DYNAMIC SEPARATION MINIMA COUPLED WITH WAKE VORTEX PREDICTIONS IN DEPENDENT RUNWAY CONFIGURATIONS

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Abstract

Wake vortices are an issue affecting both capacity and safety of air traffic and therefore need to be dealt with by appropriate measures and procedures. Today, the only means to prevent wake vortex encounters is procedural separation which however is statical and in many cases conservative. The concept of dynamic separations using wake vortex predictions aims at optimising the separation between consecutive aircraft based on the knowledge of the actual position and strength of the wake vortices. A concept for approach procedures has been developed that involves dynamical calculation of minimum safe distance, adaption of follower aircraft speed and the corresponding approach types. The concept, its implemetation and simulation test results will be presented and it will be discussed how it can be applied to contribute to an optimised use of available capacity while maintaining and improving the safety level.

1 Introduction

Wake vortex encounters pose a serious hazard to aircraft following each other in-trail, e. g. during approach and landings, but also during takeoffs and sometimes even during en-route flight phases. If following aircraft encounter this phenomenon the aerodynamic forces and moments induced by the wake vortex can lead to uncontrollable reactions and may lead to catastrophic events.

Therefore in current operations the hazard posed by wake vortices to the following aircraft is mitigated by use of fixed separation minima applied by air traffic controllers. The separation standards are based on the maximum takeoff mass and were established by the ICAO in order to be valid for the worst case conditions (i. e. no wind and calm atmosphere resulting in long vortex life times) [8]. This procedure lacks the ability to reflect the real situation, in which aircraft are often lighter than their certified weight and weather phenomena as wind or atmospheric turbulence occur that can lead to earlier decay. Consequently an adverse effect on airport and air space capacity due to wake vortex separations can be observed at various congested airports.

Therefore wake vortices are regarded as a significant obstacle to air traffic capacity increase. New technologies and procedures are sought for to elude the shortcomings of the current static separations. On the one hand, the mechanisms of wake vortex decay and transport have been investigated very thoroughly and various operational models to predict the position and strength of a wake have been developed and validated. On the other hand, new separation concepts like time-based separation have been proposed.

One obvious and also promising approach is to introduce dynamic separations taking into account the individual conditions of each situation. The dynamic separation concept is envisaged in such major research and implementation projects as SESAR and NEXTGEN and is in line with future concepts including 4D-trajectories and self separation. However, the implementation will require an adapted approach including the (partial) delegation of separation responsibility to the flight crew and the introduction of higher levels of automation of the separation process.

The concept currently investigated by the Institute of Flight Guidance at the Technische Universität Braunschweig aims at the introduction of dynamic separation minima using a wake vortex prediction model. This paper introduces a procedure developed at the institute enabling dynamic separation on the approach to closely spaced runways. This involves flight path propagation in combination with a wake vortex model for prediction of hazardous areas. Thus the separation between aircraft can be optimized allowing a better use of the available capacity while at the same time ensuring wake vortex safety.

After giving an outline of the concept's background including a description of the Ground Based Augmentation System (GBAS) technology and wake vortex behaviour and current operations, the paper will introduce the concept of dynamic separation as designed and implemented in the scope of the presented work. Exemplary simulation results of separation reduction will be presented and discussed followed by conclusions and an outlook on further work.

2 Background

The concept discussed in this paper has been developed based on the following considerations:

- There is a need to optimise the use of wake vortex separations during approach procedures;
- Wake vortex behaviour can be predicted by dedicated models and used to propagate a wake vortex-free flight path for the approaching aircraft;
- Flexible approach and landing guidance can be enabled by GNSS-based systems such as GBAS.

Wake vortex behaviour characteristics and current wake vortex related approach separations and procedures will be presented as well as a selection of innovative concepts proposed for separation reduction on single and closely spaced runways. Main principles of GBAS technology will be introduced along with the possible use of GBAS-based operations for implementation of flexible wake vortex separations.

2.1 Wake Vortex Behaviour and Procedures

The rotating masses of air shed behind any lift-generating object are referred to as its wake vortices which are generated due to the pressure and velocity differences between upper and lower surface of the wing and the resulting circulation around the wingtips and behind the trailing edge. A vortex layer that is produced in the near-field of the wing gradually rolls up until a pair of counterrotating major wake vortices develops in the far-field (see Fig. 1). Due to different interaction mechanisms between the wake vortex and the ambient atmosphere (causing friction and energy dissipation) the wake vortex ages and decays until its circulation cannot be distinguished from the ambient turbulence. The lateral and vertical transport of the wake vortex is subject to different influences such as wind, ground effects and atmospheric buoyance as well as its own induced downward velocity which is responsible for the wake vortex descent.

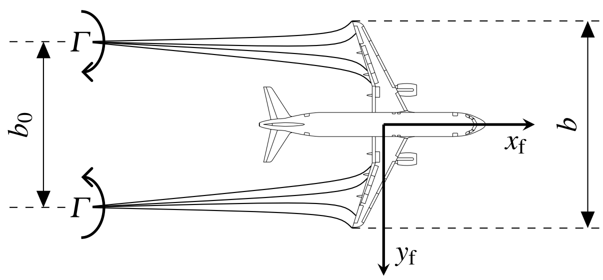

Fig. 1 Wake vortex formation behind an airborne aircraft

The velocity distribution within a wake vortex as well as the forces and moments induced on a succeeding aircraft encountering the wake are represented in Fig. 2. The hazard associated with wake vortex encounters is due to the movements induced by the up- or down-drafts of the wake vortex which in the worst case result in uncontrollable rolling and sinking of the encountering aircraft. This is especially dangerous when the control authority of the aircraft is exceeded, it is in the vicinity of ground and the encounter is unexpected.

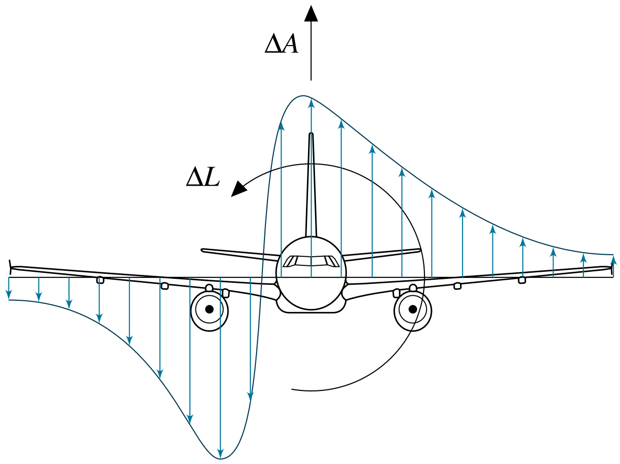

Fig. 2 Velocity distribution within a wake vortex and induced forces and momentson an encountering aircraft

To avoid such dangerous wake encounters it is necessary to establish sufficient spacing between aircraft in-trail which is ensured by the recommended ICAO separations for take-off and landing [8]. These separations are widely applied in instrument meteorological conditions (although national variations exist) however they are omitted whenever possible if operating in visual meteorological conditions due to capacity considerations. They are defined to provide safe operations in all conditions and thus are conservative not allowing to use the potential capacity. They do not take into account the actual wake vortex decay and transport (e. g. due to wind). A change of procedures that might be introduced by new concepts would aim at increasing the capacity but at the same time maintaining at least the same safety level achieved today.

The wake vortex separations and associated procedures applied today pose particular capacity contraints for operations on single as well as on dependent runways (so-called closely spaced parallel runways, CSPR). Hence several concepts have been and currently are developed to mitigate this impacts and to optimize the runway use. Among them are wind dependent concepts such as CREDOS[1], CROPS[2] and finally the current developement of Flexible and Dynamic Use of Wake Vortex Separations in the scope of SESAR WP 6.8.1 [2,3,10]. But also concepts involving flexible approach paths by use of displaced thresholds and variable glide path angles were investigated (e. g. the High Approach Landing System/Displaced Threshold Operation (HALS/DTOP) in Frankfurt [4]).

2.2 GBAS technology and approaches

GBAS is a system based on satellite navigation that is designed to provide precise lateral and vertical guidance for approach and landing. Its function and in particular the definition of approaches and its operational possibilities will be introduced here.

The main functions of the GBAS ground station are to monitor and correct satellite navigation information (including the provision of integrity information) and to provide defined approach guidance to enable precision landings. Compared to the well known Instrument Landing System (ILS), GBAS offers several advantages, e. g. one single station can provide approach guidance for several different approach paths for the same and also for multiple runways. For example, this enables to offer two approaches for the same runway end with a different glide path angle where the higher approach path can be used by the follower aircraft to avoid the wakes of its predecessor. This is possible because GBAS approach paths are defined via geometric points that are transmitted in the approach guidance message (Message Type 4)

[1]Crosswind – Reduced Separations for Departure Operations

[2]Crosswind operations

and the glide path is calculated on-board the approaching aircraft. Similar to conventional standard approaches also the GBAS approach is subdivided into segments: the Final Approach Segment (FAS) and the description of the approach procedure to follow between the initial approach fix and the final approach that it composed of several segment types [5, 9]. The FAS contains the description of the final approach segment and is defined as a straight approach with a fixed glide path angle. The pilot only needs to select the channel number of the desired approach path to receive the ILS look-a-like approach guidance on the standard cockpit instrumentation. Moreover, the aircraft position on the approach and glide path is always available on-board with a high precision and reliability and can be used to determine the real distance from other aircraft as well as from potentially dangerous wake vortices.

GBAS is thus well suited as an enabling technology to support the implementation of optimised approach separations and the concept presented here.

3 Concept and implementaion

The following section explains what can be done to overcome the problems of static wake vortex separation minima. It introduces the concept as well as the models and the simulation tool used for testing the concept and for data capturing.

3.1 Concept of dynamic separation

The described concept is based on the knowledge that a safe minimum separation can not generally be defined for all cases. Therefore the state-of-the-art strategy has been to take worst case scenarios and define minimum separations to cover these. The results for wake vortex safety are the well-known wake vortex categories light, medium and heavy.

To avoid these two problems of the current practice this paper describes another approach. It proposes a method that dynamically calculates a minimal distance for an aircraft pair ensuring safe operations. The following aircraft then tries to achieve the optimal position behind the leader. This is done by a small variation of the approach speed that causes the follower either to catch up or to enlarge the spacing whichever is necessary.

3.2 Wake vortex model

To reduce the currently used standard of wake vortex separation, it is necessary to use the knowledge about the behaviour of wake vortices. Therefore a simplified wake vortex model was derived from descriptions of HOLFORTY et. al. [6, 7] to calculate the danger areas behind the leading aircraft. It consists of a vortex pair, whereas each vortex has its initial vortex center position $\mathbf{c}_0$ at a given distance relative to the aircraft axis. The distance between both vortex centers was assumed as

$$b_0 = 0.755b \tag{1}$$

along the wing axis.

The danger area around these vortex centers was defined as a sphere with the radius

$$r_0 = b \tag{2}$$

to include all potentially hazardous wake areas. Because of uncertainties it is necessary to enlarge the danger area with time. The radius at a later time can be desribed by

$$r(t) = r_0 + 7.9\,\mathrm{m/s} \cdot (t - t_0) \tag{3}$$

which accounts for position accuracy and initial assumptions.

Due to the induced forces between the vortex pair, it also tends to drift downwards. This movement mainly depends on the vortex strength which is a function of aircraft lift and the downward velocity w was defined by

$$w = -\frac{mg}{2\pi\rho V_\infty b_0^2}, \tag{4}$$

down to a level

$$-w\,(t - t_0) = 6b, \tag{5}$$

where the vortices stay until they are considered harmless after

$$t = 130\,\mathrm{s}. \tag{6}$$

During this time it is assumed that they are moving with the ambient wind, which is combined with the downward movement to

$$\mathbf{c}(t) = \mathbf{c}_0 + \left(\begin{bmatrix} 0 \\ 0 \\ w_\mathrm{w} \end{bmatrix} + \mathbf{v} \right) \cdot (t - t_0) \qquad (7)$$

The whole volumes included in the spheres defined for each time step are considered as dangerous for following aircraft.

3.3 Implemented reference aircraft

For the evaluation of the concept the Airbus A320 was selected as a reference aircraft. This type of aircraft has a *managed speed mode* in which the flight management computer calculates the optimum speed. This speed is based upon weight, flap setting and wind speed and is automatically adopted. [1] Fig. 3 shows the standard flap changing points and the corresponding speed settings.

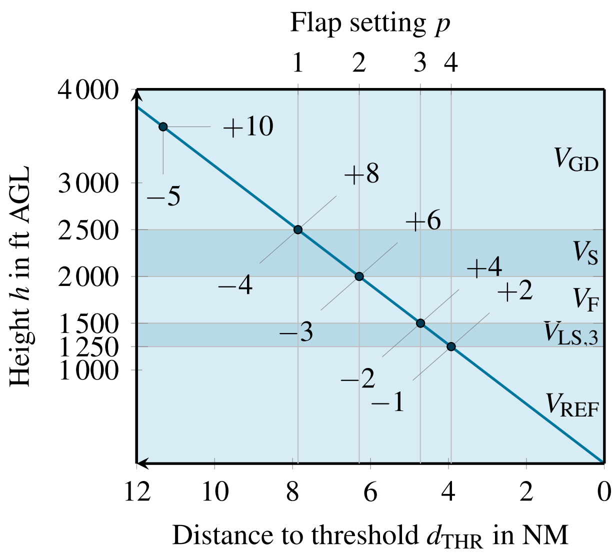

Fig. 3 Approach profile for the reference aircraft

Today this speed is set either by the computer when in automatic flight or is the target speed for pilots in manual approaches. The standard operating procedures are giving pilots a tolerance margin that allows them deviations between −5 to +10 kn. This speed offset could be used to change the separation between two approaching aircraft. For the initial phase of the approach with flaps retracted, the full range is used. Throughout the approach the offset is reduced to reach the target speed at a height of 1 000 feet above the runway. This is the decision point defining whether an approach is stable or not. Fig. 3 illustrates these possible deviations which are reduced with flap setting.

The deviation from reference speed is carried out in four profiles $P\ (-1 - +2)$ where the optimal velocity is calculated

$$V_\mathrm{opt} = V_\mathrm{target} + P \cdot (5 - \mathrm{p})\ \mathrm{kn}. \qquad (8)$$

The wake vortex avoidance strategy now aims to keep the following aircraft out of the danger areas described above. The positions of the wake vortices are calculated during a simulation run as well as the aircraft's behaviour. The speed profile is now optimized in a way that the follower's position behind the leader is chosen to be directly behind the avoidance sector. If there are no wake hits predicted within the prediction horizon the follower speeds up to reduce the separation. In cases where the separation either in the future or in the present is not considered safe, it enlarges the spacing by reducing the followers speed.

3.4 Approach types

To measure the impact of the introduced concept several approaches where defined. As the focus of interest of this study were dependent runway operations, Frankfurt with its 2010 runway layout was chosen. This configuration consists of two parallel runways that are separated around 500 m. The thresholds are displaced by about 200 m. Both runways are equipped with ILS in a standard configuration with a glide path angle of 3°.

One aspect of the analysis was the use of GBAS to define approaches that might be better suited for dynamic wake vortex separation operations. The following definitions therefore make use of the GBAS principle to define multiple approaches at the same time for the same runway.

ILS look-a-like

In this configuration today's ILS system was copied without modifications. The FAS for runways 25L and 25R where defined with an angle of 3° and the aiming point for landing was the actual threshold.

Displaced threshold 25L

As in the ILS look-a-like scenario, runway 25R remained unchanged with a FAS in ILS configuration. But to increase the vertical distance between the approach paths the threshold of runway 25L was moved by 1 000 m. This shortens runway 25L to 3 000 m usable length which is still enough for landings of most aircraft types. The approach angle remained unchanged at 3°.

Varied approach angle 25L

The last configuration was a variation of the displaced threshold case. To further increase the vertical spacing of aircraft on the approach paths the glide path angle on runway 25L was adjusted to 4°. The threshold remained unchanged 1 000 m behind the actual one.

3.5 Simulation tool

A simulation tool was developed to investigate the influence of the defined approaches together with the reference aircraft and the wake vortex model. The application (implemented in C++) is capable of calculating the aircraft position, the resulting wake vortices as well as their future evolution. It then determines the optimum speed for the following aircraft to ensure a separation that enables safe operations with minimum spacing.

The results of the simulation can be observed during calculation in a vertical and horizontal situation display for visual debugging. The data is stored in the filesystem for later analysis.

4 Results

To examine the benefits of the introduced concept all cases were simulated with an aircraft pair starting at the end of initial approach. The separation between the aircraft is shown versus the leader's distance to threshold to demonstrate the impact of the procedure. Fig. 4 illustrates how these distances are defined.

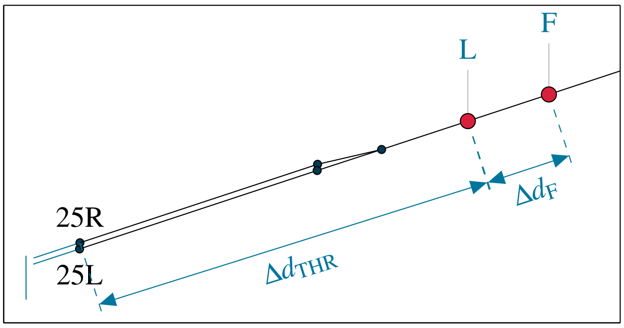

Fig. 4 Parameter definition

In all cases a reference approach was simulated. During this approach neither the follower nor the leader deviated their approach speeds from the preplanned profile. These refernce approaches were conducted to show how the separation changes during normal approaches while the minimum ICAO separation is kept until the threshold.

4.1 In-trail approach 25R/25R

The first result depicts the situation when two aircraft are approaching the same runway directly behind each other. The minimum separation in terms of radar separation is 3 NM for the assumed wake vortex categories (medium/medium) this still applies.

The diagram can be found in Fig. 5. It shows the static reference case where the follower keeps the minimum separation of 3 NM until the threshold. The dynamic simulations are starting with the same initial distance, but the follower has the ability to change its speed. Its depicted that the following aircraft speeds up to reduce the distance because it detected no wake vortex areas on the flight path. Thereafter the initial spacing between the aircraft was reduced in steps of 5 s, that corresponds to a distance of about 550 m.

With initial spacings of more than 74 s the separation is significantly reduced. The optimum

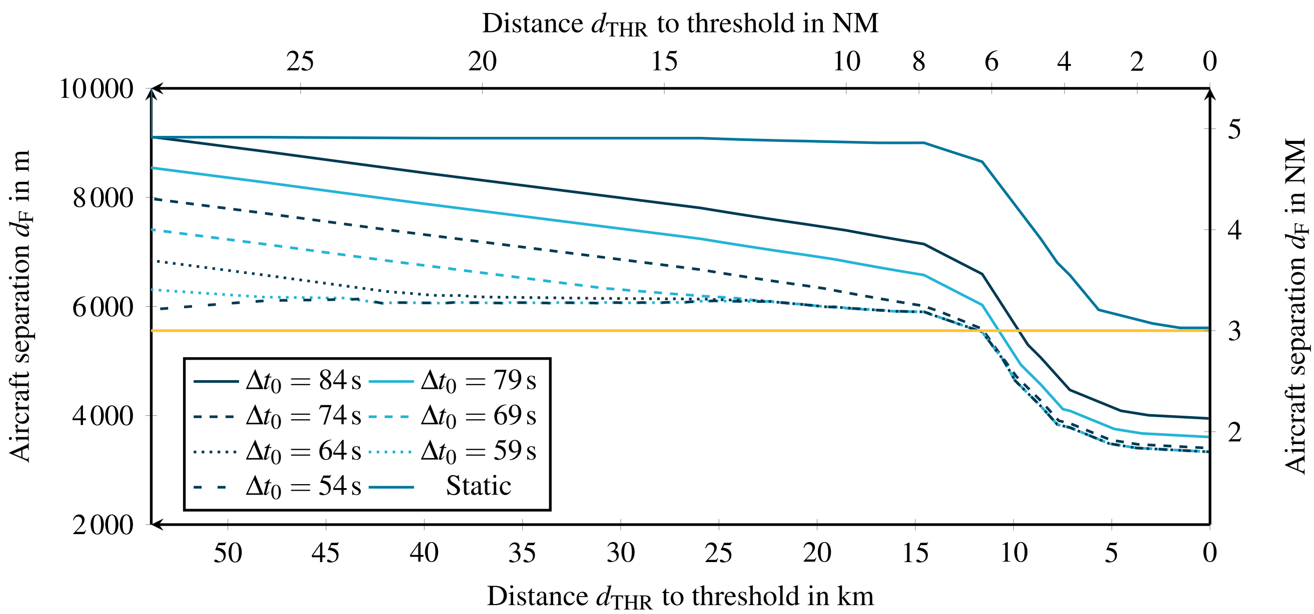

Fig. 5 Results 25R/25R

position is then reached with inital separations of 74 s or less. This can be seen because the curves are converging meaning that the algorithm found a position so near behind the leader that each further reduction would lead to entering the danger area. In the last case with an initial spacing of 54 s it can also be observed that the procedure can not only reduce the separation but is capable to increase the distance if necessary for safety reasons. That behaviour occurs in the first part of the appoach where the distance is already close to the 3 NM radar separation minimum.

Compared to the reference case where the ICAO minimum of 3 NM separation was maintained, the dynamic separation reduces to about 2 NM without entering the previously defined danger area. Compared to the reference case where the ICAO minimum of 3 NM separation was maintained, the dynamic separation reduces to about 2 NM without entering the previously defined danger area. Because the radar separation is maintained for the initial approach, it is still possible for air traffic control to guide the pilots on initial approach, before the system comes active.

4.2 Staggered approach 25R/25L

The second result demonstrated in this paper was derived from a staggered approach, where the leader approached runway 25R and the follower 25L with the ILS-like approach. The setup starts with a static reference case again whereas this time the definition of the minimum separation is different. The wake vortex separation minima is again 3 NM but this time the radar separation is dependent on distance to threshold. Until 20 NM to touchdown the separation is 3 NM. Afterwards it is reduced to 2.5 NM until 4 NM final and further to 2 NM for the remaining distance. The data is visualised in Fig. 6.

This time, the convergence can already be seen with the initial separation of 63 s, even if the starting distance is increased the follower catches up to the optimal point. It is depicted that in cases where initial separation is not sufficient the spacing can be enlarged to avoid the danger area. The convergence point is reached earlier compared to the previous cases and the spread in initial separation can be larger therefore the separation precision of air traffic control does not need to be high.

Compared to the legally necessary 2 NM final separation, the system does not have the same

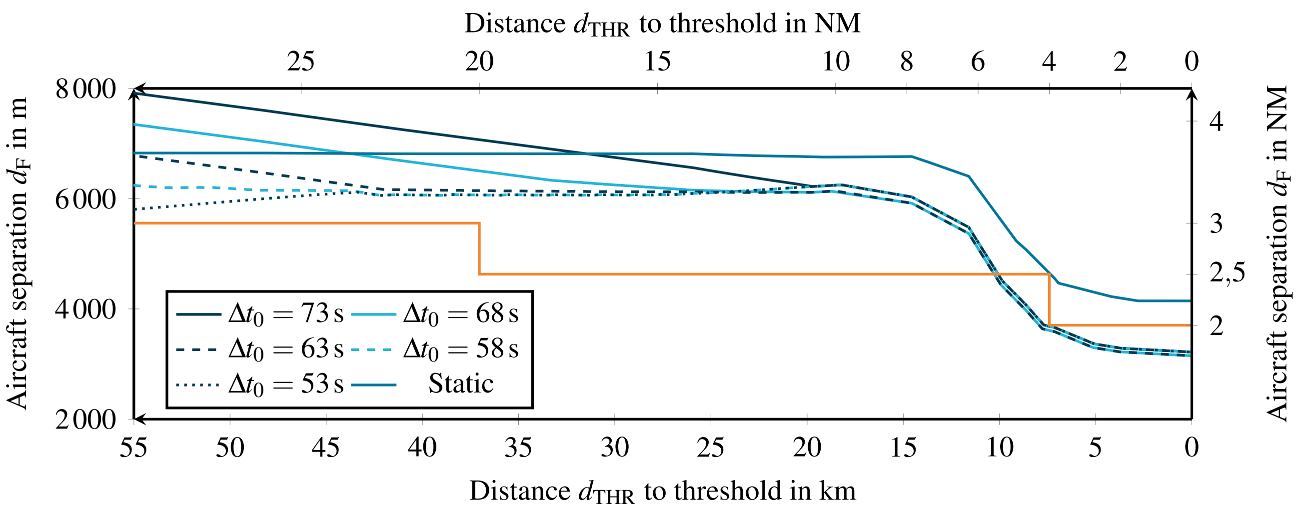

Fig. 6 Results 25R/25L

impact as in the previous case but it can be seen that it is still reduced and can be minimized to around 1.7 NM. While this increases capacity, it still maintains safety and even takes changed environmental conditions into account. That leads to an optimisation where safety and capacity can be increased, depending on the circumstances.

5 Conclusion

The simulation results reveal a significant impact on separation distances if actual data of wake vortex hazard areas are available. It was shown that with such data and a small modification of the approach technique the separation can be optimised. This is not a one way optimisation as in situations where more separation is needed for the safety of the involved aircraft, the separation is as well adjusted to a safe level.

This concept is useful for operations on closely separated runways at airports that have a demand for higher capacities. Although the system worked in the described configuration, there might also be cases in which there is no benefit because today's handling of wake separations already underruns the calculated minimas of such a model. In this cases the safety can be increased by enlarging the separation. Therefore the dynamic separation technique trades off between safety and capacity.

6 Outlook

To confirm the results of this preliminary research, further investigations with more aircraft types and pairings need to be evaluated. The analysis of such investigations is also necessary to find out the impact on longer arrival queues as the presented evaluation only aimed at single pairs of aircraft.

For those cases an interface to other planning tools like arrival managers (AMAN) could be established. These tools can then preplan the order of arriving aircraft to ensure the best possible wake separation sequencing.

One problem in the introduction phase for such a concept is the inhomogenity as not all aircraft will be equipped with a compatible system. This problem should be thouroughly analysed to ensure that the concept still delivers benefits.

Another factor would be the acceptance of pilots of the concept. Flight trials in simulators could answer the question how the workload in the cockpit changes if speed changes are calculated by the computer.

Nevertheless the introduced procedures seem to be promising, there might still be further enhancement by the use of alternative GBAS approaches and similar techniques. One possibility could be the use of curved approaches to further improve wake vortex avoidance. Another idea could be the coupling of 4D trajectory planning within the introduced concept. Then a 4D-FMS would calculate the wake vortex separation to reduce the pilot workload.

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