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PROBABILISTIC WAKE VORTEX INDUCED ACCIDENT RISK ASSESSMENT

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ABSTRACT

New Air Traffic Management (ATM) concepts for departure and landing on busy airports might have a major impact on capacity if the wake vortex induced risks are better understood. The present wake vortex separation standards for the use of a single runway are often limiting capacity too much. To give ATM concept developers feedback with respect to the safety of new ATM concepts, a novel probabilistic methodology is under development for the assessment of wake vortex induced accident risks. The results of the safety assessment give insight in critical ATM design issues and thereby well-founded advice can be given on improvement of the design of the ATM concept.

The probabilistic wake vortex induced accident risk assessment is based on recent progress in wake vortex research. Commonly accepted models for wake vortex evolution and wake encounter have been adapted and integrated in the stochastic modelling and analysis setting of the TOPAZ (Traffic Organization and Perturbation AnalyZer) methodology.

This paper outlines this probabilistic wake vortex induced accident risk assessment methodology and illustrates its initial application to the case of multiple aircraft landing on a single runway.

1. INTRODUCTION

New ATM concepts for departure and landing on busy airports with multiple runways might have a major impact on capacity if the wake vortex induced risks are better understood. In particular, there is a need for identifying the conditions under which the present wake vortex separation standards would limit capacity too much. In (Kuzmin, 1997) an initial probabilistic methodology has been developed to assess such safe separations in case of a single runway. There are several reasons why there is a need to extend this initial methodology, e.g.:

- To guide and incorporate ongoing developments in wake vortex induced risk modelling;
- To generalise its application from a single runway to closely spaced runways;
- To allow the evaluation of advanced ground and/or airborne procedures that make use of wake vortex detection and decision support systems;
- To allow the evaluation of safe separation standards for new aerodynamic aircraft designs;
- To integrate it with a methodology that assesses risk of collision with other aircraft in the air or on the ground.

These reasons provided a clear motivation to extend the accident risk assessment methodology in order to enable the determination of safe separations for advanced ATM (Blom et al., 1998). This extension resulted in a complementary and novel probabilistic methodology for the assessment of wake vortex induced accident and incident risks.

The aim of this paper is to show how the accident risk assessment methodology can be used to support the assessment of wake vortex induced accident and incident risks, and how advantage is taken from recent progress in wake vortex research, e.g. (Kuzmin 1997) and (Corjon and Poinsot, 1996 and 1997). The novel methodology is also illustrated for an example of a medium-weighted aircraft landing behind a heavy-weighted aircraft on a (single) runway.

The paper is organised as follows. Section 2 outlines the risk assessment methodology and the supporting tool sets. In Section 3 the wake vortex specific models are explained in more detail. Section 4 illustrates the application to the specific single runway example. Section 5 draws conclusions. References and a biography of the first author are given in Sections 6 and 7, respectively.

2. RISK ASSESSMENT METHODOLOGY

As the basis for the development of the wake vortex risk assessment methodology use is made of the TOPAZ (Traffic Organization and Perturbation AnalyZer) methodology to assess accident risks for advanced ATM operations (Blom et al., 1998). This methodology supports the spiral development cycle that is part of modern Safety Case building for new ATM operational concepts (Blom & Nijhuis, 1999; Blom et al., 1999). Such a cycle is typically of the form:

A. Design of an ATM operational concept.
B. Assessment of the ATM concept, resulting in a cost-benefit overview.
C. Detailed analysis of the assessment results, which results in recommendations for improvements of the ATM concept.
D. Review ATM concept development strategy and plan.
E. Back to A: adapted and/or more detailed ATM concept design using the results from C resulting in a new or optimised ATM concept.

The TOPAZ risk assessment methodology is based on a stochastic modelling approach towards risk assessment and has been developed to provide designers of advanced ATM with safety feedback following on a (re)design cycle, see Figure 1.

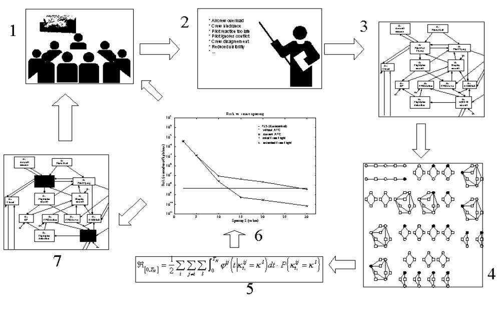

Figure 1 TOPAZ risk assessment cycle.

During the assessment cycle four stages are sequentially conducted:

- *Stage 1: Identification of operation and hazards (upper box in Figure 1)*
  Information about nominal and non-nominal behaviour of the ATM concept or procedure is gathered, through hazard identification sessions with a variety of experts.
- *Stage 2: Mathematical modelling (lower right box in Figure 1)*
  A stochastic dynamical model of the operation is developed that incorporates both all the nominal and all the non-nominal events of the operation. During this stage all model assumptions made are systematically specified.
- *Stage 3: Accident risk assessment (middle box in Figure 1)*
  The mathematical model of stage 2 supports an effective procedure, consisting of a number of steps to be followed, to quantify the accident risk. In addition to such numerical approach, a qualitative analysis of the model assumptions is performed.
- *Stage 4: Feedback to operational experts (lower left box in Figure 1)*
  The results of the quantitative safety assessment are fed back to and discussed with the designers and operational experts, who can use the results to redesign or optimise their proposed ATM design if necessary.

For the second and third stages use can be made of the following TOPAZ tools:

- SIMULATOR is a tool set that allows to specify and implement the mathematical model and to subsequently run Monte Carlo simulations with that implementation. SIMULATOR can simulate all aspects of operations, including the stochastic non-nominal aspects.
- COLLIR is a methodology and tool set that supports the evaluation of collision risks in the Terminal Manoeuvring Area (TMA) and en-route.
- WAVIR is a methodology and tool set that supports the evaluation of wake vortex induced accident risk.
- TAXIR is a methodology and tool set that supports the evaluation of accident risks at the airport.
- CRITER is a risk criteria framework that is needed to judge the acceptability of the risks that are assessed by COLLIR, WAVIR and TAXIR.

The methodological parts of COLLIR, WAVIR and TAXIR incorporate the evaluation of statistical data that are obtained either through empirical data collections or Monte Carlo simulations (e.g., SIMULATOR). One should be aware that for each of the tools further extensions are ongoing at NLR.

3. WAKE VORTEX RISK ASSESSMENT

3.1 Overview

For the assessment of the wake vortex induced accident and incident risks the following tools are used:

- Flight path evolution (in SIMULATOR)
- Wake vortex evolution and decay (in WAVIR)
- Wake encounter model (in WAVIR)
- Integration and risk evaluation model (in WAVIR)
- Risk criteria framework (in CRITER).

These tools are described in Sections 3.2-3.6, together with references that give more details about the models used.

3.2 Flight path evolution

The flight path evolution model yields the following stochastic variables:

- The lateral and vertical co-ordinates of the leader if its longitudinal co-ordinate *x* is given,
- The period of time elapsed between the generation of the wake and the time instant that the trailer has longitudinal position *x*,
- The lateral and vertical co-ordinates of the trailer when it has longitudinal co-ordinate *x*.

The flight path evolution model is a stochastic dynamical model, which incorporates the established (ICAO-CRM, 1980) as baseline, and which has been further developed to handle the dependent usage of closely spaced runways (Everdij et al., 1996).

The flight path evolution model is represented in a form (Everdij et al., 1997) that allows a straightforward extension of the SIMULATOR tool set for new air and/or ground procedures and advanced vortex detection and decision-support systems.

3.3 Wake vortex evolution and decay

The wake vortex evolution model yields the position and strength stochastic variables of the wake vortex at any time instant after the generation of the wake vortex. The wake vortex evolution model is mainly based on (Corjon and Poinsot, 1996) and (Corjon and Poinsot, 1997). The models in the latter papers have been probabilitised and they have been completed for application to the wake vortex induced risk assessment.

This wake vortex evolution model is able to take into account probabilistic models for stratification, atmospheric turbulence, ground effects (rebound, divergence) and crosswind (advection, shear). It can also handle probabilistic models for the vertical and horizontal wind fields and their impact on wake evolution.

During many landings the trailer aircraft does not meet any wake vortex. In the wake vortex evolution model two possible causes are distinguished:

- The wake vortex has disappeared due to a gradual diminishing of its strength.
- The wake vortex has disappeared due to a sudden bursting or linking,

In (Corjon and Poinsot, 1996) for the latter an analytical model has been proposed that assumes bursting and linking to happen in time as a function of some meteorological parameters. To better account for observed data, in WAVIR the probabilistic bursting and linking period is modelled independently of the vortex evolution and decay as a stochastic variable with a Rayleigh density, the mean of which is assumed equal to 50s. This Rayleigh density is depicted in Figure 2 together with empirical data for vortex residence period. This Rayleigh density modelling also differs significantly from the theoretical probability density model of Kuzmin (1997).

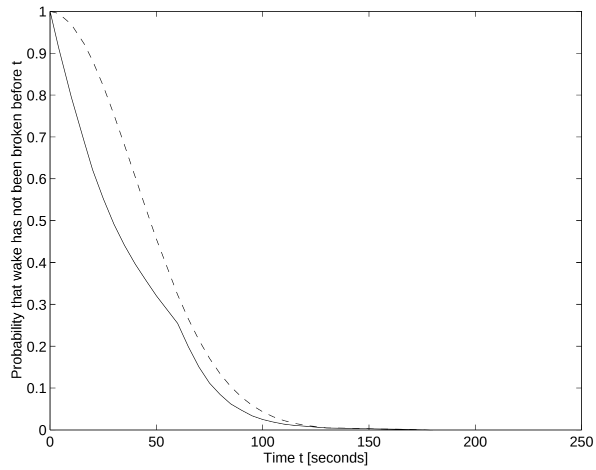

Figure 2 Solid line: observed vortex residence time distribution for B-747 vortices with initial height 30 metres, initial strength of the wake of 600 m^2/s and wingspan 60 metres (From figure 2 in EC, 1996)). Dashed line: Rayleigh density adopted in WAVIR for the vortex bursting or linking period.

3.4 Wake vortex encounter model

The wake vortex encounter model yields the probability that the wake vortex induced rolling moment is larger than the maximum control capability – in terms of rolling control moment – of the encountering aircraft.

The wake vortex control capability model is based on (Kuzmin, 1997) and accounts for the fact that the encountering aircraft tries to compensate for the wake vortex flow field generated by the leader only. In line with this the key effect is to reduce the rolling moment calculated with the wake vortex evolution model. The aircraft control capability model is also based on (Kuzmin, 1997) and (Woodfield, 1995), using information from the British Civil Airworthiness Requirements (BCAR).

It is important to realise that this approach inherently involves an important modelling assumption: the pilot is *not* able to anticipate timely on the first signs of a wake vortex. In practice, a pilot of an encountering aircraft might respond with the immediate initiation of a missed approach when its aircraft experiences a slight roll upset, i.e. in a very early stage of a possible wake encounter. Hence, this Kuzmin model implies a major pessimistic effect on the calculated risk near the threshold.

3.5 Integration and risk evaluation model

To assess numerically the wake vortex induced accident risk the models described in Sections 3.2-3.4 are integrated. The resulting numerical assessment is carried out in a seven-step procedure.

Step 1: The parameters in the wake vortex evolution model are identified and the parameter distributions are based on empirical data and/or state-of-the-art literature. In addition a set of relevant longitudinal positions x is determined.

Step 2: Run Monte Carlo simulations with the wake vortex evolution model for the case that the wake vortex is generated when the leading aircraft has longitudinal position x. The position, strength, and core radius of the wake vortex are obtained at the time instant that it has the same longitudinal co-ordinate as the trailer aircraft. The latter time instant follows from Monte Carlo simulations with the SIMULATOR tool.

Step 3: The simulation results from Step 2 are analysed. Based on this analysis a dedicated probability density fitting procedure is identified that accounts for dependencies between the position co-ordinates, the strength, and the core radius of the wake vortex. The probability density fitting procedure is carried out and the joint distribution of the wake vortex position, strength, and core radius is obtained.

Step 4: Monte Carlo simulations are carried out to simulate the wake vortex encounter. In this step the joint distribution from Step 3 is used and distributions of the position of the trailer aircraft obtained with the SIMULATOR tool set are used.

Step 5 concerns the numerical evaluation of the wake induced accident risk due to a wake vortex that is generated when the leading aircraft was at position x.

Step 6: The wake induced accident risk is obtained by maximising over x the risk obtained in Step 5.

Step 7: Perform a qualitative evaluation of the influence of the modelling assumptions on the estimated accident risk.

The results for these seven steps are illustrated for the case of a single runway example, in section 4.

3.6 Risk criteria framework

To judge whether a newly proposed ATM concept is safe or to determine more appropriate safe separation distances, a suitable metric for quantification of wake vortex induced risk is required. Up to now several metrics have been used to quantify the risk imposed by wake vortices: e.g. bank angle, roll angle, roll rate roll control ratio. However, since they do not relate to the safety perception of involved interest groups (e.g. crew, passengers, controllers, regulators, people living in the airport vicinity), they are felt to be insufficient. Other possible risk metrics are e.g. the risk probability per movement and the risk probability per year.

In (Speijker et al., 1999) some initial guidelines are developed for the assessment of safety requirements. It discusses two possible safety management approaches: the As-Low-As-Reasonably-Practicable (ALARP) approach and the Target Level of Safety (TLS) approach. Ranges are suggested from which to adopt a TLS for the risk event *probabilities per movement.*

For the adoption of applicable risk criteria, it is clear that policy makers definitively have to be involved, and also the relation with existing wake vortex induced incident and accident frequencies should be clearly identified.

3.7 From risk to safe separation

By assessing accident risks for various separation distances, one arrives at a curve that shows the risk as a function of the separation distance between successive aircraft. Figure 3 illustrates how such a curve subsequently maps an ALARP region in terms of risk into one in terms of separation distances.

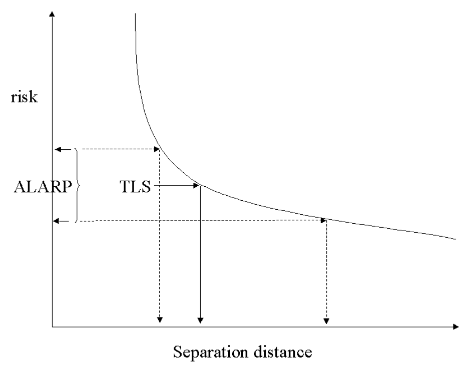

Figure 3 Wake vortex risk versus separation distance.

4. SINGLE RUNWAY APPROACH

4.1 B737-400 behind B747-400

To illustrate the novel wake vortex induced accident risk assessment methodology we consider a (single) runway, on which a B737-400 aircraft, which is in the ICAO medium weight class, is landing behind a B747-400 aircraft, which is in the ICAO heavy weight class, with controller expected separation distance of 5 Nm when the heavy is at the threshold. For both aircraft it is assumed that the approach is ILS Cat I.

The landing phase starts at about 20 km before the threshold, and ends at touchdown, which is 300 metres beyond threshold. Figure 4 shows the side view of the runway and glide slope, where the *x*-axis is along the runway centerline and positive in runway direction.

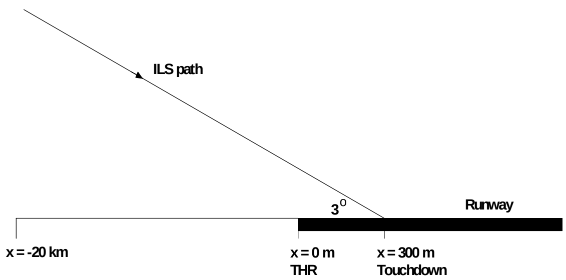

Figure 4 Side view of runway and glide slope.

Due to its stochastic dynamical modelling basis, the novel wake induced risk assessment methodology clearly allows to bring the assumptions made to the foreground. For the example considered, the following main assumptions have been adopted:

A.1. Long landings (landings far beyond threshold) do not happen.

A.2. A wake vortex induced accident event is characterised by the wake induced rolling moment being larger than the aircraft control capability.

A.3. A pilot does not respond with the initiation of a missed approach when its aircraft experiences a slight roll upset.

A.4. Bursting and linking probabilities are modelled by a Rayleigh density with mean 50 seconds.

A.5. There is no head wind, no tail wind and no vertical wind. The wind speed in lateral direction is normally distributed with expectation 0 and standard deviation 1.5 m/s.

A.6. There are no wind shear layers.

A.7. Turbulence of the air is 10% of the wind speed.

In addition to these main assumptions, several other assumptions have been made. It would go beyond the scope of this paper to list all these assumptions.

4.2 Numerical results

With support of the SIMULATOR and WAVIR tool sets, the wake vortex induced accident risk is evaluated for the single runway scenario.

Figures 5 and 6 show data plots of the left vortex for the case that the wake vortex is generated at 4 km before threshold (cf. Output of Step 3 in Section 3.5).

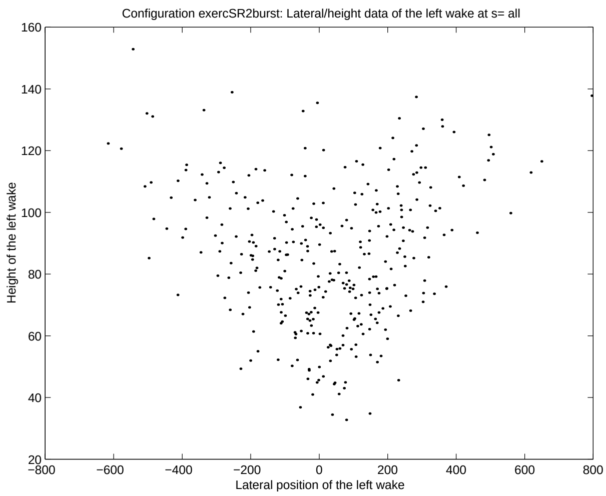

Figure 5 Monte Carlo simulation results of the lateral and vertical co-ordinates ([m]) of the centre of the left wake that is generated at 4 km before the threshold.

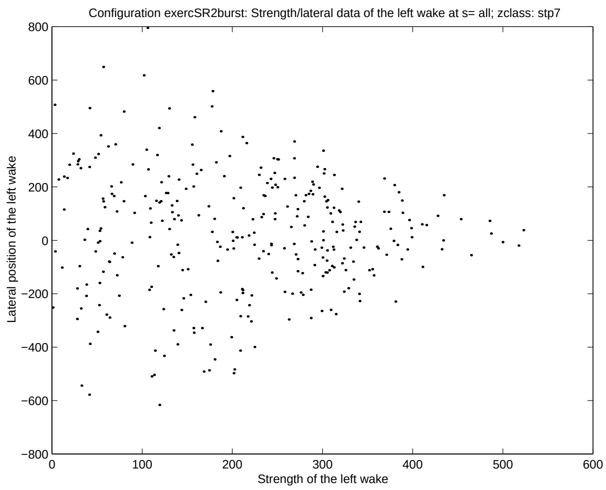

Figure 6 Monte Carlo simulation results of the lateral co-ordinate ([m]) and the strength ([m2/s]) of the centre of the left wake that is generated at 4 km before the threshold.

Subsequently, Figure 7 shows the results for the wake induced accident risk resulting from a wake that is generated at –*x* km before the thresholds. The vertical axis has a logarithmic scale. The + signs indicate the values of *x* (cf. Output of Step 5 in Section 3.5).

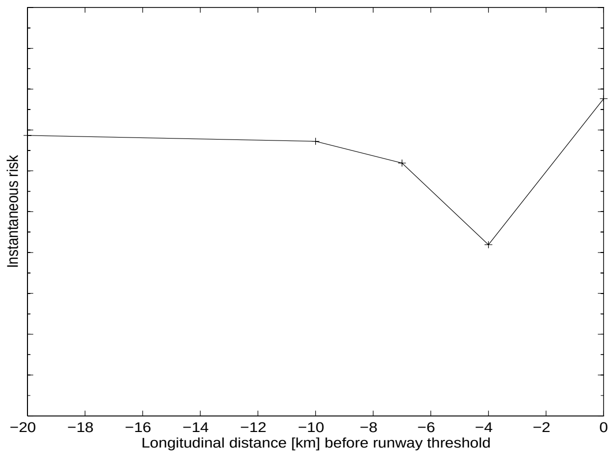

Figure 7 Estimated values for the severe risk that is instantaneously induced by wake vortex along the glide slope. The vertical axis has a logarithmic scale.

Figure 7 shows that the estimated values for the accident risk that is instantaneously induced by wake vortices along the glide slope decrease from 20 km till approximately 4 km before the threshold. The decrease is due to the descent of the wake and the higher navigation precision (in height) of the trailer. At shorter distance from the threshold, the instantaneous risk increases due to the rebound of wakes near the ground.

4.3 Qualitative uncertainty analysis

A straightforward maximisation over *x* for the curve in Figure 7 would lead to an overall maximum risk at the threshold. However, prior to the maximisation one should bring into account that the calculated wake vortex induced accident risk curve may bear significant bias and/or uncertainty both in positive and negative directions. Usage of such a curve without taking into consideration existing bias and/or uncertainty can inspire undue conclusions.

In order to understand the impact of the assumptions on the wake vortex induced risk, A.1-A.7 have been analysed in a qualitative way. The results are given in Table 1. The first column refers to the assumptions. The second column gives for each assumption the expected direction of the effect on the wake vortex induced risks (optimistic, pessimistic or neutral), and the last column gives the expected magnitude (major or significant). A pessimistic expected direction means that the modelled risk increases due to the assumption. An optimistic expected direction means that the modelled risk reduces due to the assumption. A neutral direction means that there exists uncertainty about the direction.

A.#	Expected direction of effect on wake vortex induced accident risk	Expected magnitude
A.1	Optimistic	Significant
A.2	Neutral	Significant
A.3	Pessimistic	Major
A.4	Neutral	Significant
A.5	Optimistic	Significant
A.6	Optimistic	Major
A.7	Pessimistic	Significant

Table 1 Expected effects of the main assumptions on assessed risk.

This qualitative analysis has also been applied to all other assumptions. Since their effect on the wake induced accident risk has been estimated as being either minor or negligible, these assumptions are not listed in the current paper.

4.4 Discussion of results

If one takes into account the impact of the assumptions A.1-A.7 then the curve in Figure 7 shows that there are two distinct areas where the instantaneous wake vortex induced accident risks along the ILS are not negligible:

- Near the threshold: this is due to the ground effect on the wake evolution.
- At distances larger than 10 km from the threshold: this is due to larger ILS navigation errors at further distance from the threshold.

Near the threshold the effect of assumption A.6 is negligible. A.3 is the only assumption that has a major impact (pessimistic). The net effect of all assumptions is that the very right part of the curve in Figure 7 has a major level of uncertainty with a clear bias in the pessimistic direction.
At distances larger than 10 km from the threshold the effect of assumptions A.1 and A.3 is negligible. A.6 is the only assumption that has a major impact (optimistic). The net effect of all assumptions is that the left part of the curve in Figure 7 has a major level of uncertainty with a clear bias in the optimistic direction.

The example shows that there are a few directions that specifically deserve the development of improved wake vortex induced risk models. These directions can be placed in the following two groups:

- General modelling is needed to mitigate the need for the neutral and pessimistic assumptions A.2, A.3, A.4 and A.7.
- Airport specific modelling is needed to mitigate the need for the optimistic assumptions A.1, A.5 and A.6.

5. CONCLUDING REMARKS

5.1 The novel methodology

This paper has outlined a novel probabilistic methodology (WAVIR), to assess wake vortex induced accident and incident risks as part of the TOPAZ accident risk assessment methodology of (Blom et al., 1998). The initial methodology developed by Kuzmin (1997) constituted a major element in the motivation to start this development. In addition to this, ample needs and opportunities have been identified to further motivate this challenging development.

The novel methodology, the tool sets and the models initially adopted have been outlined in Sections 2 and 3 respectively. They are developed to understand the safety evaluation of established separation standards for current operations, and of new separation standards for new operational concepts and aircraft designs for busy airports with closely spaced runways. The novel methodology incorporates:

- Wake vortex evolution and decay model;
- Wake vortex encounter model;
- Flight path evolution model;
- Integration and risk evaluation model;
- Risk criteria framework.

Subsequently, in Section 4, the novel methodology has been illustrated for a B737-400 aircraft landing on a single runway behind a B747-400 aircraft, with expected separation distance of 5Nm at the threshold. The numerical and complementary qualitative results obtained for this example clearly show that the novel methodology is able to identify the key bottlenecks in developing advanced wake vortex procedures. In the current situation the safety of the established operations is insufficiently understood in a few key areas. Most of these areas ask for general modelling effort. A few areas only ask for airport specific modelling effort.

5.2 General modelling areas

There are four key general modelling areas that deserve significant modelling effort. A relatively simple one is to improve the probabilistic modelling of navigation performance and long landing models under different navigation modes and various wind conditions. The basis for this activity is one of collecting statistical data of aircraft navigation performance.

The second area is to improve the modelling of auto-pilot reactions to wake induced roll upset, and missed approaches initiated by pilots as a reaction to experiencing a roll upset during the ILS approach. The basis for this activity seems to be one of analysing pilot incident reports on missed approaches. In addition, flight simulation data should be used to develop models that represent the pilot behaviour during wake vortex encounter.

The third area is to improve the modelling of bursting and linking phenomena. Because of the existing uncertainty about bursting and linking, and their dependency on weather condition, it is strongly recommended to model bursting and linking with appropriate probability distributions. The distributions are to be validated with real experiments or state-of-the-art computational fluid dynamic models for wake vortex evolution.

The fourth area is the further development of a risk management framework for wake vortex induced accident and incident risks such that it becomes clearly connected to existing wake vortex incident and accident data. This modelling effort can only be concluded in discussions with regulatory authorities and other relevant interest groups (e.g. pilots and controllers). In the current European constellation this process still is very much airport specific.

5.3 Airport specific modelling areas

The key airport specific modelling area that deserve significant modelling effort is weather. It is important to realise the major influence of specific weather conditions, in particular wind fields, turbulence, stable stratification and wind shear (Darracq et al., 1999). These weather conditions are such airport specific that the developed models have to be tuned for the airport under consideration.

Another key airport specific modelling issue is that each particular airport runway geometry may lead to all kind of dependencies between runway usage. The particular geometry of an airport layout often leads to airport specific dependencies that involve combinations of wake vortex induced accident risks and risk of collision with another aircraft.

It should also be taken into account that due to these airport specific modelling needs, different appropriate and safe separation distances might result for different airports.

5.4 Ongoing developments

The results obtained so far form a clear motivation to continue the development of the TOPAZ/WAVIR methodology towards the assessment of wake vortex induced accident and incident risks. The results obtained with the methodology in its current state already provide clear overall insight into the large variety of wake vortex subproblems.

Apart from the single runway example illustrated in this paper, also a closely spaced runway example has been evaluated with the TOPAZ/WAVIR methodology (this was under a study contract with the DFS). This study also provided valuable overall insight into the wake vortex subproblems in case of parallel flying aircraft.

Since January 2000 NLR is leading a major three-year project (named S-WAKE) for the European Commission in which key European wake vortex experts are collaborating to develop solutions for the outstanding modelling areas.

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7. BIOGRAPHY 1ST AUTHOR

Dr. J. Kos graduated in 1991 at the Vrije Universiteit, Amsterdam. He obtained his doctorate in 1995 at the same university with a thesis in the fields of Mathematical System Theory and Linear Operator Theory. He joined the National Aerospace Laboratory NLR in 1995. Since then, his interest has been to apply system & control theory concepts in various applications such as validation strategies for ATM, computer working environments for computer-aided control engineering and simulation, and the integration of wake vortex models for risk assessment. Recent interest concerns integration of air condition simulation models and control of air conditioning systems.