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Full-flight simulator study for wake vortex hazard area investigation ☆

Full-Flight Simulatorstudie zur Untersuchung von Wirbelschleppen-Gefährdungsräumen

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Abstract

Simplified hazard areas (SHA) can help to overcome the wake vortex problem. Avoiding these zones allows safe and undisturbed flight operations. The definition of the hazard areas is based on the nominal required roll control power. The nominal limit for this value must be chosen carefully to ensure that outside the hazard area all wake vortex effects are noncritical. For the determination of such a limit offline simulations and full flight simulator studies were conducted. For a given roll control limit the hazard area dimensions are established with the "simplified hazard area prediction" method (SHAPe). Parameterization of the input parameters makes this method universally applicable to different aircraft types. SHAPe represents an essential element of the wake vortex prediction and observation system within the DLR project Wirbelschleppe II, for the generation of safe dynamic wake vortex separations.
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Zusammenfassung

Zur Vermeidung unakzeptabler Wirbelschleppeneinflüge werden vereinfachte Gefährdungsräume (SHA – simplified hazard areas) definiert. Bei Nichtverletzung dieser Zonen ist ein sicherer und ungestörter Flugbetrieb möglich. Zur Bestimmung der Gefährdungsräume dient der normierte Rollsteuerbedarf. Hierfür kann ein nominaler Wert so bestimmt werden, dass außerhalb des Gefährdungsraumes sämtliche Auswirkungen der Wirbel unkritisch sind. Zur Ermittlung solcher Grenzwerte wurden offline Simulationen sowie Full-Flight Simulator Versuche durchgeführt. Mit Hilfe der Methode der "simplified hazard area prediction (SHAPe)" werden die vereinfachten Gefährdungsräume bestimmt. Durch die Parametrisierung der Eingangsgrößen ist das Gefährdungsraumkonzept universell auf verschiedene Flugzeugtypen anwendbar. SHAPe stellt ein wesentliches Element des Systems zur Wirbelschleppen-Vorhersage und -Beobachtung im Rahmen des DLR Projekts Wirbelschleppe II dar, zur Erzeugung sicherer dynamischer Wirbelschleppen-Staffelungsabstände.
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Keywords: Wake vortex; Wake vortex encounter; Simplified hazard area; Simplified hazard area prediction; Hazard criteria

Schlüsselwörter: Wirbelschleppe; Wirbelschleppeneinflug; Vereinfachter Gefährdungsraum; Vereinfachte Gefährdungsraumvorhersage; Gefährdungskriterien

1. Introduction

Due to the possible hazard posed by lift-generated wake vortices (Fig. 1) minimum separation distances are mandatory especially for approach and landing [22], which is limiting airport capacity. In order to alleviate capacity restrictions, current separation rules, which are only depending on three aircraft weight classes, have to be modified without reducing safety. This could

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Fig. 1. DLR test aircraft ATTAS with visualised wake vortex.

be achieved for example by accounting for the actual aircraft pairing or atmospheric conditions like the approach presented in this article does (in cooperation with other models for vortex dynamics).

For the investigation of wake vortex encounters dynamic simulation is an appropriate method [3]. But aircraft behavior during wake vortex encounters depends on a great variety of conditions and parameters. Accordingly the evaluation of the corresponding hazard is difficult. To prevent potentially dangerous encounter situations a hazard area can be defined around a wake vortex which has to be avoided. For a simple and universal application of these hazard areas their determination has to be straightforward and is therefore based on conservative simplifying assumptions.

2. Simplified hazard area (SHA)

The commonly accepted position regarding wake vortices is that no planned wake vortex penetration is permitted [21]. The question is what is the meaning of "no wake vortex encounter"? It has to be ensured that flight operations are safe and undisturbed so that the wake vortex effect is not distinguishable from other acceptable atmospheric phenomena. The presented approach for solving this fundamental problem follows the idea that it is possible to define an area around a wake vortex *outside* which the vortex flow is definitely not hazardous to an aircraft.

2.1. Nonhazard approach

The evaluation of the aircraft reaction during a wake vortex flow field penetration is mainly influenced by the following factors:

- Encounter scenario
  - state of the encountering aircraft
  - orientation of flight path and wake vortex
  - relative position of encountering aircraft and wake vortex
  - encounter altitude;
- Aircraft pairing
  - vortex generator (aircraft geometry, vortex strength, core radius, velocity distribution)
  - follower (aircraft geometry and inertia, airspeed, aerodynamics, control power);
- Meteorological conditions
  - wind
  - atmospheric turbulence
  - visual conditions;
- Aircraft control
  - individual pilot behavior
  - performance of automatic controllers.

This underlines the difficulties (especially if a pilot is in the loop) to set up a clear criterion of what is hazardous (in terms of constraints leading unquestionably into an unsafe situation).

Different approaches exist to identify the safety relevant parameters, for example from the seventies [32] and the recent EU project S-Wake [17,18,26]. Considering the context of approach separation minima, safety is not the only requirement. In addition passenger comfort as well as undisturbed operations have to be ensured. The latter means that there must be no go-arounds due to wake vortex encounters.

The distance of an encountering aircraft from a wake vortex is of primary importance. With increasing distance the effect on the aircraft decreases. This spatial character of the phenomenon suggests to form a hazardous space around the wake vortex. As described previously this is not easy to achieve. For this reason and also to account for operational aspects a hazard area shall constitute a region outside of which safe and undisturbed operations are possible [12,34]. This does not necessarily mean that any penetration of that zone results in an unsafe situation (conservative approach). But avoiding that area allows safe and unhindered operations, like in natural gusts and turbulence conditions.

2.2. Definition

For approach and landing parallel-like encounters are typical. Especially in that case the wake vortex induced rolling moment is the dominating effect [3,15]. This is especially the case for the outer regions of the wake vortex, which are relevant for the determination of the hazard area dimensions, since the core region has to be avoided in any case (as long as the vortex is not largely decayed). Therefore the definition of the simplified hazard areas (SHA) is based on the induced rolling moment. The worst case is the quasi stationary flight parallel to the vortex axis where the vortex disturbances are permanently acting on the aircraft. In order to relate the induced rolling moment to the controllability of the encountering aircraft the magnitude of the required aileron deflection ξ_{req} (to compensate for the induced rolling moment[1]) is related to the maximum possible

[1] The relationship between aileron deflection and rolling moment is assumed to be linear.

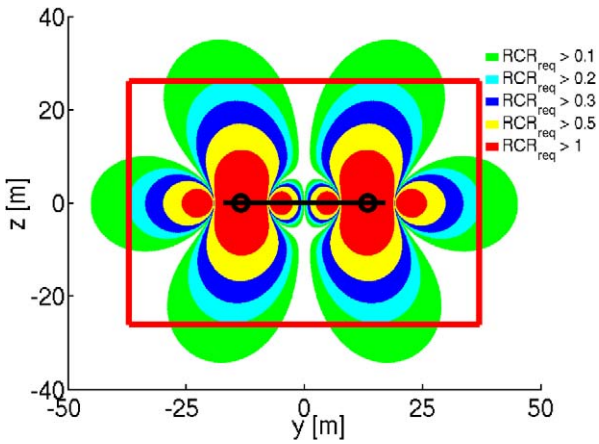

Fig. 2. Wake vortex induced required roll control power and simplified hazard area (SHA, for $\mathrm{RCR}_{\mathrm{nom}} = 20\%$, $t_{\mathrm{age}} = 50$ s, 'light' behind 'medium', no turbulence) in the cross section behind the vortex generating aircraft (with indicated generator wing and vortex cores).

deflection [11]. This way the dimensionless roll control power ξ^*_{req} (also roll control ratio $\mathrm{RCR}_{\mathrm{req}}$) is determined:

$$\xi^*_{\mathrm{req}} = \left|\frac{\xi_{\mathrm{req}}}{\xi_{\mathrm{max}}}\right|. \tag{1}$$

For the determination of this parameter it is assumed that the velocity field of the wake vortex remains unchanged due to the penetrating aircraft, which is feasible as long as only the global forces and moments acting on the aircraft are of interest [35].

By choosing an upper limit for the required aileron deflection (roll control ratio respectively) the hazard area is defined (conservatively) approximated by a rectangle (Fig. 2). This value is called nominal aileron deflection ξ^*_{nom} (nominal RCR respectively), because it is the maximum theoretical value for quasi stationary flight outside the simplified hazard area

$$\xi^*_{\mathrm{req}} \overset{!}{<} \xi^*_{\mathrm{nom}}. \tag{2}$$

If the nominal roll control ratio is sufficiently small, the resulting hazard area covers also the other relevant aspects of aircraft response (aircraft state and flight path deviations) affected by a wake vortex. The suitability of this approach is investigated in Section 3. But first the applied models are introduced briefly.

2.3. Modelling

The essential components for the hazard area determination are the description of the vortex generation and aging, as well as the representation of the wake vortex induced velocity distribution. Another important element is the modelling of the interaction between vortex flow disturbance and encountering aircraft. Largely the same elements are used for hazard area calculation and for the 6 DoF simulation of wake vortex encounters [34].

The initial vortex strength (circulation) according to the Kutta–Joukowsky theorem for an aircraft (leader "L") in level flight with the weight W_{L}, wing span b_{L}, and airspeed V_{L} is

$$\Gamma_0 = \frac{W_{\mathrm{L}}}{\rho V_{\mathrm{L}} b_{\mathrm{L}} \frac{\pi}{4}}, \tag{3}$$

where $\pi/4$ applies for elliptical lift distribution and ρ is the air density. According to measurements from flight tests the initial core radius r_{c0} is identified to be 3.5% of the generator wing span[2] [8,23]

$$r_{c0} = 0.035 b_{\mathrm{L}}. \tag{4}$$

Vortex decay and transport are modelled by the probabilistic two phase model (P2P) depending on the atmospheric conditions [19,20]. The core radius r_c is growing with increasing vortex age. Different simulations revealed that the core diameter has no significant effect on the upset of encountering aircraft [24,33]. Parameter variation showed that simplified hazard zone (SHA) dimensions decrease with increasing core radius for a given circulation. Therefore a constant core radius is used as a conservative approach [34]

$$r_c = r_{c0}. \tag{5}$$

The wake vortex induced velocities are calculated by superimposing two single vortices, using the analytical tangential velocity (V_t) model of Burnham–Hallock [4] (based on Rosenhead [31]), which yields good results for wake vortex encounters [8,23]

$$V_t = \frac{\Gamma_{\mathrm{L}}}{2\pi} \cdot \frac{r}{r_c^2 + r^2}. \tag{6}$$

As a result of vortex ageing the wake vortices break up into wavy vortex filaments and finally vortex rings. These perturbed wake vortex structures impose a reduced aircraft reaction on encountering aircraft compared to straight vortices [24]. Straight wake vortices are therefore used as a conservative approach again.

For the determination of the vortex induced forces and moments acting on the encounter aircraft the strip method is used [6,7]. Using the strip method as aerodynamic interaction model the lift generating surfaces are subdivided into sections for which the vortex influence is determined. This method was deemed feasible in [1], verified against windtunnel tests in [2] and validated with flight test data in [9] and [23]. Thus for the hazard area calculation as well as for the non-linear numerical encounter simulation there are validated models and methods available.

Fig. 2 exemplarily shows the areas of different normalized required aileron deflections (differently shaded regions) in the cross section of a wake vortex with the indicated wing of the vortex generator and the position of the two vortices. The rectangle represents the simplified hazard area for an $\xi^*_{\mathrm{nom}} = \mathrm{RCR}_{\mathrm{nom}} = 20\%$, taking into account aircraft pairing, vortex age and atmospheric conditions.

3. Simplified hazard area boundaries

The suitability of the quasi stationary required roll control ratio for the assessment of wake vortex encounters is investigated by means of offline simulation, full flight simulation and

[2] Using the vortex velocity distribution model Rosenhead–Burnham–Hallock.

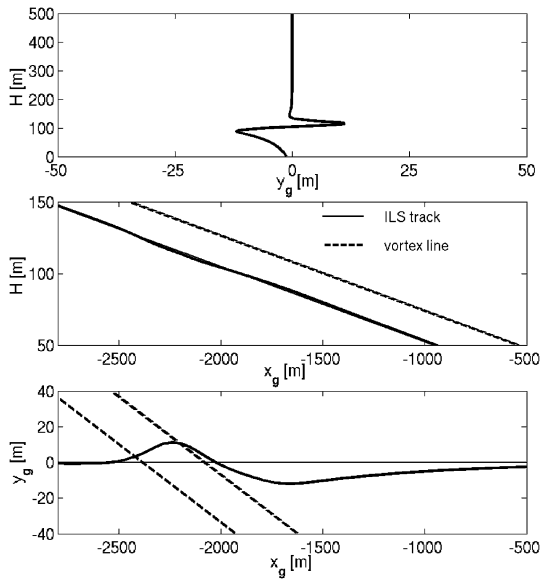

Fig. 3. Flight track of a flight along the lower hazard area boundary: cross-sectional view, side view and top view (offline simulation with regular autopilot/auto-throttle system, $RCR_{nom} = 30\%$).

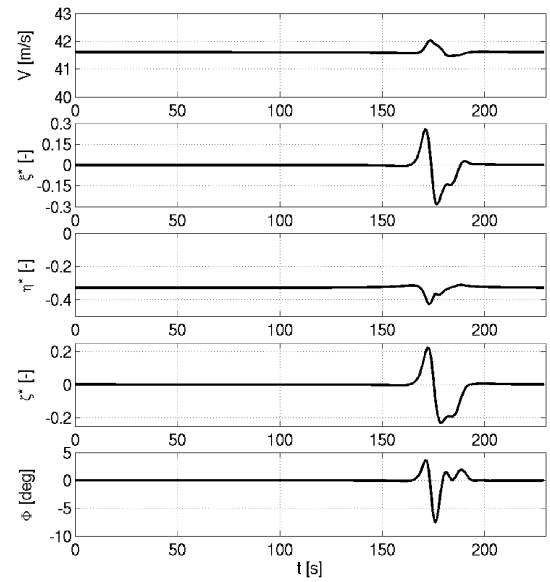

Fig. 4. Parameters of a flight along the lower hazard area boundary (offline simulation with regular autopilot/auto-throttle system, $RCR_{nom} = 30\%$).

in-flight simulation. It is the goal to establish a roll control limit to ensure safe and undisturbed flight operations.

3.1. Offline simulation

For offline simulation the respective models mentioned in Section 2.3 are integrated into a 6 DoF simulation [11,34]. For the investigation of the hazard areas and their limits flights are performed with the nominal trajectories along the hazard area boundaries. In order to maintain the required flight path a regular autopilot/auto-throttle system [11] (based on a model following controller concept) is applied, which results in only minor flight path deviations for the investigated scenarios.

Fig. 3 shows an example flight path for passing along the lower hazard area boundary (category 'light' behind 'medium', wake vortex age $t = 50$ s). The side view and the top view only show the relevant part of the wake vortex encounter. The flight path as well as the wake vortex is inclined ($\gamma = 3°$) to represent an approach situation. The horizontal intercept angle of the flight track relative to the wake vortex is $\Delta\psi = 5°$. This can be the case for crosswind situations, where the wake vortex is transported laterally. Small encounter angles lead to longer encounter durations and constitute the more critical cases, because the wake vortex disturbance is acting for a longer time.

The nominal required roll control power of $RCR_{nom} = 30\%$ is reached during the example encounter, but not exceeded (Fig. 4). The corresponding normalised elevator and rudder deflections are even smaller than the aileron control inputs. Thus sufficient control power remains for all three control axes. The bank angle response stays well within acceptable limits (compare Table 1).

The results of the offline simulations with autopilot generally suggest that the concept of simplified hazard areas is appropriate for wake vortex hazard avoidance. Furthermore a nominal roll control ratio of $RCR_{nom} = 30\%$ seems to be adequate to prevent hazardous situations for automatically controlled flights [14].

Table 1
Limits for acceptable conditions

Parameter	Acceptable limits
Glide slope deviation	-0.5 DOT $\leqslant \Delta$GS $\leqslant 1$ DOT
Localizer deviation	ΔLOC $\leqslant \pm 1$ DOT
Bank angle deviation	$\Delta\Phi \leqslant \pm 20°$
Indicated airspeed dev.	-5 kt $\leqslant \Delta$VIAS $\leqslant 15$ kt
Descent speed	$dz_g/dt \leqslant 1000$ ft/min
Roll rate deviation	$\Delta p \leqslant \pm 15°/s$
Load factor	$0.6 \leqslant n_z \leqslant 1.6$

3.2. Full flight simulation

Manually controlled wake vortex encounters in a full flight simulator providing an authentic environment with realistic acceleration impressions to the pilot permit a subjective pilot evaluation in addition to the objective data analysis. A simulator campaign was conducted at the "Centre of Flight Simulation Berlin" (ZFB) in cooperation with the TU Berlin. The simulated aircraft was a twin engine turboprop commuter aircraft (ICAO class 'light'). However the simulator cockpit was an Airbus A330/340 cockpit. Especially because of the side stick there was a greater control sensitivity compared to a conventional control column and wheel. According to the pilots the real aircraft is easier to handle so that under normal conditions the results would be rather better and the campaign can be considered being conservative.

The experiment scenario begins 6 nm before runway threshold and consists of an ILS approach and the landing (Fig. 5). Turbulence is varied within the range of weak turbulence and visual conditions are either VMC or IMC. The combinations of the following parameters define the different encounter scenarios:

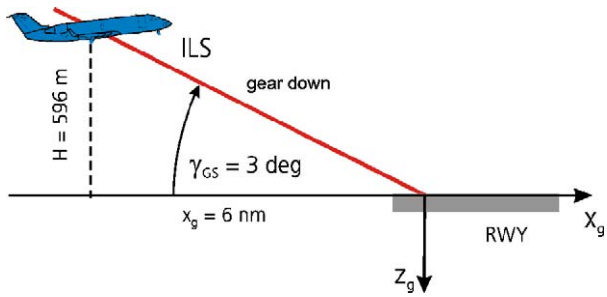

Fig. 5. Approach scenario (side view).

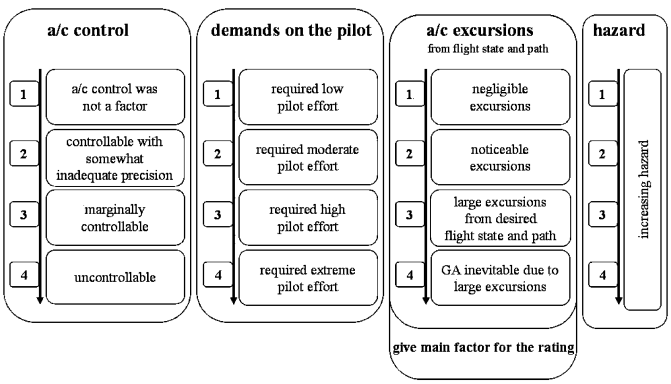

Fig. 6. Pilot rating scales [13,14].

- nominal roll control ratio RCR_{nom} of 20%, 25% and 30%;
- nominal flight trajectories along the upper, lower and the lateral hazard area boundaries;
- horizontal and vertical encounter angles;
- encounter altitude.

The pilot ratings for each approach comprise four categories: aircraft control, demands on the pilot, aircraft excursions from flight state and path and over all hazard. The rating scale is graduated into four levels, with a rating of 1 denoting an uncritical case and a 4 denoting an unacceptable one (Fig. 6). Ratings of 1–3 are considered acceptable.

For the objective assessment of the recorded data (e.g. flight path and state, control inputs) limits are applied, which were derived from several sources [16,25,27,29,32]. These limits are assumed to define whether an encounter is acceptable or not (Table 1). If the flight conditions are not acceptable the pilot has to initiate a go-around. But this does not necessarily mean that the corresponding situation is unsafe since the go-around is a standard flight procedure. Nevertheless, from a view point of undisturbed flight operation a go-around is an unwanted event. It should be remarked that it turned out from the simulator campaign that violations of the defined values for a very limited period were tolerated by the pilots if the overall impression was acceptable.

A total of 82 approaches were carried out by three different pilots, including training and reference flights without wake vortices. An extensive description and analysis of the study is available in [13]. The vortex generating aircraft is in any case a category 'medium' aircraft (MTOW = 94 t) with a vortex age of $t = 50$ s. Fig. 7 shows an example of a flight along

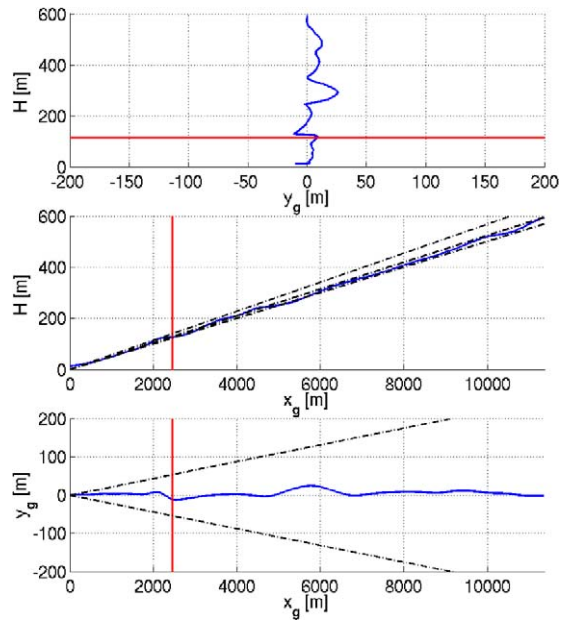

Fig. 7. Flight track of a manually controlled flight along the lower hazard area boundary: cross-sectional view, side view and top view (full flight simulator, $RCR_{nom} = 20\%$).

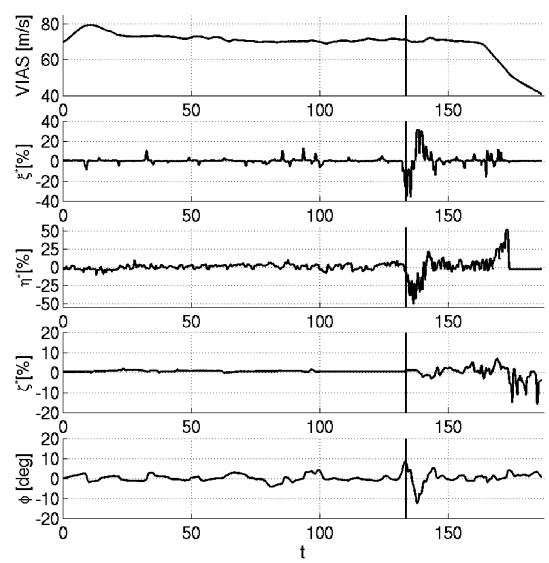

Fig. 8. Parameters of a flight along the lower hazard area boundary (full flight simulator, $RCR_{nom} = 20\%$).

the lower hazard area boundary for $RCR_{nom} = 20\%$. The case is analogue to the example shown in Section 3.1: flight track and the wake vortex have an inclination of $\gamma = 3°$ corresponding to an approach situation. The horizontal encounter angle is $\Delta\psi = 5°$. The encounter (marked by a horizontal/vertical line respectively) takes place at an altitude of $H = 117$ m under IMC conditions. The flight path deviation is comparable to deviations caused by weak turbulence and the absolute value of the maximum bank angle is approximately $|\Phi| = 10°$ (Fig. 8) and well within acceptable limits. The maximum aileron deflection applied by the pilot is approximately $\xi \approx 30\%$. This is more than the nominal value of 20% used to define the hazard area. But first of all the objective parameters are within

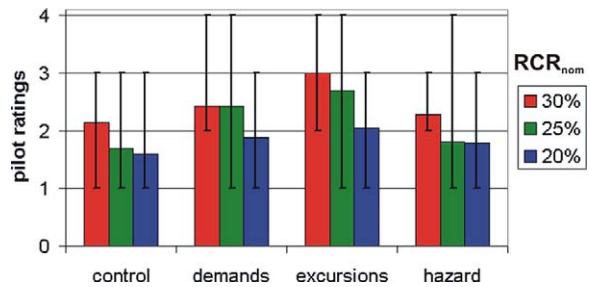

Fig. 9. Pilot ratings for different RCR$_{nom}$.

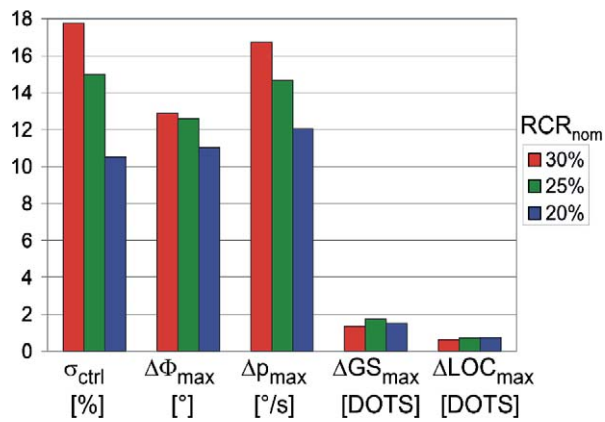

Fig. 10. Simulation parameters for different RCR$_{nom}$.

acceptable boundaries. And secondly the pilot ratings for this approach are 3 for all categories, which is also acceptable. It is important to note that the simplified hazard area does serve its purpose, no matter if the actual roll control ratio actually exceeds the nominal value.

The primary objective of the study is the investigation of the nominal required roll control ratio. Fig. 9 shows the ratings broken down according to the different RCR$_{nom}$ values. The different bars represent the mean values for all approaches and the black lines indicate the maximum and minimum ratings, respectively. There is a clear tendency that the mean ratings decrease with decreasing nominal required RCR. For RCR$_{nom} = 20\%$ there was no rating of 4 at all. In addition to this there was no go-around carried out for these cases. Consequently this means that all flights with the 20% limit were acceptable. The analysis of the recorded parameters also supports this statement. Fig. 10 displays the mean values of some parameters for the different RCR$_{nom}$ categories. For the sum of the standard deviations of the control activities of all three control axes, the maximum bank angle deviation of each flight and the maximum roll rate deviation there is also a clear decreasing tendency with decreasing RCR$_{nom}$. Generally the aircraft response for RCR$_{nom} = 20\%$ is acceptable. So it can be stated that the data basis of this simulator study suggests that this value is an appropriate limit for manually controlled wake vortex encounters in order to avoid hazardous situations, which is the case for the different investigated visual conditions (VMC and IMC) and encounter positions, angles and altitudes.

The analysis of the visual conditions yields higher pilot ratings for instrumental meteorological conditions than for visual

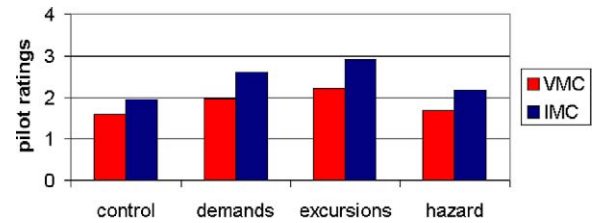

Fig. 11. Pilot ratings for visual conditions.

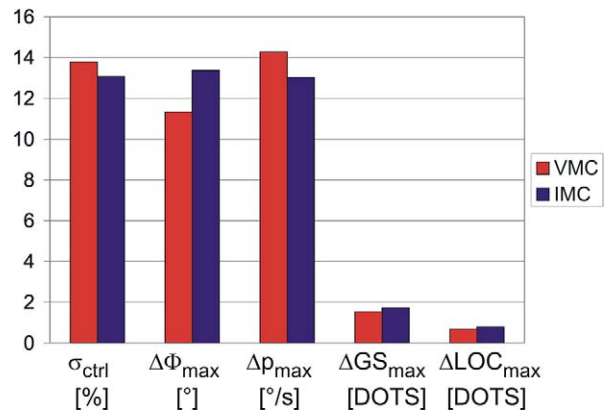

Fig. 12. Simulation parameters for visual conditions.

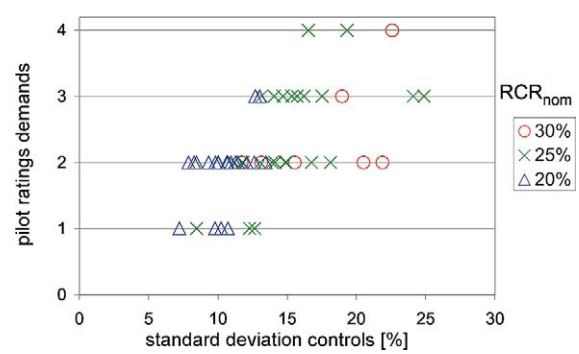

Fig. 13. Pilot demands ratings vs. control activity.

flight (Fig. 11), as one would expect. This is based on all available flights, without regarding the other conditions, like RCR$_{nom}$. For IMC conditions the average of the maximum bank angle deviations of each flight is higher than for VMC, which is also the case for the flight track deviations (Fig. 12). The control activity and the maximum roll rate deviation do not exhibit this tendency.

In order to relate the subjective pilot ratings to the recorded simulation parameters, Fig. 13 shows the pilot ratings for the demands on the pilot plotted versus the standard deviation of the control activities of all three control axes. No matter what the nominal value of the required roll control ratio is, the ratings are clearly corresponding to the control activity. The same relationship can be observed for the ratings for the controllability and the maximum bank angle deviation of each flight (Fig. 14). Such an explicit correlation cannot be observed for all recorded parameters. But the two examples shown here support the significance of the subjective as well as of the objective evaluation criteria.

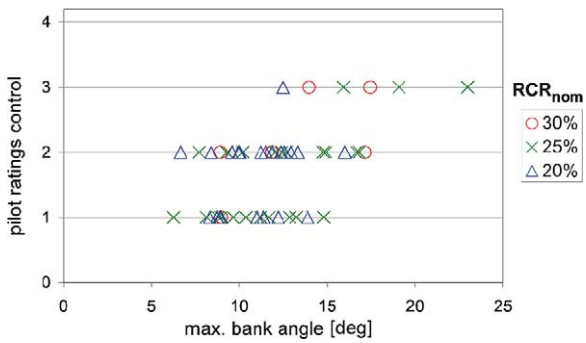

Fig. 14. Pilot control ratings vs. bank angle.

3.3. In-flight simulation

Further validation of the hazard area limits is done with in-flight simulations. The experiments in real flight provide the most realistic simulation environment. The DLR fly-by-wire test aircraft ATTAS (Advanced Technologies Testing Aircraft System, Fig. 1) is particularly designed for this task. During the in-flight simulation the computers onboard the real test aircraft run a non-linear 6 DoF simulation of a model aircraft encountering a wake vortex. The simulated model aircraft response is feed into a model following controller which calculates the necessary control inputs for the host aircraft (real test aircraft) to make it behave like the simulated one. So the real aircraft is flying through a simulated wake vortex and acts like the simulated aircraft, which encounters the vortex. The feasibility of wake vortex in-flight simulations was already demonstrated [30]. A good simulation fidelity is achieved for an $RCR_{nom} < 50\%$. Within the DLR wake vortex project Wirbelschleppe II, there are additional in-flight simulations underway, with the goal to investigate the hazard area limits introduced above.

4. Hazard area prediction concept

The determination of the simplified hazard areas requires a number of input parameters and aircraft data, mainly for the encountering aircraft. In order to allow a broad applicability independent of available specific aircraft data, a "Simplified Hazard Area Prediction" (SHAPe) can be applied with various levels of abstraction [12,14,34]. For the highest level of abstraction the parameterization of aircraft data is related to only one quantity, the maximum take-off weight (MTOW). Based on a database of existing aircraft a functional relationship is established between the relevant aircraft parameters and the MTOW. This way the required input parameters for the hazard area calculation can be determined. Because of the statistical uncertainty a worst case approach has to be applied. For example a low airspeed of the encounter aircraft results in a stronger aircraft reaction because the wake vortex induced angles of attack are higher. So the lowest airspeed for a certain aircraft category within the database represents the respective worst case. This way the hazard area calculation can be executed for any (generic) conventional transport aircraft.

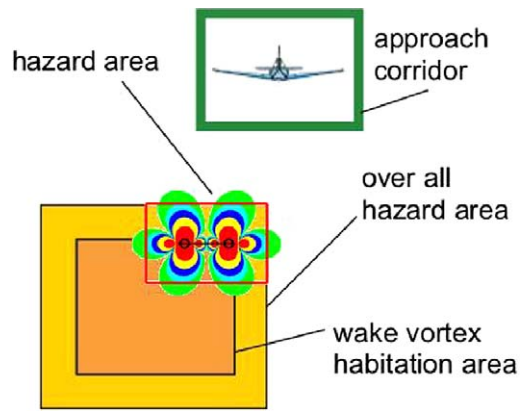

Fig. 15. Approach corridor and hazard areas.

5. Dynamic separation distances

Dynamic wake vortex separation minima are generally depending on vortex decay and transport. Both aspects are considered to have the potential to reduce existing separation minima while retaining at least the same level of safety [3,5,20]. Implementing this is the goal of the wake vortex prediction and monitoring system within the DLR project Wirbelschleppe II [10].

For the ILS approach the approach corridor can be determined (conservatively approximated by a rectangle), which covers the positions of the approaching aircraft with a certain likelihood [28] (Fig. 15). The wake vortex evolution model P2P mentioned in Section 2.3 yields the actual vortex strength for both vortices and their probable habitation area. For the worst case at least one vortex is exactly on the border of that area. For this case the simplified hazard area is superimposed with the wake vortex habitation area which yields the overall hazard area. In general this area departs from the approach corridor due to the wake vortex motion (vortex decent and wind drift). If this overall hazard area after a certain period of time Δt does not overlap anymore the approach corridor, a save approach is possible for the next aircraft. This way the minimum separation time is derived for a specific position along the approach path. The procedure can be repeated for different windows along the approach corridor, to obtain a minimum separation for the entire approach. This method accounts for the atmospheric conditions and can be executed for any combination of aircraft classes (e.g. "medium" behind "heavy"). The weather dependent application allows for dynamic separation minima. Additional capacity gains could be achieved by introducing more aircraft classes.

6. Conclusion

With the application of simplified hazard areas unacceptable wake vortex encounters can be avoided. The presented method is based on the principle, that outside of a defined area around a wake vortex aircraft can be assumed to fly safely and operation is undisturbed.

It becomes apparent that the normalized quasi stationary required roll control power is a measure for the determination of simplified hazard areas, while covering not only the rolling motion but also the other wake vortex induced effects. Using

offline and full flight simulations the following limits for the determination of the hazard area size were obtained: for automatic control $RCR_{nom} = 30\%$ and for manual control (based on the limited data base of the presented full-flight simulator study) $RCR_{nom} = 20\%$. The latter one is supposed to be validated using in-flight simulations on the DLR testing aircraft ATTAS within the DLR wake vortex project Wirbelschleppe II. For a sustainable validation of the manual control limit a larger number of pilot-in-the-loop simulations is essential.

The simplified hazard areas are determined by means of the "Simplified Hazard Area Prediction" method (SHAPe), where the aircraft data are parameterized with respect to the maximum take-off weight. This way the hazard area concept is universally applicable to any conventional aircraft type. SHAPe represents a major element of the wake vortex prediction and monitoring system that is being developed within the DLR project Wirbelschleppe II, in order to safely reduce wake vortex related separation minima.

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