus A330, Dornier 228, Cessna Citation, Fokker 100, VFW614-ATD); see [10].

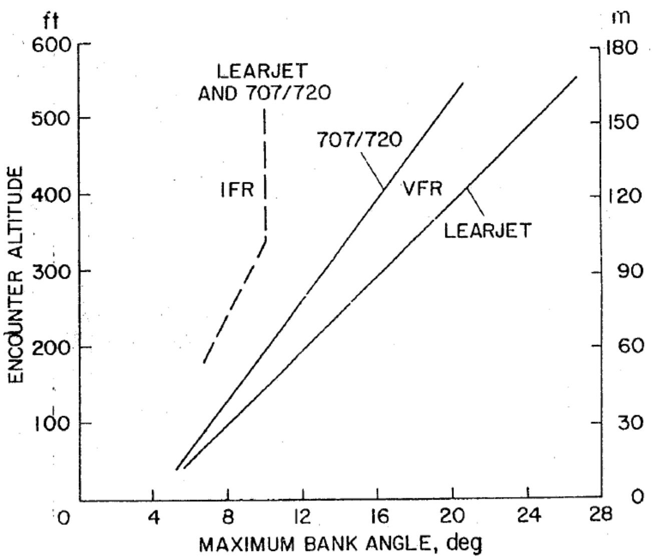

Fig. 2: NASA Bank angle boundary (from [14])

A simple approach that covers the complete aircraft reaction by using only one metric is DLR's *Simplified Hazard Area Prediction* method (*SHAPe*), see [15]. The boundary between acceptable and unacceptable encounters is defined by a (conservative) RCR limit that was determined in offline WVE simulations and pilot-in-the-loop flight simulator as well as in flight tests. It was found that pilots rated all WVEs below this boundary as acceptable and all relevant aircraft upset parameters stayed within their typical operational envelope [16].

However, still there exist no severity criterion (and no boundary that separates acceptable and unacceptable WVEs) that has been agreed upon by all stakeholders to be used in risk assessments.

6.2 RECENT DEVELOPMENTS

Current research on hazard metrics and on models for severity assessment was presented by FAA, NLR and TU Berlin.

- **Characterizing wake vortex encounters for hazard analysis**

  R. Greenhaw presented the status of the FAA project *"Characterizing wake vortex encounters for hazard analysis"* for purposes of the Safety Management System (SMS), see [R. Greenhaw]. The objectives are: (i) to develop a wake hazard severity matrix that conforms to SMS severity and likelihood practices; (ii) develop standards for determining acceptability of wake vortex encounters (distinguish safe and unsafe encounters) from a pilot's perspective; (iii) to develop metric(s) to evaluate WVEs in terms of hazard severity and acceptability. Those standards should be harmonised with current SMS guidance, procedures, and practice. FAA proposes a wake vortex risk matrix for the final approach phase (revision 4, not final) that has been derived from the general risk matrix that relates safety effects and probabilities and that is also used in aircraft certification. FAA uses "observable effects" to assess all possible situations that may affect crew's workload, expose passengers to injuries, or death or may cause damage to or loss of equipment and property, or damage the environment. This leads to a multi-parameter approach. However, currently no established WVE tolerance criteria exist. The need for such criteria consistently arises as an issue, e.g. Re-Cat, NLA, introduction of new operations and procedures as well as for WVE census. Such safety criteria are essential to: Safety Management System requirements, absolute safety cases to support changes and for the implementation of NextGen initiatives.

  WVE data collection is ongoing in a Boeing 737-800 and Airbus 330-200 full flight simulators in Oklahoma City with current and qualified pilots. Wake scenarios are embedded in simulations for other testing purposes in order to minimize learning effects. The objective is to generate a data base for development of a Hazard Severity Matrix. This FAA project is expected to last for 2 years.

- **Wake vortex severity criteria developed by NLR,** (see [P. van der Geest])

  Fokker developed the C-criterion, which takes changes of energy (energy rate) and induced moments into account, as a severity measure for atmospheric disturbances. It is an algorithm that addresses aircraft performance and handling, and it is an extension of the accepted F-factor (TSO-C117). The criterion that was developed for windshear prediction in the 1970ties is also suited to define the severity of a wake vortex encounter.

  NLR has used the C-criterion alongside Roll Control Ration (RCR) in several WV projects, resulting in comparable severity assessment results. Due to its simple and integrated concept the C-criterion is a possible candidate for extending the accepted F-Factor criterion to applications in the WV domain, but still further research into the viability of the C-criterion is required.

- **Wake vortex severity criteria for departure**

S. Amelsberg presented a multi-parameter severity criterion that was developed by TU Berlin for assessment of WVEs during departure, see [S. Amelsberg]. The work was performed in the CREDOS project. The criterion consists of four two-parameter sub-criteria, each addresses certain safety relevant metrics: aircraft pitch and roll attitude, vertical and lateral cabin accelerations, attitude control and air flow parameters (angle-off-attack and angle-of-sideslip). The sub-criteria are plotted in two-dimensional diagrams. For each metrics pair, two limits that confine the envelopes for normal operations and unacceptable aircraft upsets were derived from several sources: flight manuals, reference data for passenger comfort, results from the European S-WAKE project and published papers. The overall severity criterion is a combination of all sub-criteria. All criteria parameters can be measured.

The hazard ratings for simulated WVEs, which were computed with the criterion, were compared and verified with the hazard ratings of the pilots. The reference data were recorded during piloted tests in a certified Airbus A330 full flight simulator with current and qualified airline pilots and in an A320 development simulator.

The criterion was implemented into VESA and it was used to analyse the influence of parameter variations (e.g. crosswind velocity) on encounter risk, i.e. the probability of having an encounter that exceeds a certain level and may be hazardous.

6.3 DISCUSSION AND CONCLUSIONS

The same questions as for pilot control behaviour models were asked to start the discussion:

1. Is the performance of current Pilot Models (severity assessment) satisfying for WVE risk assessment?
2. Is there further research required? In which area?
3. How can validation and credibility of models be achieved?

Supplemented by questions from FAA for Re-Cat Phase II and III, see [J. Tittsworth, page 14]:

4. Which metrics should be considered as a measure of safety? Are simple metrics such as wake induced roll moment, roll control ratio sufficient to define the safety level for risk assessments?

And additional questions from the audience:

5. What is the safety level of worst-case WVEs under current ICAO separation rules (safe baseline)? This knowledge is important for quantitative safety assessments.
6. Are subjective pilot severity ratings from flight simulator studies valid e.g. because of (missing reality of motion system) be used for the validation of severity criteria?

Recent research on hazard metrics and on boundaries between acceptable and unacceptable WVEs has investigated multi-parameter criteria that take into account aircraft reaction, passenger comfort and pilot control effort. This work is still on-going. Current research at FAA, TU Berlin, NLR and DLR addresses the following areas:

- improvements of criteria quality,
- the definition of hazard boundaries that are accepted by all stakeholders,
- validation of results in order to “clear” them for being usable in risk assessments.

The definition of hazard boundaries requires establishing a common understanding at all stakeholders with respect to the definition of suitable metrics and limits for acceptable or nonacceptable wake encounter. The validation process should follow the same risk analysis process of FAA's Flight Systems Laboratory that was mentioned above and that is described in [9].

The choice of the right models for risk assessment is an important question for the Joint Eurocontrol/FAA Wake Turbulence Re-Categorization Effort. TU Berlin will organise another WakeNet3-Europe Workshop that addresses this topic.

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