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National Aerospace Laboratory NLR

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Assessment of Wake Vortex Safety to Evaluate Separation Distances

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Biography 1st Author

Lennaert Speijker graduated in 1995 at Delft University of Technology, with a Master's degree in Applied Mathematics. He then joined National Aerospace Laboratory NLR to conduct research on risk analysis and safety issues with applications to civil aviation. His main interest has been modeling of accident risk to support evaluation of safe separation distances between aircraft.

Abstract

The steady increase in air traffic imposes a need for enhanced airport capacity, and the desire to safely reduce existing separation standards. An important limiting factor in establishing required separation standards is the risk imposed by wake vortices.

A probabilistic model is developed for the determination of wake vortex induced accident risk. The modeling approach is integrated within a stochastic framework. Four probabilistic sub models are being used:

- Wake vortex evolution model;
- Wake vortex interaction model;
- Aircraft control capability model;
- Flight path evolution model.

This probabilistic model can be used for an assessment of wake vortex safety related to different ATM concepts or procedures. It provides a tool to evaluate the separation standards for the current practice, and for promising new concepts which may enable a safe reduction of the current separation standards. Numerical evaluation results can be fed back to ATM designers, who can use these results to redesign or improve their proposed ATM concept.

A safety management framework, which describes how to judge the acceptability of the obtained safety assessment results, is developed. It consists of identified suitable safety measures and safety requirements based on a combination of the TLS and the ALARP approach.

1 Introduction

With the steady increase in air traffic, there is an urgent need to use existing and newly proposed technologies in an efficient way. This is reflected in the design of new high capacity aircraft and new advanced ATM concepts and procedures.

However, it is also recognized that safety is a key quality that should be guaranteed. In particular the wake vortex problem becomes more important, for example at Heathrow where many incidents occurred due to wake vortex encounters, and at Frankfurt where there are two closely spaced parallel runways and no extension possibility that is publicly acceptable.

This requires tools and methods to enable a quantitative assessment of wake vortex safety. In view of the uncertainties and the difficulties in understanding of the wake vortex phenomena, this paper proposes a *probabilistic* approach.

To support the design of new aircraft and new advanced ATM concepts, a probabilistic wake vortex induced risk model has been developed. The model is based on a stochastic framework that incorporates a flight path evolution model and three wake vortex related sub models:

- *Wake vortex evolution model*
  To determine the stochastic wake vortex motion, decay and strength in time at certain positions relative to the generator aircraft;
- *Wake vortex interaction model*
  To determine the stochastic vortex-induced rolling moment on the encountering aircraft;
- *Aircraft control capability model*
  To determine the control capability – in terms of maximum rolling control moment – of the encountering aircraft.

This model can be used to evaluate the separation distances for the current practice, and promising new concepts that may enable a safe reduction of the current separation standards. Identified safety criticalities, which have a large contribution to the wake vortex induced risk, can be fed back to the ATM designers, who can use these results to redesign or improve their proposed ATM concept.

The present separation distances are based on a matrix of different aircraft weight classes. For aircraft (Leader and Follower) approaching a single runway the required separation distances as recommended by ICAO are given in table 1.

Table 1 Minimum required separation distances

L / F	Heavy	Medium	Light
Heavy	4	5	6
Medium	-	3	4
Light	-	3	3

These required separation distances stem from the early 70's and are not based on safety requirements. Although over the last 30 years they have 'proven to be safe', the current safety level is unclear and there is a deficiency of tools and methods to determine more appropriate separation distances. The proposed modeling approach aims at solving this deficiency.

Under contract to DFS, this probabilistic model has been applied to evaluate the wake vortex induced risk related to the newly proposed High Approach Landing System (HALS) at Frankfurt airport. The model will be extended and applied in the S-Wake project for the European Commission. S-Wake aims to develop and apply tools for assessing appropriate safe separation distances. An assessment will be made of the wake vortex safety level under various operational and weather conditions.

Section 2 contains the safety management framework, including identified suitable safety measures and adopted safety requirements. In Section 3 the developed probabilistic safety assessment model is described. Section 4 describes how the quantitative safety assessment results can be used to evaluate safe separation distances. It also motivates the benefits of the proposed probabilistic modeling approach. The conclusions and recommendations are given in Section 5.

2 Safety criteria framework

This section proposes a safety criteria framework, which describes how to judge the acceptability of the obtained safety assessment results. It consists of selected safety measures and safety requirements that are based on a combination of the TLS and the ALARP approach.

2.1 The ALARP approach

The ALARP approach is based on a banded assessment of decision structure, which contains a tolerable region bounded by maximally negligible and minimally unacceptable levels of risk. Within the tolerable region the risk must be proven to be As Low As Reasonably Practicable (ALARP) in order to be acceptable (Ref. 12). Cost-Benefit Analysis (CBA) is a method that can be used to demonstrate that any further risk reduction in the tolerable region is impracticable.

Up to now, the ALARP approach has mainly been used in industries other than aviation (e.g. the chemical, offshore, nuclear and some transport industries). Recently the development of the ALARP approach for use in aviation risk management has been investigated within the context of Reduced Vertical Separation Minimum (RVSM) in ECAC countries (Ref. 9).

It was concluded that for aviation there seems to be no case for replacing any accepted Target Level of Safety (TLS) approach with ALARP. However, since most practical applications of the ALARP approach use fixed risk criteria like the TLS to determine the boundaries of the ALARP region, there appear to be good grounds for *combining* the TLS and ALARP approach for application to aviation risk management. In reference 9 it is argued that a combination of these two safety management approaches in a way as given in figure 1 is indeed beneficial to aviation risk management. This approach will therefore be followed to assess the safety requirements for wake vortex induced risk.

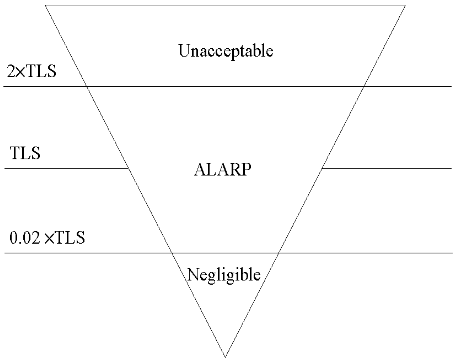

Figure 1 ALARP framework for safety requirements [9]

According to figure 1, the ALARP region will be determined in the following way:

- The TLS is calculated on the basis of a common method for TLS assessment;
- This TLS is supplemented by an ALARP region extending from 0.02%TLS to 2%TLS;
- Risks above 2%TLS (the least stringent boundary) are judged unacceptable and must be reduced;
- Risks below 0.02%TLS (the most stringent boundary) are judged negligible and do not need further reduction;
- For risks within the ALARP region, a range of risk reduction measures should be identified and evaluated using CBA.

2.2 Identification of safety measures

In order to judge whether a newly proposed procedure is safe or to determine more appropriate safe separation distances, a suitable measure for quantification of the wake vortex induced risk is required. Up to now several measures have been used to quantify the hazard imposed by wake vortices: e.g. bank angle, roll angle, roll rate and roll acceleration. However, since they do not relate to the safety perception of most involved actor groups (e.g. crew, passengers, controllers, regulators, people living in the airport vicinity), they are felt to be insufficient (Refs. 6, 14).

It is argued that a distinction can be made between the following 3 risk events:

1. *Incident* occurs if an encountering aircraft experiences a roll upset, with possibly some minor injuries to, but no fatalities among, occupants;
2. *Accident* occurs if a wake vortex encounter results in serious injuries to, or death of, a relatively small proportion of the occupants, due to rolling and normal accelerations throwing them about inside the aircraft;
3. *Crash-into-terrain* occurs if an encountering aircraft hits the ground as a result of height loss and an increase in rate of descent during the encounter.

It is also argued that there may not be *one* most appropriate type of risk measure. Three types of suitable risk measures emerged:

1. Risk event probability per movement (e.g. take off or landing);
2. Risk event probability per year (or expected average time interval between 2 risk events);
3. Economic risk per year.

In this paper, the safety requirements are assessed on the basis of the most commonly used safety measure: the risk event probability per movement. However, the method described in section 2.1 can easily be used to assess safety requirements based on the other two identified safety measures.

2.3 Adoption of safety requirements

The Joint Aviation Authorities (JAA) have established a Joint Airworthiness Requirements (JAR) risk categorization, which relates a number of hazard categories (catastrophic, hazardous, major, minor, and no effect) to a maximum probability of occurrence (Refs. 10, 11). This generally accepted risk categorization, which was designed for ATC *systems,* is used to derive the safety requirements for the 3 wake vortex induced risk events. According to references 10 and 11, the 3 wake vortex induced risk events can be categorized as follows:

- *Incident:* Major Effect;
- *Accident:* Hazardous Effect;
- *Crash-into-terrain*: Catastrophic Effect.

The JAR hazard categories are related to maximum probabilities of occurrence *per flight hour* as described in reference 10 (Amendment JAR 25.1309, Change 13; 3.3.1-3.3.4). This measure is felt not suitable for approach and take-off, since these phases only take a relatively small amount of time. Below, a method is used that applies to the selected safety measures.

A *crash-into-terrain* was categorized as Catastrophic, i.e. the maximum probability of occurrence *per flight hour* when all Failure Conditions are taken together, must be assessed to be Extremely Remote: in between 10^{-7} and 10^{-9} .

Depending on the world region, the mean flight time may be estimated at 2 to 4 hours. Assuming 3 hours, this implies a maximum probability of crash-into-terrain that is in between 3%10^{-7} and 3%10^{-9} per flight. Dividing the risk equally between the three parts of a flight (take off, en-route and approach) implies for the crash-into-terrain probability per movement:

$$TLS_{crash-into-terrain} \in [1\times10^{-9}, 1\times10^{-7}]$$

An *accident* was categorised as Hazardous, i.e. *each Failure Condition* leading to this risk event should be assessed as Extremely Remote: have a probability of occurrence in between 10^{-7} and 10^{-9} per flight hour. Of course, there are *a number of* possible Failure Conditions. The JAR requirement for the Catastrophic category implies that there might be 100 possible Failure Conditions leading to a risk event (Ref. 10). Using this implication and a similar reasoning as above implies for the accident probability per movement:

$$TLS_{accident} \in [1\times10^{-7}, 1\times10^{-5}]$$

An *incident* was categorised as Major, i.e. each Failure condition which may lead to this risk event should be assessed as "Remote": have a probability of occurrence in between 10^{-5} and 10^{-7} per flight hour. A similar reasoning as in the above implies for the incident probability per movement:

$$TLS_{incident} \in [1\times10^{-5}, 1\times10^{-3}]$$

A method is described suggesting ranges from which to adopt the Target Level of Safety (TLS). In order to set *the* TLS, policy makers should be consulted. Once a unique TLS has been set, it is possible to determine the ALARP region extending from 0.02%TLS to 2%TLS.

3 Wake vortex safety assessment model

3.1 Overview of the risk model

To determine the selected safety measures for the three possible risk events, an appropriate safety assessment model is required. In view of the uncertainties and the difficulties in understanding of the wake vortex phenomena, it is proposed to follow a *probabilistic* modeling approach.

The probabilistic model should enable the evaluation of wake vortex safety under various operational and weather conditions. It should be possible to evaluate the current practice as well as promising new concepts, such as aircraft design changes, operational improvements, or weather related separation distances. An initial version of the model should focus on the airspace around the airport (i.e. landing and take off operations), since this sector is most limiting to air traffic capacity. The modeling approach should be able to cover the situation of a sequence of aircraft that fly towards different kinds of runway configurations (e.g. a single runway or closely spaced parallel runways).

Considering this, four probabilistic sub models are required to be integrated within a stochastic framework that enables calculation of the incident, accident and crash-into-terrain risk:

- *Wake vortex evolution model*
  To determine the stochastic wake vortex motion, decay and strength in time at certain positions relative to the generator aircraft;
- *Wake vortex interaction model*
  To determine the stochastic vortex-induced rolling moment on the encountering aircraft;
- *Aircraft control capability model*
  To determine the control capability – in terms of maximum rolling control moment – of the encountering aircraft;
- *Flight path evolution model*
  To describe the stochastic flight path evolution of the involved aircraft.

Reference 13 contains an extensive literature survey leading to the selection of the following deterministic wake vortex related sub models:

- A wake vortex evolution model that is based on references 1 and 2 (Corjon and Poinsot);
- A wake vortex interaction model that is based on reference 3 (Kuzmin);
- Aircraft control capability model that is based on reference 4 (Woodfield).

These deterministic models can be probabilitised in three steps as follows (Ref. 14):

1. Representation of uncertainty about the variables by histograms and/or probability distributions;
2. Execution of Monte Carlo Simulations to obtain histograms for the model outputs;
3. Execution of goodness-of-fit tests to obtain probability distributions for model outputs.

A probabilistic flight path model is used that is based on references 5 and 15. The lateral and vertical flight path deviations are based on the ICAO Collision Risk Model (CRM) Manual for ILS operations (Ref. 5). The longitudinal flight path deviations are based on a stochastic model, which takes into account wind and controller/ pilot interactions (Ref. 15).

In Sections 3.2 and 3.3 descriptions are given of the three wake vortex related deterministic sub models. Together with the flight path model, these are integrated into a stochastic framework that is based on the TOPAZ methodology (Ref. 8), which is described in Section 3.4.

Figure 2 below gives an overview of the main elements of the probabilistic safety assessment.

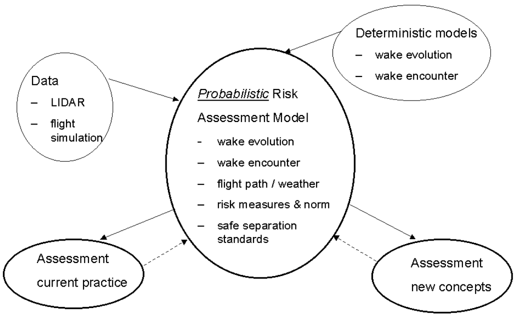

Fig. 2 Overview of the probabilistic approach

3.2 Wake vortex evolution model

This section provides a mathematical description of the used wake vortex evolution model, which originates from references 1 and 2. This "Corjon-Poinsot" model takes into account stratification, atmospheric turbulence, ground effects (rebound, divergence) and crosswind (advection, shear). It is extended with probabilistic wind field models to include the impact of wind in the vertical and lateral direction during the evolution (Ref. 14).

The model enables determination of the wake vortices motion, decay and strength in time at certain positions relative to its generator aircraft. This aircraft generates two counter rotating vortices of which the positions and strengths are to be determined. The positions are given relative to a rectangular xyz-coordinate system, with x-axis in longitudinal direction, y-axis in lateral direction and z-axis in the vertical direction.

The positions of the left and right centers of two vortices, are represented by $X_t^- = \{x_t^-, y_t^-, z_t^-\}$ and $X_t^+ = \{x_t^+, y_t^+, z_t^+\}$. The strengths of the two vortices at time t are denoted by $\Gamma_t^- \in \Re$ and $\Gamma_t^+ \in \Re$ respectively. The initial positions at time t=0 are denoted by X_0^- and X_0^+, and are determined by the three dimensional position of the center of the leader aircraft at time t=0. The initial strengths are denoted by Γ_0^- and Γ_0^+.

3.2.1 Wake vortex strength and decay

The basic equation of wake vortex decay is that the rate of change of circulation strength equals the sum of the rates of change of circulation due to viscosity, buoyancy, turbulence, and crosswind:

$$\frac{d\Gamma^\pm}{dt} = \left.\frac{d\Gamma^\pm}{dt}\right|_{visc} + \left.\frac{d\Gamma^\pm}{dt}\right|_{buoy} + \left.\frac{d\Gamma^\pm}{dt}\right|_{turb} + \left.\frac{d\Gamma^\pm}{dt}\right|_{crossw}$$

The rate of change for viscosity depends on vortex descent speed, viscous force coefficient (C_D), wake oval width (L_{wv}), angle between force and drift velocity of a vortex (θ_t), and the initial spacing between the vortices (b_0), and is equal to

$$\left.\frac{d\Gamma^\pm}{dt}\right|_{vis\cos ity} = \frac{\left|\dot{X}_t^\pm\right|^2 C_D L_{wv} \cos\theta_t^\pm}{2b_0}$$

The rate of change for buoyancy force depends on the area of the wake oval (A_{wv}), the Brunt–Väisälä frequency (N), the descent distance of a vortex, the angle between the force and drift velocity of a vortex (θ_t), and the initial spacing between the two vortices (b_0), and is given by:

$$\left.\frac{d\Gamma^\pm}{dt}\right|_{buoyancy} = \frac{A_{wv} N^2 \left[z_t^\pm - z_0^\pm\right]\cos\theta_t^\pm}{b_0}$$

The rate of change for atmospheric turbulence depends on the rms turbulence velocity (q), the vortex circulation (Γ_t), and the initial spacing between the vortices (b_0), and is given by:

$$\left.\frac{d\Gamma^\pm}{dt}\right|_{turbulence} = -0.82\frac{q\Gamma_t^\pm}{b_0}$$

An effect of crosswind is the acceleration of the decay of the vortex with the opposite sign vorticity from the crosswind. The decay rate of the other vortex is not influenced significantly. This effect can be modeled by adding a term in the basic equation of wake vortex decay:

$$\left.\frac{d\Gamma^+}{dt}\right|_{crossw} = -\frac{2}{3}C_{DV}\sigma w_0 b_0 \quad \text{and} \quad \left.\frac{d\Gamma^-}{dt}\right|_{crossw} = 0$$

with C_{DV} the viscous coefficient caused by crosswind, σ the wind shear coefficient, and w_0 the crosswind magnitude at initial height z_0^+.

The initial value of the circulation at t=0 depends on the weight of the leader (W^i), the initial aircraft true airspeed, the initial spacing between the vortices (b_0) and the density (ρ) (Ref. 17):

$$\Gamma_0^\pm = \frac{W^i}{\rho b_0[\dot{x}_0^i - \omega_{x,0}]}$$

The vortex lifetime depends on two influencing phenomena: Crow instability and vortex bursting

3.2.2 Wake vortex position

In order to determine the wake vortex induced rolling moment on an encountering aircraft j, the trajectories of the counter-rotating wake vortices are also required. References 1 and 2 provide basic equations for these trajectories, thereby accounting for divergence and rebound effects. The model gives equations for the total induced velocity of primary and secondary vortices. These equations are modified to include the wind speed □ in all three directions. The equations from which the trajectories of the two counter-rotating vortices can be computed are given by:

$$\frac{dx_i}{dt} = \omega_x$$

$$\frac{dy_i}{dt} = \omega_y + \sum_{j \neq i} \frac{\Gamma_j}{2\pi} \frac{z_j - z_i}{r_{ij}^{\,2}} + \frac{\Gamma_i^{''} \cos\theta_i}{2\pi r_i^{''}}$$

$$\frac{dz_i}{dt} = \omega_z + \sum_{j \neq i} \frac{\Gamma_j}{2\pi} \frac{y_j - y_i}{r_{ij}^{\,2}} + \frac{\Gamma_i^{''} \sin\theta_i}{2\pi r_i^{''}}$$

$$\frac{d\theta_i}{dt} = \frac{\Gamma_i - \Gamma_i^{''}}{2\pi [r_i^{''}]^2}$$

$$r_{ij}^{\,2} = (y_j - y_i)^2 + (z_j - z_i)^2$$

where i=1,2 and j=1,..,4. An explanation of the terms in these equations can be found in references 1, 2, 13, and 14.

The wind field model has to be tuned for the airport situation. To evaluate the wake vortex induced risk of the proposed High Approach Landing System (HALS) procedure at Frankfurt airport with its closely spaced parallel runways, this has been done on the basis of statistical measurement based data.

The horizontal wind model accounts for height dependency. It appeared that horizontal wind can have a major impact to the wake vortex induced risks. Head wind reduces the effective distance between the trailer and the wake vortex that has been generated by the leader, whereas tail wind effectively enlarges this distance.

The impact of head/tail wind on the risk depends largely on the ATM procedures and runway layout: for some situations head wind is more dangerous, in other situations tail wind. Crosswind may transport wakes to other runways. In the case of a single runway strong crosswind may transport the wake vortex so that it is far from the trailer (in lateral direction).

The vertical wind field model accounts for varying weather conditions. The strongest vertical wind speeds occur in case of a convective atmosphere. In this case, wakes can travel significant distances. In addition, the left wake can be in an upwind, whereas the right wake is in a downwind. Hence the distance between the left and right wake can become so large that they may be considered as isolated wakes. In a convective atmosphere there may be isolated wakes that stay at the height at which they have been generated (or they may rise). This implies a relative high wake vortex induced risk.

3.3 Wake encounter model

This section provides a description of the used wake encounter model, consisting of two parts:

- A wake vortex interaction model;
- An aircraft control capability model.

It is based on the assumption that a risk event occurs if the vortex-induced rolling moment exceeds the maximum control capability of the encountering aircraft. The severity of the risk event increases if the difference between the two increases and/or the wake vortex encounter occurs at an altitude closer to the ground.

3.3.1 Wake vortex interaction model

The wake vortex interaction model is based on reference 3, and results from the VORSAF project carried out by TsAGI under contract to ISTC. The description of the deterministic version that has been probabilitised is given.

The aircraft encountering the vortex alters, to some extent, the wake vortex flow field as generated by the leader. In general, one effect is to reduce the rolling moment as calculated with the wake vortex evolution model.

The vortex-induced rolling moment on the encountering aircraft j is modeled as a function of vortex strength and the distance between aircraft axis and vortex axis. The rolling moment is estimated for the situation with vortex axis parallel to the aircraft axis with the assumption of a rectangular wing, and is given by (Ref. 3):

$$M^{j}_{induced}(t) = \frac{\Gamma_t^{\pm} C^{j}}{2\pi V_t^{j} b^{j}} F(\tilde{dy}, \tilde{dz})$$

The vortex-induced rolling moment depends on the flight speed of the encountering aircraft (V_t^j), its wing span (b^j), the vortex strength (Γ_t), the aircraft specific coefficient C^j, and a function F.

This function F, describing the influence of the distance between vortex axis and aircraft axis, is:

$$F(\tilde{dy}, \tilde{dz}) = 1 + \frac{\tilde{dz}}{2}\ln\left[\frac{\tilde{dy}^2 + (1/2 - \tilde{dz})^2}{\tilde{dy}^2 + (1/2 + \tilde{dz})^2}\right] - \tilde{dy}\left[\arctan\left[\frac{1/2 - \tilde{dz}}{\tilde{dy}}\right] + \arctan\left[\frac{1/2 + \tilde{dz}}{\tilde{dy}}\right]\right]$$

where the required input values of F depend on the distance between vortex axis and aircraft axis in lateral and vertical direction (dy and dz), the vortex core radius (r_{core}) and the wing span (b^j) of the encountering aircraft j, according to:

$$\tilde{dy} = \frac{\sqrt{r_{core}^{\,2} + dy^2}}{b^j}$$

$$\tilde{dz} = \frac{dz}{b^j}$$

For vortex core radius growth in time of vortices that did not have changed state by bursting or linking the following equation is used:

$$r_{core}(t) = \max(r_{core,t=0}, 0.0125\sqrt{\Gamma_o t})$$

Note that the vortex-induced rolling moment attains its maximum at distance equal to the vortex core radius from the vortex axis. This indicates that the majority of angular momentum is in the regions farthest from the core. Outside the core radius, the rolling moment is negligible.

3.3.2 Aircraft control capability model

The aircraft control capability model is based on references 3 and 4. The deterministic version that has been probabilitised is described below.

The basic equation for the maximum roll control moment of an aircraft j depends on the wing span (b^j), the wing area (S^j), the air density (ρ), the aircraft true airspeed ($\dot{x}_t^j - \omega_{x,t}$), the maximum steady roll rate ($\hat{p}$), and the roll damping coefficient (C^j_{rd}), and is given by:

$$M^{j}_{control}(t) = -\rho \frac{S^j [b^j]^2}{4}\left[\dot{x}_t^j - \omega_{x,t}\right] C^j_{rd}\,\hat{p}$$

The equation for the maximum steady roll rate depends on encounter time (t_{enc}), bank angle ($\phi(t_{enc})$) and roll mode time constant (τ), and is:

$$\hat{p} = \frac{\phi(t_{enc})}{t_{enc} - \tau\left(1 - e^{-t_{enc}/\tau}\right)}$$

Reference 3 provides a method for estimating $\hat{p}$ on the basis of the British Civil Airworthiness Requirements (BCAR). An aircraft approaching to land must be capable of rolling through 60° from 30° of bank angle in 7 seconds. Assuming that an aircraft meets this requirement, and using the fact that the roll mode time constant is usually around 1 sec. leads to $\hat{p}$ =0.175 rad/sec.

The equation for the roll damping coefficient depends on the local lift curve slope of the wing (a^j) and the ratio between local wing chord (c^j) and standard mean chord ($\bar{c}^{\,j}$), and is given by:

$$C^j_{rd} = -4\int_0^{1/2} a^j \frac{c^j}{\bar{c}^{\,j}}\left[\frac{y}{b^j}\right]^2 d\left[\frac{y}{b^j}\right] = -4\int_0^{1/2} a^j \frac{c^j}{\bar{c}^{\,j}}\, y'^2 dy'$$

The roll damping coefficient strongly depends on the shape of an aircraft wing, thus reflecting the aircraft design in the developed risk model. To estimate this coefficient, some assumptions must be made regarding the shape of the aircraft wing.

3.4 Integration with TOPAZ methodology

The four probabilistic sub models are integrated into a stochastic framework as described in reference 6. It is based on NLR's Traffic Organizer and Perturbation Analyzer (TOPAZ). The TOPAZ methodology has been developed to provide designers of ATM concepts or procedures with safety feedback following on a re-design cycle. An overview of how such safety feedback is obtained is given in figure 3 (Ref. 8).

During the assessment cycle two types of assessments are sequentially conducted:

1. *Qualitative Assessment (steps 1-3)*
   Information about nominal and non-nominal behavior of the ATM concept or procedure is gathered, through hazard identification sessions with a variety of experts, resulting in a list of potential wake vortex hazards.

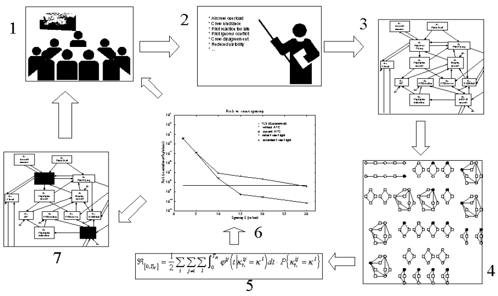

Fig. 3 TOPAZ assessment cycle

2. *Quantitative Assessment (steps 4-7)*
   A stochastic dynamical model representation characterization of the wake vortex induced risk is developed. This led to an effective procedure, consisting of a number of steps to be followed, to determine the incident risk, accident risk, and crash-into-terrain risk.

The results of the quantitative safety assessment are fed back to the designers, who can use the results to redesign or optimize their proposed ATM design if necessary.

4 Evaluation of safe separation distances

This section illustrates the benefits of the probabilistic approach, on the basis of the main outputs of quantitative safety. Assume that an operational scenario has been defined, which characterizes a specific operational procedure for a given type of runway configuration.

For each of the three identified wake vortex induced risk events, a figure will be produced that provides the risk (in terms of one of the selected risk (or safety) measures) as a function of the separation distance between successive aircraft. Figure 4 illustrates this approach for a combination of leader-follower aircraft {i,j} .

An ALARP framework as proposed in section 2 can now be used to determine an appropriate and adequately safe minimum separation distance for this combination of aircraft {i,j}.

In order to do so, the calculated risk curve should be compared with the safety requirements based on the ALARP region. For separation distances corresponding to the tolerable region, Cost-Benefit Analysis (CBA) may be used to demonstrate whether or not further reduction of the separation distance is practicable.

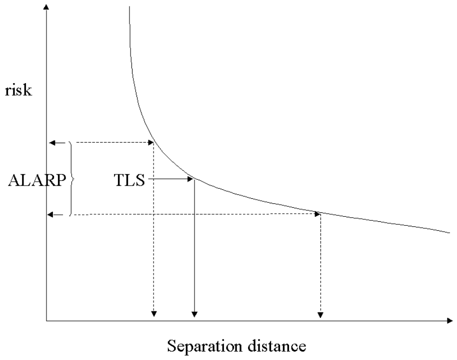

Fig. 4 Wake vortex risk versus separation distance

In order to investigate whether a safe reduction of the current minimum required separation distances might be possible, it is of major importance to identify the safety criticalities, which have the largest contribution to the wake vortex induced risk. Therefore sensitivity analysis should be carried out, especially focused on aircraft design improvements, operational improvements, and weather impact.

Sensitivity analysis focused on aircraft design changes might produce two figures, showing the risk and minimum required separation distance as a function of aircraft design. Based on these figures, it will be possible to identify ‘optimal’ aircraft design changes, provided that these changes are feasible and cost-beneficial. Figure 5 illustrates this approach for a combination of leader-follower aircraft. A similar approach can be followed to evaluate and compare different kinds of possible operational procedures.

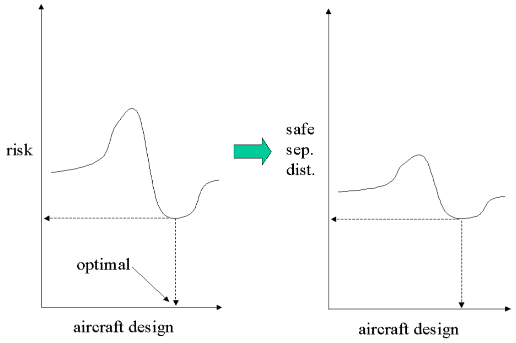

Fig. 5 Impact of aircraft design

Sensitivity analysis focused on weather type might also produce two figures, showing the risk and minimum required separation distance as function of weather type. Based on these figures, it is possible to ‘optimise’ air traffic capacity by authorizing different minimum required separation distances under different types of weather. Figure 6 illustrates this approach for a combination of leader-follower aircraft {i,j}.

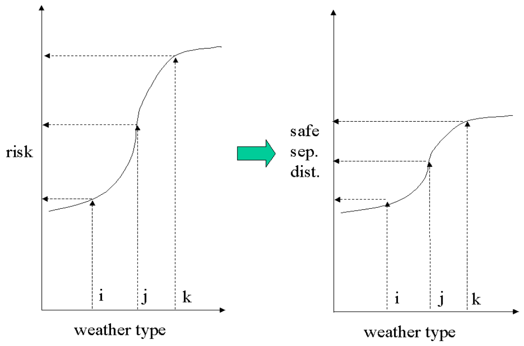

Fig. 6 Impact of weather type

The steady increase in air traffic imposes a need for enhanced airport capacity, and the desire to safely reduce existing separation standards. Therefore new concepts are being developed to reduce the risk imposed by one of the main limiting factors: the wake vortex risk. Examples of such new concepts are:

- Wake Vortex Warning System (WVWS);
- High Approach Landing System (HALS);
- Aircraft Vortex Spacing System (AVOSS).

Such new concepts may provide roughly 2 possible benefits, as illustrated in figure 7:

- Increase the safety level while maintaining current separation standards;
- Increase airport capacity by reducing current separation standards while maintaining the current safety level.

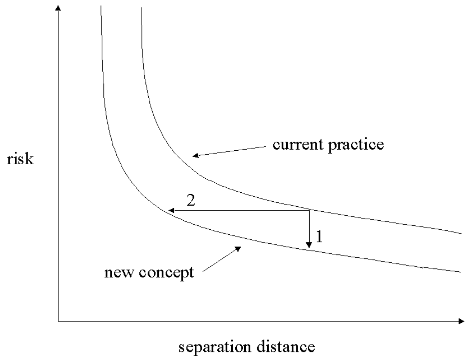

Figure 7 Possible benefits of promising new concepts

5 Conclusions

This paper describes the development of a probabilistic wake vortex safety assessment model. It can be used as a tool to evaluate the separation standards for the current practice, and for promising new concepts which may enable a safe reduction of the current separation standards.

Identified safety criticalities (bottlenecks), which have the largest contribution to the wake vortex induced risk, can be fed back to the ATM designers, who can use them to redesign or improve their proposed ATM concept.

A safety management framework, which is based on a combination of the TLS and the ALARP approach, has been proposed. It is based on 3 defined wake vortex induced risk events, i.e. incident risk, accident risk, and crash-into-terrain risk. Three suitable safety measures evolved:

- Risk event probability per movement;
- Risk event probability per year;
- Economic risk per year.

For each of the three risk events TLS ranges have been proposed from which policy makers may adopt a unique TLS. Once the TLS has been set, it is possible to determine the ALARP region extending from 0.02%TLS to 2%TLS.

The developed wake vortex safety assessment model integrates the following sub models:

- *Wake vortex evolution model*
  To determine the stochastic wake vortex motion, decay and strength in time at certain positions relative to the generator aircraft;
- *Wake vortex interaction model*
  To determine the stochastic vortex-induced rolling moment on the encountering aircraft;
- *Aircraft control capability model*
  To determine the control capability – in terms of maximum rolling control moment – of the encountering aircraft;
- *Flight path evolution model*
  To describe the stochastic flight path evolution of the involved aircraft.

Mathematical descriptions of the wake vortex related *deterministic* sub models have been given. These models have been adapted, probabilitised, and integrated with NLR’s Traffic Organizer and Perturbation AnalyZer (TOPAZ) methodology (Ref. 8).

The benefits of the developed probabilistic modeling approach have been illustrated on the basis of the main outputs of a quantitative safety assessment.

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