

Safe Limits for Wake Vortex Penetration

Klaus-Uwe Hahn* and Carsten W. Schwarz†

German Aerospace Center DLR, Institute of Flight Systems, Aircraft Department, Braunschweig, Germany

The strength of the vortices increases with the weight of the vortex generating aircraft. Therefore, weight dependent separation distances have been established to avoid dangerous wake vortex encounters. To solve the future capacity problems at airports these proven separation distances have to be investigated carefully with the aim to discover possible margins. This demand forms the need for more flexible separation procedures taking into account the actual weather situation and the parameters of the individual aircraft pairing. In any case the separation distance of approaching aircraft has to be determined in such a way that the approach corridor is free of hazardous vortex flows for the trailing aircraft. The question to be answered is what is the meaning of “hazard free”, respectively how close is an aircraft allowed to approach a vortex without adversely affecting undisturbed flight operation? The determination of a reliable threshold is only possible with pilot-in-the-loop investigations. This paper presents the results of flight simulator studies and in-flight simulations using real flight test aircraft. Based on the required normalized roll control power tolerable and safe situations can be distinguished from unacceptable encounters and a threshold value can be established. The tolerable threshold value can be increased if the pilots control task is supported by an automatic controller.

Nomenclature

b	= wing span	V	= airspeed
H	= altitude, HEAVY AC	W	= weight
L	= rolling moment, LIGHT AC	γ	= flight path angle
m	= mass	Γ	= circulation
M	= MEDIUM AC	ε	= ILS inclination angle
p	= roll rate	ρ	= density of air
r	= radial coordinate	ξ	= roll control input
t	= time	*	denotes normalized quantity

subscripts

0	= initial value	min	= minimum
age	= vortex age	nom	= nominal
max	= maximum	req	= required

abbreviations

AC	aircraft	NOWVIV	nowcasting wake vortex impact variables
AIM	aerodynamic interaction model	D2P	deterministic two phase model
ATTAS	Advanced Technologies Testing AC System	MTOW	maximum take off weight
BFU	Bundesstelle für Flugunfalluntersuchung	P2P	probabilistic two phase model
DoF	degrees of freedom	RCR	roll control ratio
cg	center of gravity	SHA	simplified hazard area
DLR	German Aerospace Center (<i>Deutsches Zentrum für Luft- und Raumfahrt</i>)	SHApe	simplified hazard area prediction
ICAO	International Civil Aviation Organization	TU	Technical University
ILS	instrument landing system	VMC	visual meteorological conditions
		WSVBS	Wake Vortex Prediction and Monitoring System (German abbreviation)

*Corresponding author, research scientist, DLR Institute of Flight Systems, Aircraft Department, Lilienthalplatz 7, 38108 Braunschweig, Germany, k-u.hahn@dlr.de, AIAA Member

† Research scientist, DLR Institute of Flight Systems, Aircraft Department

I. Introduction

THE principle of dynamic lift generation is coupled with the generation of two strong rotational flow fields located at the aircraft's wing tips.¹ Fig. 1 illustrates this flow phenomenon at the left wing tip of DLR's flight test aircraft ATTAS (Advanced Technologies Testing Aircraft System) indicated by colored smoke. The strength and dimension of these two counter rotating vortices are aircraft dependent with a predominating impact of aircraft mass and airspeed. The superimposed flow fields of the two vortices form the well known phenomenon of a wake vortex. The lifespan and decay process of this phenomenon is strongly affected by atmospheric conditions, e.g. stability and turbulence. In addition the wake vortex is shifted by the geodetic air mass motion. The high velocities in the wake vortex flow field make it a threat for a following aircraft getting close to it. Such a situation has to be especially expected when aircraft are approaching an airport for landing. Then, all planes have to gather in designated areas and finally on a precisely defined approach path accurately heading to the runway. The closer the aircraft get to the runway the more condensed the traffic will become and the probability to meet a wake vortex will increase. The encounter conditions become worse if a small and light aircraft hits the wake vortex of a big heavy one. A wake vortex is invisible for human eyes which makes an encounter a sudden and unexpected event for the pilot. This can lead into a hazardous situation for the encountering aircraft and the passengers on board. Adverse load variations and a very fast dynamic response hardly to be counteracted by a human pilot have to be expected which at least have to be considered to disturb flight operations.



Figure 1. Vortex Generated at the Left Wing Tip of DLR'S Test Aircraft ATTAS

To avoid unintended encounters separation distances have been established for approach and landing. The current standard separations² can be assumed to be proven by their daily operational application. These proven separation distances are limiting the landing capacity of airports especially during the rush hours. There is a demand to improve these situations of air traffic congestions. Moreover there is the requirement to cope with the forecasted air traffic increase³ of the coming decades. To boost the traffic throughput the currently applied separation distances have to be investigated carefully with the aim to discover possible margins. In any case the separation of approaching aircraft has to guarantee safe and undisturbed flight operation. The commonly accepted position regarding wake vortices is that no wake vortex penetration is permitted.⁴ Consequently aircraft separation has to be determined in such a way that the approach corridor is free of hazardous vortex flows for the trailing aircraft. How can this be achieved with regard to the fact that theoretically the dimension of a wake vortex flow field is infinite? So, the question to be answered is: what is the meaning of "hazard free", respectively how close is an aircraft allowed to approach a vortex without adversely affecting undisturbed flight operation? At the latest when a wake vortex encounter cannot be distinguished from for example normal natural turbulence, the situation can no longer be assumed to be hazardous. The determination of a reliable penetration threshold is only possible with pilot-in-the-loop investigations. This paper presents the results of piloted flight simulator studies and real flight tests using in-flight simulations. Wake vortex encounters were simulated with the goal to investigate the relevant parameters and to establish an acceptable penetration threshold. The presented work was performed in the frame of the DLR *Wirbelschlepp II* project.

II. Modeling the Wake Vortex Encounter

For the investigation of aircraft behavior during wake vortex penetration mathematical models of this phenomenon and its effect on the flight vehicle are needed. The quality of the models is essential for the reliability of the results. Therefore, the models have to be selected carefully with special attention regarding their level of validation. The highest level of validation can be assumed to be the model identification using measured real world data. The models used for the presented study will be briefly introduced in the following.

A. Wake Vortex Model

1. Initial Vortex Strength. For a vortex generating AC (\rightarrow leading AC, index L) the initial vortex strength defined by the circulation for elliptical lift distribution can be calculated according to the equation of KUTTA-JOUKOWSKY¹

$$\Gamma_0 = \frac{W_L}{\rho V_L b_L \frac{\pi}{4}} \quad (1)$$

It can be seen that the circulation depends only on aircraft parameters and on the density of air. The circulation is direct proportional to the aircraft's mass. For the presented study the initial circulation was calculated for a transport type aircraft with a max. landing weight (MLW) of about $W_L \approx 65\text{tons}$ and wing span b_L of about 35m .

The trailing vortices are not exactly located at the wing tips but they are shifted inboard. The term

$$b_0 = b_L \cdot \frac{\pi}{4} \quad (2)$$

of the denominator defines the distance b_0 between the two vortex lines which is smaller than the aircraft's wing span.

2. Vortex Decay. When a vortex is ageing its circulation intensity becomes weaker due to the loss of energy. Several models are available describing this effect.⁵⁻⁸ For this study the vortex decay is modeled using the deterministic two phase model (D2P)¹⁰. The two different phases represented by the model are at first the diffusion phase (slow decay) followed by a rapid decay phase (fast decomposition). The principle is sketched in Fig. 2 showing the effective circulation normalized by the initial circulation versus the dimensionless time coordinate. t^* is calculated from real vortex age versus a characteristic time scale $t^* = t/t_c$. The characteristic time scale is

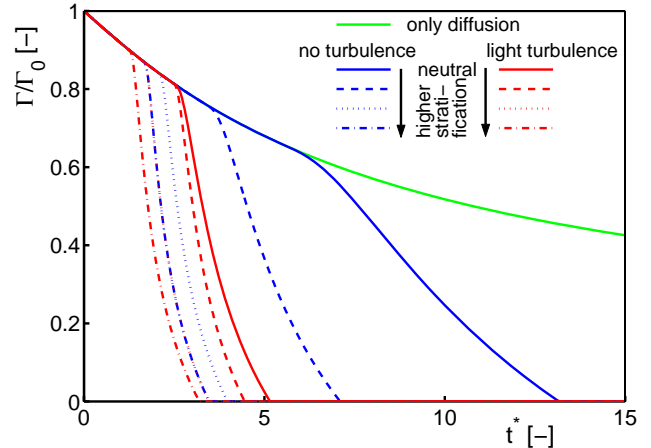


Figure 2. Deterministic Two Phase Vortex Decay model

the time it takes the vortex to sink a distance equal to the distance between the two vortex lines. The model considers actual atmospheric conditions, e.g. stratification and level of turbulence. Due to the complexity of the underlying physics of the vortex phenomenon it is clear that in reality the decay behavior will need an uncertainty margin around the nominal mathematical calculation. This can be modeled by a probabilistic model extension (P2P). Comparisons with real world data demonstrate the correctness of this approach.^{10,11} But this probabilistic model feature was not used for the presented study since each single piloted simulation requested deterministic constraints. The vortex age for the study was defined to be $t_{age} = 50\text{s}$.

3. Vortex Core radius. The size of the vortex core is mainly affecting the peak amplitude of the vortex flow. The smaller the core size the higher the maximum rotational flow speed. Different studies offer different suggestions for the core size. The specified range of the vortex core radius is in between 1% to 5% of the aircraft's wing span. Real flight experiments have been executed within the European S-WAKE project^{12, 22} to performed precise in-situ wake vortex measurements during wake encounters.¹³ From these flight test data an initial core radius of

$$r_{c0} \approx 0.035 \cdot b_L \quad (3)$$

was determined by means of parameter identification.¹⁴ Equation (3) applies for a fully developed but young wing tip vortex. Further more FISCHENBERG^{13,14} shows that the core radius increases with vortex age. This results into decreasing peak amplitudes of the vortex flow. For the presented study the vortex core radius is chosen to be the initial one $r_c = r_{c0}$, which yields the strongest possible flow field.

4. Wake Vortex Flow Field. Various approaches to model are available for the two dimensional rotational flow in the plane perpendicular to the vortex line.¹⁵⁻²⁰ All the models provide calculation rules for a completely developed vortex to transform the circulation Γ_L into a radial dependent velocity distribution. The model identification from flight tests^{13,14} shows that the best fit of a continuous model compared with real flight test data is obtained by the approach of ROSENHEAD¹⁷/BURNHAM-HALLOCK¹⁸

$$V_t = \frac{\Gamma_L}{2 \cdot \pi} \cdot \frac{r}{r_c^2 + r^2} \quad (4)$$

Equation (4) applies for both wing tip vortices (left and right). The distance between the two vortex lines b_0 is defined by Equation (2). For the complete wake vortex flow behind the leading aircraft a pair of counter rotating vortices one for each wing tip are superimposed as sketched in Fig. 3. Looking into the direction of flight the left wing vortex is clockwise rotating. Fig. 4 illustrates the result of this wake vortex model compared with data from in-flight measurement.

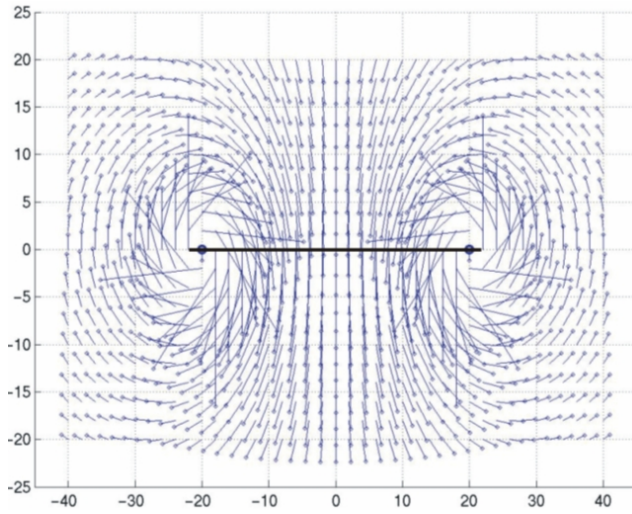


Figure 3. Wake Vortex Flow Field Composed of Two Counter Rotating Vortices

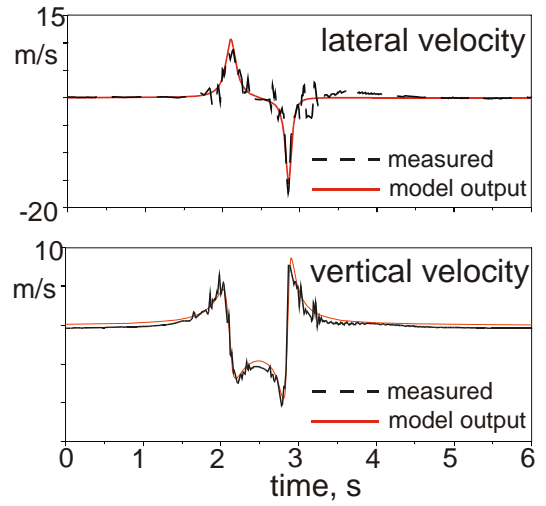


Figure 4. Comparison of Measured Wake Vortex Velocity Field and Model¹⁴

5. Wake Vortex Transport. The wake vortex motion was not a factor in the presented study. In fact the used encounter scenarios were always arranged for a wake vortex hit under precisely predefined conditions. This also includes the encounter geometry which was not wanted to be altered by a wake vortex motion.

B. Aerodynamic Interaction Model

The standard aerodynamic model for non-linear numerical simulation is based on the assumption that the airflow variations occur uniformly over the whole aircraft dimension. This applies only for atmospheric disturbances which are of large scale compared with the aircraft's dimension itself. The scale of velocity variation within the flow field of a wake vortex has to be regarded small compared to the size of aircraft geometry. Thus, the effect of local flow variation along the air force generating surfaces has to be modeled.

To allow further usage of the standard rigid body aerodynamics model the effect of wake vortex flow disturbance was modeled as a superimposed add-on effect. The effect of the wake vortex flow induced supplementary angle of attack was considered using a strip model²¹. This model calculates the forces and moments from the local angle of attack variations due to the vortex flow. These computations are executed at different sections, so called strips, along the wing and along the horizontal stabilizer (see Fig. 5). This so called aerodynamic interaction model (AIM) was also validated by a parameter identification method applied to flight test data^{13,14} coming from real encounter flights²². Already a limited number of strips (each side of wing: 4 strips, HTP: 4 strips, vertical fin: 2 strips) will give good results. Fig. 6 illustrates the comparison of time histories of wake vortex encounter from flight test and from simulation. The results show that the model can be regarded to be a good approach in terms of realistic encounter representation, especially for the vertical and roll axes.

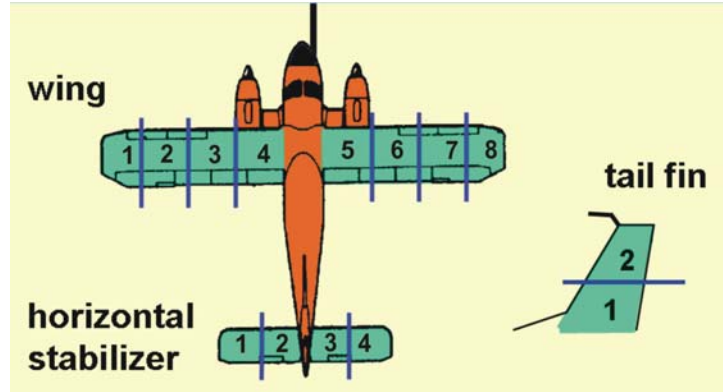


Figure 5. Principle Aerodynamic Interaction Model (AIM) Based on the Strip Method

III.

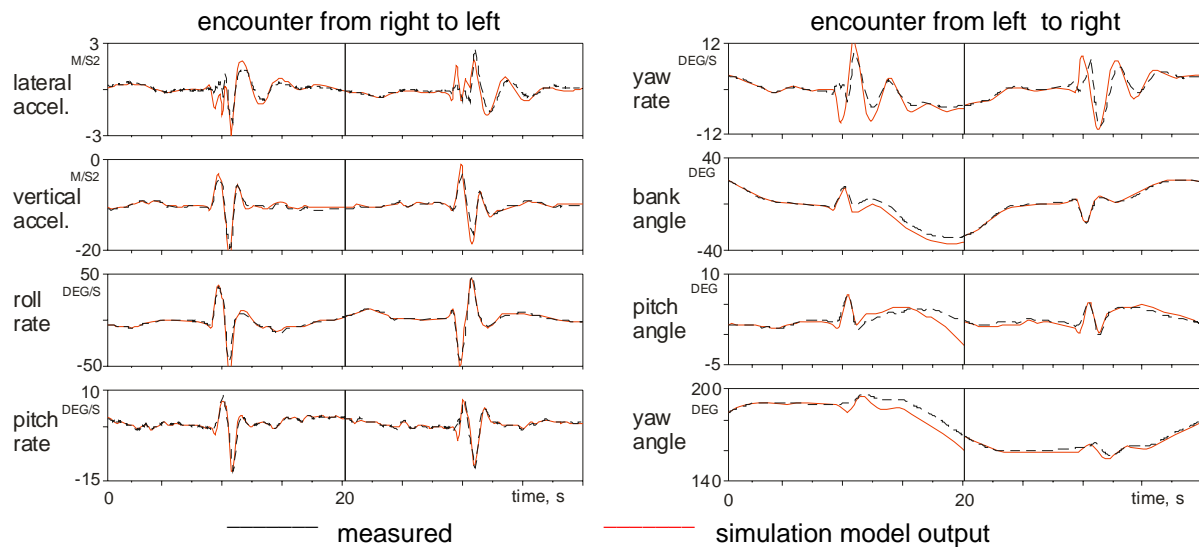


Figure 6. Time Histories of Real World and Simulated Wake Vortex Encounters¹⁴

III. Wake Vortex Encounter Response of Aircraft

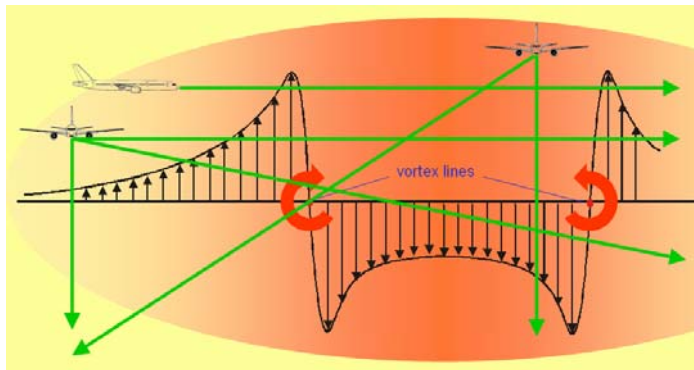


Figure 7. Flight Paths through a Wake Vortex Flow Field

path is essential for the flow disturbances the aircraft is exposed to. But the worst case regarding the aircraft response has been identified to result from wake vortex encounters which are in parallel to the vortex lines.²³ Thus, wake flow penetrations with small encounter angles representing parallel encounters are chosen for the following study. For this encounter situation a very fast roll reaction is the predominating dynamic response of the aircraft²⁴ as illustrated by Fig. 8. For $t = 0s$ the aircraft is approaching from right below the left wing vortex of the vortex generating AC (vortex core indicated by smoke). Regarding the horizon it can be seen that within two seconds the aircraft reaches a bank angle of nearly $\Phi \approx 80^\circ$. Although Fig. 8 was taken from the encounter situation of a small/light aircraft (Do128) penetrating the wake of a medium aircraft (VFW614 ATTAS) the same response applies for encounters of medium behind heavy AC. For example during normal flight operation of medium aircraft (B737 and A320) behind heavy aircraft (e.g. B747) bank angle excursions definitely attributed to wake vortex penetration with max. amplitudes of more than $\Phi > 45^\circ$ according to the pilots were reported by the BFU^{25,26}.



Figure 8. Pilot's Cockpit View during a Wake Vortex Encounter with Fixed Controls²²
(Do128 Test Aircraft (m=4.35tons) of the Institute of Flight Guidance of TU Braunschweig)

IV. Encounter Criterion

The difficulty to define a numerical encounter criterion for severity assessment comes from the great variety of parameters of influence. Even if it is accepted that the relevant encounter scenario (at least for approach and landing) is described by parallel wake vortex encounters (see chapter III) there are manifold parameters affecting the course of such an event. Further factors are²⁷

- Aircraft Pairing
 - vortex generator (AC dimension, vortex strength, shape of velocity distribution)
 - follower (mass, AC dimension, airspeed, aerodynamics, cg, control power)
- Meteorological Conditions
 - wind (e.g. cross wind, wind shear)
 - atmospheric turbulence
 - VMC, IMC (ceiling, visibility)

- Aircraft Control
 - individual pilot behavior (skill)
 - performance of automatic controllers

The list above claims not to be complete. But it 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) as many attempts illustrate.^{32,33,34}

Approaching the problem from a safety point of view leads to 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. This does not imply that any encounter (slight penetration) of the so defined Hazard Zone must result in a threatening situation. But the area outside the Hazard Zone has to be an absolute Safety Zone.²⁸ This idea will be introduced briefly.²⁹

Following this approach it is necessary to identify safe boundaries around a wake vortex defining the Hazard Zone. The today policy to avoid hazardous situations is formulated by the obligation that “no vortex should be encountered by intention”⁴. But what does “no vortex encounter” means? A qualitative statement can easily be made: the more distant the encountering AC flies away from the vortex cores, the less are the noticeable effects of a wake penetration.

Accepting that the compensation of the vortex induced roll momentum is the predominant matter²⁴ the worst case situation at a certain distance is the quasi stationary flight parallel to the vortex axis. Then the wake vortex is 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} is related to the maximum deflection²⁸. This way the dimensionless roll control power ξ_{req}^* (also RCR_{req}) is determined:

$$RCR_{req} = \xi_{req}^* = \left| \frac{\xi_{req}}{\xi_{max}} \right| \quad (5)$$

Using Equation (5) areas of equal required roll control ratios $\xi_{req}^* = RCR_{req}$ behind a lift generating airfoil can be computed from the models described in chapter II. By choosing a maximum allowable required (nominal) roll control ratio (aileron deflection respectively)

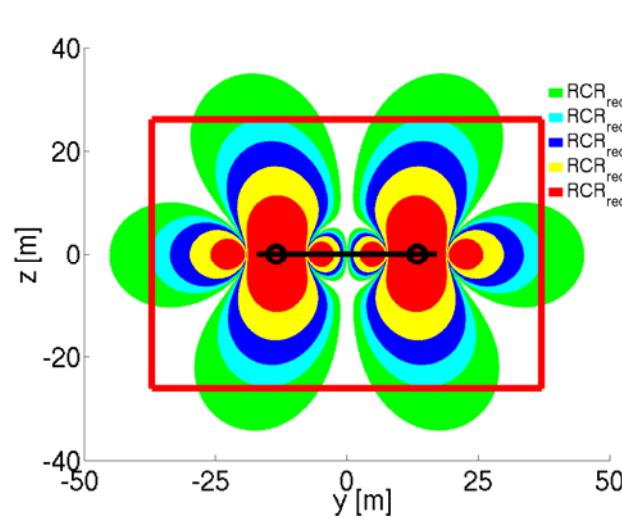


Figure 9. Flight vortex induced required roll control power and simplified hazard area (SHA)

$$RCR_{req} < RCR_{nom} \quad (6)$$

the hazard area is defined. For simplification this hazard area is (conservatively) approximated by a rectangle (marked by red lines in Fig. 9). The nominal roll control ratio has to be determined in such a way that the resulting simplified hazard area (SHA) covers all the risks posed by the wake vortex, e.g. loss of lift leading to an increased sink rate. The dimension of this SHA depends on the amount of RCR_{nom} which is tolerable without any adverse effect on safety. If such a nominal RCR_{nom} value can be found a limit for safe flight operation is established which is defined by only one single parameter. The appropriate safety threshold needs to be validated by pilot-in-the-loop investigations.

V. Validation Methodology

The safety threshold for the required roll control ratio is investigated using fixed based, full-flight, and in-flight simulators. The goal is to establish a threshold to ensure safe and undisturbed flight operations. The validation concept was based on the following methodology: Wake vortex penetration paths were set up directing the encountering AC aircraft along the bounds of the SHA defined by the specific RCR_{nom} to be investigated. For each landing approach only one side of SHA could be investigated (upper, lower, left or right side). This was achieved by

positioning the wake in such a way that the flight path was in coincidence with one of the 4 sides (indicated by red lines in Fig.9) forming the SHA for the respective RCR_{nom} .

A. Investigation Scenario

For the investigations a clear scenario has to be defined. The experiment scenario represents a typical approach scenario. It begins 6 nm before runway threshold and consists of an ILS approach with landing (Fig. 10). The ILS has an inclination of $\gamma = 3^\circ$. The pilot has to track the nominal ILS path following the standard approach procedures to configure the aircraft for landing. This includes flaps and speed settings as well as gear operation.

To make use of the element of surprise the vortex encounters took place at different altitudes not known by the pilot. There will be only one or sometimes no encounter for every approach. The flight path leads the AC either along the upper, the lower or the lateral hazard area boundaries. The horizontal and vertical encounter angles were slightly altered but of course were kept small to be close to a parallel like encounter.

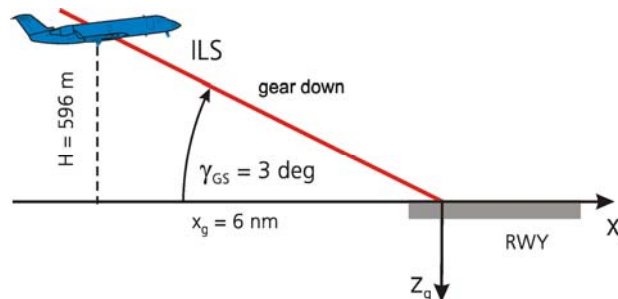


Figure 10. Approach Scenario for Pilot-in-the-Loop Simulations

B. Pilot Ratings

Immediately after any approach (no matter if ground based or flying simulator) the experimental pilot has to fill in a questionnaire (Fig. 11). For each approach the questionnaire comprises four assessment 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. A pilot rating of 1 is denoting a situation when any unwanted effects are hardly noticeable. A rating of 4 denotes a situation the pilot would have avoided if he had known in advance. But a rating of 4 is still far from a fatal event. Ratings of 1-3 are considered acceptable.

a/c control		demands on the pilot		a/c excursions from flight state and path		hazard		
1	a/c control was not a factor	1	required low pilot effort	1	negligible excursions	1	increasing hazard	
2	controllable with somewhat inadequate precision	2	required moderate pilot effort	2	noticeable excursions	2		
3	marginally controllable	3	required high pilot effort	3	large excursions from desired flight state and path	3		
4	uncontrollable	4	required extreme pilot effort	4	GA inevitable due to large excursions	4	4	unacceptable

give main factor for the rating

Figure 11. Pilot Questionnaire and Rating Scale

C. Full-Flight Simulator Concept

The concept of the Full-Flight Simulator study is sketched in Fig.12. The specific number of RCR_{nom} to be investigated and the selection where the wake has to be passed (above, below, left or right) defines the position of the wake relative to the flight path. When the selected encounter altitude is reached the time histories of the wake vortex induced forces and moments computed for the respective encounter situation were fed into the equations of motion affecting the behavior of the simulated AC. The applied forces and moments were calculated as if the AC follows exactly the nominal flight path along the selected border line of SHA. This procedure of using time fixed disturbances was explicitly chosen to make sure that exactly the conditions along the borderlines of SHA could be investigated.

The visual conditions were chosen to be VMC or IMC and weak turbulence was selected. The simulated aircraft was a twin engine turboprop similar to the Do 228 which is classified 'light' by ICAO classification². The simulator campaign was conducted using the Full-Flight Simulator at the "Center of Flight Simulation Berlin" (ZFB) in cooperation with the TU Berlin.^{40,29}

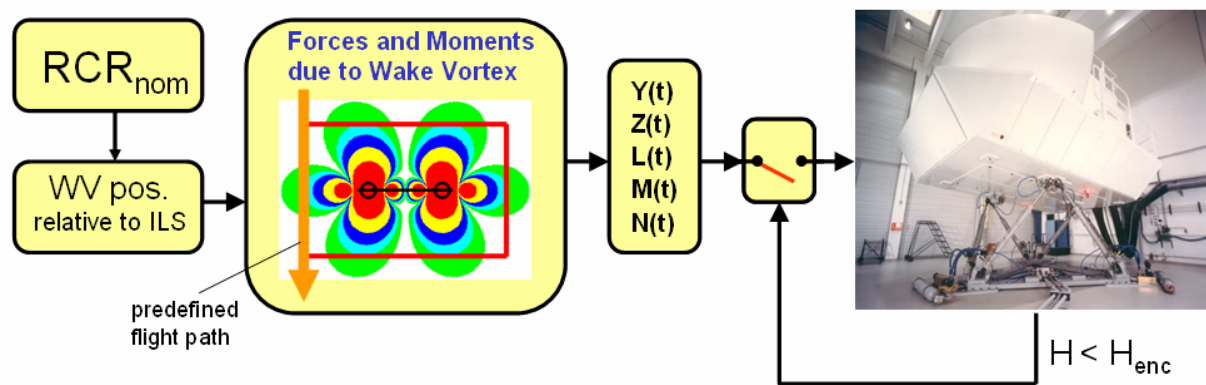


Figure 12. Concept Used for the Moving Cockpit Full-Flight Simulator of ZFB

D. In-Flight Simulation Concept

In-Flight Simulation (IFS) can be regarded to be the most realistic simulation tool since it takes place within the real world environment of flying. The IFS is DLR's standard method to investigate pilot-in-the-loop behavior in real flight conditions³⁰. DLR's full fly-by-wire/light testbed ATTAS Advanced Technologies Testing Aircraft System, Fig. 13) is especially designed for this application. The principle of the IFS is roughly sketched in Fig. 14. The complete simulation system to be simulated in real flight (AC model to be simulated, aerodynamic interaction model, wake vortex model) has to be implemented on the computers on board the host aircraft ATTAS.



Figure 13. DLR's Flying Testbed ATTAS (Advanced Technologies Testing Aircraft System)

The experimental pilot sitting on the left cockpit side of ATTAS is flying the simulated AC using his real controls. These inputs are fed into the onboard computers stimulating the model AC which reacts on his inputs and on the effects coming from the virtual wake vortex flow. The resulting model AC states are fed into the model following control system. The model following controller calculates the control surface deflections of the host AC which are necessary to make the host AC behave like the simulated AC. So the flight states of the host AC experienced by the experimental pilot are in coincidence with the flight states of the simulated AC. For the wake vortex experiments we had the special situation that the simulated AC is identical to the host AC which is not a necessity for the IFS. That the described concept

can also be applied to wake vortex encounter experiments (up to $RCR_{nom} \leq 50\%$) was successfully demonstrated³¹ before the flight test campaigns were planned and conducted.

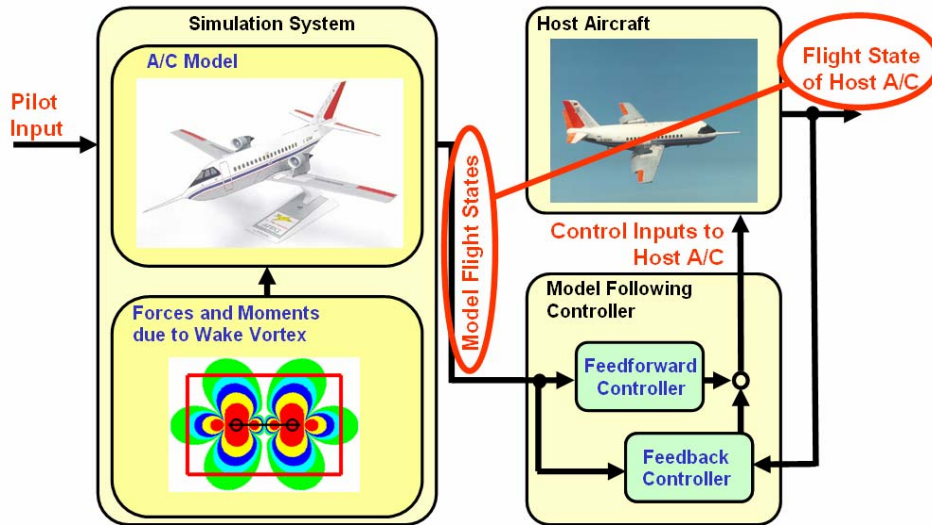


Figure 14. Concept In-Flight Simulation

Two different encounter concepts have been used for the in-flight simulation. The first one is the same as already applied for the full-flight simulator (see Fig. 12). That means time fixed disturbances are used to stimulate the simulated AC. But now the real test aircraft and not the moving cockpit behaves like if it experiences a wake vortex encounter. The second concept considers no time simple histories but the actual flight path through the wake vortex. In other words: the wake vortex flow field is space fixed and the aircraft's path through it defines the effective forces and moments which now are space dependent (as sketched in Fig. 15 by the bending flight path arrow). The disturbance calculations are done online and of course in real time.

The space fixed concept is the more realistic but has the disadvantage that the wake vortex is never hit at the exact position the experimenter wants to. Sometimes the wake is not hit at all due to inaccuracies in nominal flight path tracking. To overcome this problem the position of the wake vortex is always shifted slowly (via low pass filter) to the correct location in front of the AC to provide the wanted encounter situation.

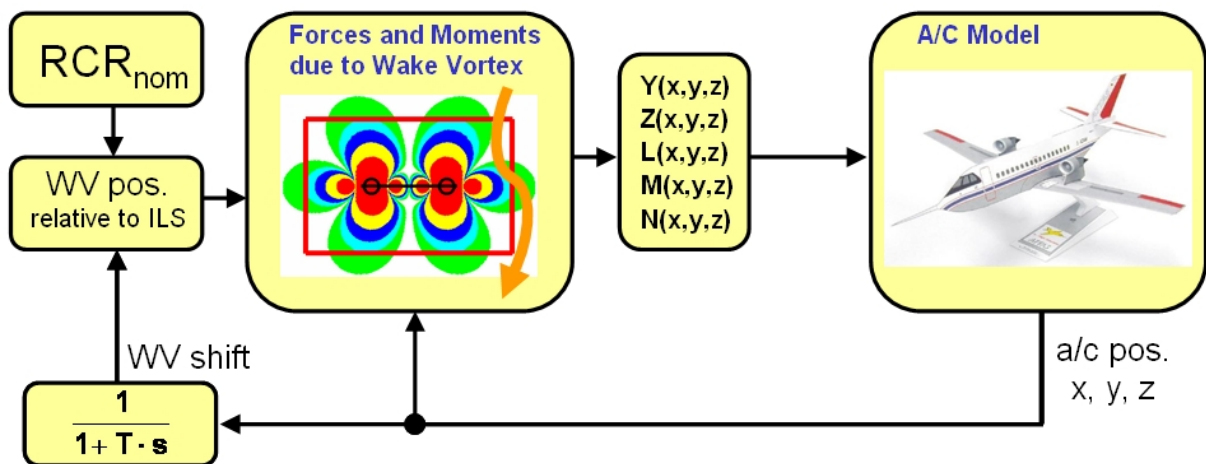
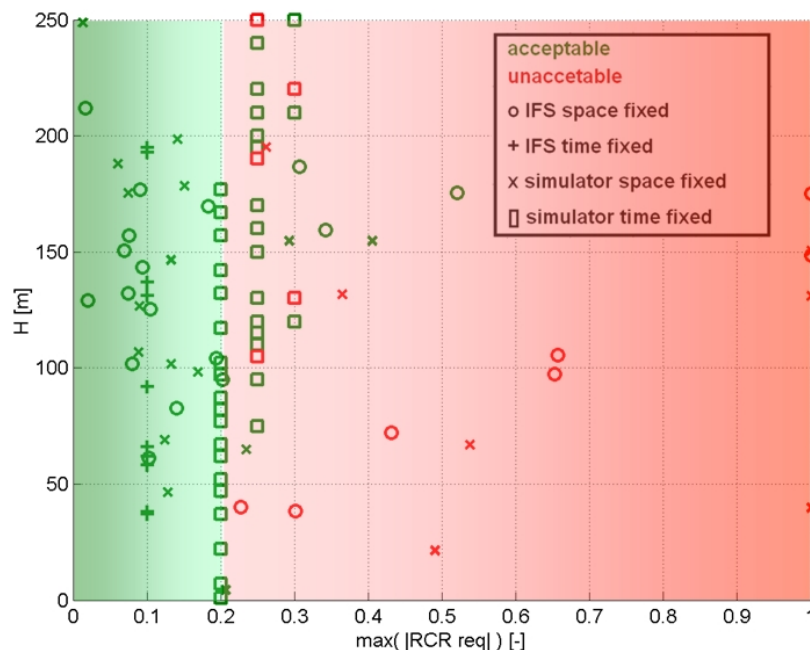


Figure 15. Concept Used for Space Fixed Encounters for the In-Flight Simulation

[illegible]

Figure 17. ATTAS System Simulator (with real cockpit)

In Fig. 18 all results of the encounter studies are put together. The figure shows the maximum required roll control ratio RCR_{req} which occurred during the approach and the height above threshold where this maximum was experienced. First of all it should be noticed that from a statistics point of view 114 encounter events flown by 4 different pilots are not very convincing. So it is clear, that more experiments have to follow to have a wider data base. But at least a first guess and the discussion of tendencies is supposed to be possible.



11
American Institute of Aeronautics and Astronautics

The green indicated symbols in Fig. 18 represent acceptable encounters and the red symbols the unacceptable ones. It is obvious that the red symbols appear more often for bigger numbers of RCR_{req} . It can also be remarked that for $RCR_{req} < 0.2$ no red icons are found. Thus, this number of $RCR_{nom} < 0.2$ is proposed to be the provisional safety threshold to allow undisturbed flight operations. Of course there are acceptable encounters for $RCR_{req} > 0.2$ but this is not in contradiction with the presented approach. But it is important that there are no unacceptable encounters below the safety threshold.

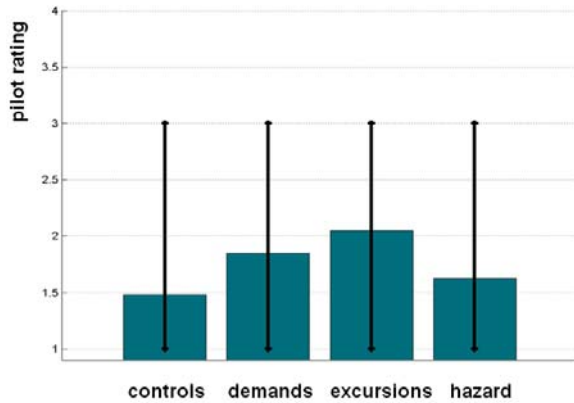
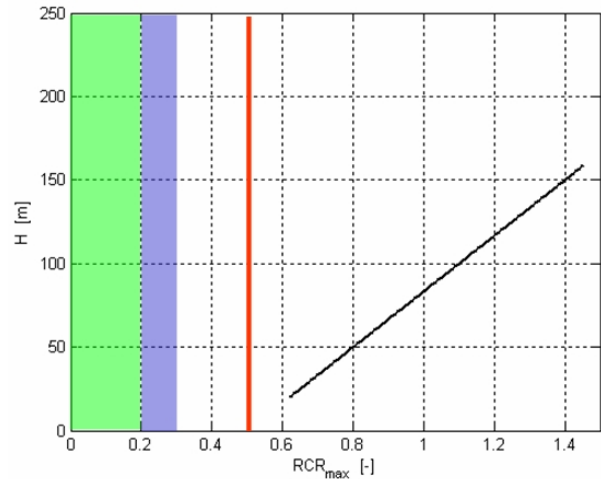


Figure 19. Average and Min/Max Ratings of Pilots for Encounters with $RCR_{req} < 0.2$

The diagram in Fig. 19 gives the averages (blue columns) of the pilot ratings for wake vortex encounters with a maximum roll control ratio of $RCR_{req} < 0.2$. The worst average rating is for flight path and flight state excursions, which is about 2. All the other assessment categories expose better average ratings. So excursions seem to be the most evident factor for the pilots. The black lines in the diagram give the minimum and maximum rating of any pilot for the respective category. As claimed the worst rating does not exceed 3. A comparison with other RCR related studies is shown in Fig. 20. The figure illustrates that the DLR proposal can be marked to be a conservative approach. Therefore, this threshold of $RCR_{nom} < 0.2$ is used for DLR's wake vortex prediction and observation system which is designed to generate dynamic wake vortex separations for safe and undisturbed flight operation.^{37,38,39}



$RCR < 0.5 + 0.006 H_{RCRmax}$ (2002, Höhne, G, et.al.)

$RCR < 0.5$ (1988, Rossow V. J., Tinling, B. E.)

$RCR < 0.2$ to 0.3 (1998, Stewart E. C.)

$RCR < 0.2$ (DLR proposal)

Figure 20. Comparison with Other Studies^{34, 35, 36}

VII. Pilot Assistance System

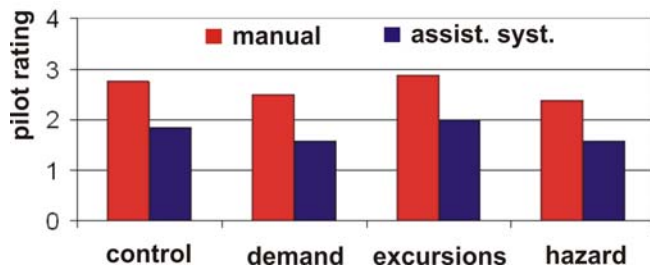


Figure 21. Effect of a Pilot Assistance System on Pilot Average Rating

came from In-Flight Simulation flight tests with time fixed wake vortex disturbances showing a maximum required roll control ratio of $RCR_{req} = 0.5$. Altogether 9 approaches were conducted in fine weather, 7 approaches were executed in IMC and 4 in light turbulence. Although the diagram is based on only 20 approaches (12 approaches with assistance system, 8 without) the tendency of improved rating can clearly be seen when the automatic controller is engaged.

The AC performance during wake vortex penetration can be improved by a pilot assistance system.⁴¹ The investigated assistance system is based on a feed forward control concept²⁸. This principle of disturbance compensation has the advantage that the AC characteristics remain unchanged. The control system is only active if an external disturbance is detected. For this concept it is assumed that the airflow in front of the aircraft can be measured by a forward looking sensor (e.g. LIDAR system).

Fig. 21 shows the effect of the pilot assistance system on the pilot average ratings. The results

VIII. Conclusion

A methodology is presented to establish safe limits for wake vortex penetrations, based on models identified and validated using flight test data. By means of these models piloted simulations were executed using fixed based and full-flight simulators. Finally real flight experiments applying the in-flight methodology were conducted using DLR's flying testbed ATTAS.

Taking into account the results from all the experiments it seems to be possible to establish a safe threshold for undisturbed flight operations applying the roll control ratio RCR parameter. This parameter relates the severity of the disturbance to the available control power of an aircraft. The charm RCR is its simplicity and the fact that it is only one single parameter assessing the encounter situation. For manual control a safe threshold seems to be $RCR_{nom} < 0.2$.

By means of the RCR parameter a simplified hazard area (SHA) can be computed around a wake vortex outside which a safe and undisturbed flight operation can be assumed. Thus, the safe threshold for the normalized roll control power is used for the set up of the "Simplified Hazard Area Prediction" method (SHAPE) to forecast a "hazard free" approach corridor. SHAPE represents a major element of the wake vortex prediction and monitoring system within the DLR project *Wirbelschlepe II*, in order to safely reduce wake vortex related separation minima.

Automatic control systems can improve the aircraft behavior during wake penetrations by supporting the pilot's control task. This increases safety since more severe encounter situation can be coped. With regard to the worldwide attempt to revise (and decrease) wake vortex separation distances special automatic control systems can play a major role concerning safety. Therefore, DLR is planning to intensify its activities in this area.

Acknowledgement

The presented results come mainly from work performed within the DLR project "*Wirbelschlepe II*". The authors would like to thank the whole project team for their fruitful discussions and contributions. Special thanks are given to our DLR colleagues from the flight test department and from the simulator branch who gave us a great support to perform the experiments.

References

- ¹Schlichting, H., Truckenbrodt, E., Aerodynamik des Flugzeuges, Teil 2, 2. neubearbeitete Auflage, Springer-Verlag, Berlin Heidelberg New York, 1969
- ²International Civil Aviation Organization (ICAO), Doc 4444-RAC/501 Rules of the Air and Traffic Services, 13th Edition – 1996
- ³EUROCONTROL, European Organization for the Safety of Air Navigation, Challenges to Growth 2004 Report (CTG04), Edition Number 1.0, EATMP Infocentre Reference 041109-01, Brussels, 2004.
- ⁴IFALPA Wake Vortex Policy, International Federation of Air Line Pilots' Associations, July 1998
- ⁵Greene, G.C., An Approximate Model of Vortex Decay in the Atmosphere. *Journal of Aircraft*, Vol. 23, No. 7, pp 566-573, 1986
- ⁶Han, et al., Large Eddy Simulation of Aircraft Wake Vortices in a Homogeneous Atmospheric Turbulence: Vortex Decay and Decent. *AIAA 99-0756, 37th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, 1999
- ⁷Sarpkaya, T., A New Model for Vortex Decay in the Atmosphere. *AIAA 99-0761, 37th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, 1999
- ⁸Donladson C and Bilanin AJ. Vortex Wakes of Conventional Aircraft. *AGARDograph* No. 204, AGARD-AG-204, Princeton, 1975
- ⁹Holzäpfel, F., A Probabilistic Two-Phase Wake Vortex Decay and Transport Model, *Journal of Aircraft*, Vol. 40, No. 2, March - April 2003, 2003
- ¹⁰Holzäpfel, F., Probabilistic Two-Phase Wake Vortex Decay and Transport Model, DLR Institut für Physik der Atmosphäre, Report No. 163, Oberpfaffenhofen, Germany, 2001
- ¹¹Holzäpfel, F., Robins, R. E., Probabilistic Two-Phase Aircraft Wake Vortex Model: Application and Assessment, *Journal of Aircraft*, Vol. 41, No. 5, 2004
- ¹²Bruin, A. de, S-Wake Assessment of Wake Vortex Safety - Publishable Summary Report, NLR-TP-2003-243, 2003
- ¹³Fischenberg, D., Results of Flight Test Data Analysis, SWAKE-TN-222_1, 2002
- ¹⁴Fischenberg, D., Bestimmung der Wirbelschleppencharakteristik aus Flugmessdaten, German Aerospace Congress, Stuttgart, 23.-26. September 2002, DGLR-JT2002-170, DGLR-Jahrestagung 2002, Jahrbuch. Bonn: Deutsche Gesellschaft für Luft- und Raumfahrt, 2002
- ¹⁵Oseen, C. W., *Arkiv för Mat., Astron. och Fys.*, Nr. 14, 1911
- ¹⁶Lamb, H., Hydrodynamics. Cambridge University Press, pp 590-592, Cambridge, 1932

- ¹⁷Rosenhead, L., The Formation of Vortices from a Surface of Discontinuity, *Proceedings Royal Society of London, Ser. A.*, Vol. 134: p.170-192, 1932
- ¹⁸Burnham, D. C., Hallock, J. N., Chicago Monostatic Acoustic Vortex Sensing System. Vol. 4, *Wake Vortex Decay*, Springfield, VA, National Information Service, 1982
- ¹⁹Proctor F H. The NASA-Langley Wake Vortex Modelling Effort in Support of an Operational Aircraft Spacing System. *36th AIAA Aerospace Sciences Meeting and Exhibit*, AIAA 98-0589, Reno, 1998
- ²⁰Winckelmans, G., Effect of non-uniform windshear onto vortex wakes: parametric models for operational systems and comparison with CFD studies. *4th WakeNet Workshop "Wake Vortex Encounter"*, Amsterdam, 2000
- ²¹Escande, B., FORTRAN code of strip method for implementation into simulators - Documentation (Ver-sion 2), SWAKE-D-212_1, 2001
- ²²Krag, B., D 221_2_1 Flight Test Report, DLR IB 111-2001/40, DLR Institute of Flight Systems, Braunschweig, 2001
- ²³Loucel, R.E., Crouch, J.D., Flight-simulator study of airplane encounters with perturbed trailing vortices. AIAA 2004-1074, 42nd AIAA Aerospace Sciences Meeting and Exhibit, 5 – 8 January 2004, Reno
- ²⁴Bruin, A. de, "S-Wake Assessment of Wake Vortex Safety - Publishable Summary Report", NLR-TP-2003-243, 2003
- ²⁵BFU, Bulletin, Unfälle und schwere Störungen beim Betrieb ziviler Luftfahrzeuge, Hrsg. Bundesstelle für Flugunfalluntersuchung, Braunschweig, September 2005
- ²⁶BFU, Bulletin, Unfälle und schwere Störungen beim Betrieb ziviler Luftfahrzeuge, Hrsg. Bundesstelle für Flugunfalluntersuchung, Braunschweig, November 2005
- ²⁷Hahn, K.-U., Schwarz, C., Friehmelt, H., A Simplified Hazard Area Prediction Model (SHAPE) for Wake Vortex Encounter Avoidance, *International Congress of Aeronautical Sciences*, Yokohama (Japan), 29 August-3 September 2004, ICAS, 24th International Congress of Aeronautical Sciences Proceedings, paper 4.6.4, 2004, pp. 4.6.4-1 - 4.6.4-13
- ²⁸Hahn, K.-U., Coping with Wake Vortex, 23rd International Congress of Aeronautical Sciences, Toronto (Canada), 8-13 September 2002, ICAS, 23rd International Congress of Aeronautical Sciences Proceedings, S. 732.1-732.14, 2002
- ²⁹Schwarz, C., Hahn, K.-U., Simplified Hazard Area for Wake Vortex Encounter Avoidance, AIAA 5903, *AIAA Atmospheric Flight Mechanics Conference*, San Francisco, CA, August 2005, pp. 5903.1 -5903.9.
- ³⁰Hanke D. In-Flight Simulation – An Advanced Simulation Technique. *7th Annual International Symposium "Aviation Technologies of the XXI Century: New Aircraft Concepts and Flight Simulation"*, ILA 2002, Berlin, 7-8 May 2002, TsAGI Central Aerohydrodynamic Institute, 2002
- ³¹Reinke, A., Leibling, D., Bauschat, J.-M., Simulation des Einflugs in Wirbelschleppen mit dem ATTAS Flugsimulator, German Aerospace Congress, Munich, 17.-20. November 2003, DGLR-JT2003-245, DGLR-Jahrestagung, Jahrbuch 2003. Bonn: Deutsche Gesellschaft für Luft- und Raumfahrt, 2003
- ³²Luckner, R., Höhne, G., Fuhrmann, M., Hazard Criteria for Wake Vortex Encounters During Approach, *Aerospace Science and Technology*, Vol. 8, No. 8, 2004
- ³³Sammonds, W. A., Stinnet jr, G. W., Larsen, W. E., Wake Vortex Encounter Hazard Criteria for Two Air-craft Classes, NASA TM-X-73113, Ames Re-search Center, Moffett Field, 1976, (FAA RD-75-206, 1976)
- ³⁴Hoehne, G., Reinke, A., Verbeek, M., Wake Vortex Encounter Flight Simulation: Metrics, Hazard Criteria, and Influence of Cockpit Motions, SWAKE-TN-320-1, Airbus Deutschland GmbH, 2002
- ³⁵Rossow V. J., Tinling, B. E., Research on Aircraft/ Vortex-Wake Interactions to Determine Acceptable Level of Wake Intensity; *Journal of Aircraft*, Vol. 25, No. 6, 1988
- ³⁶Stewart, E. C., A piloted simulation study of wake turbulence on final approach, AIAA Paper 98-4339, 1998
- ³⁷Hahn, K.-U., Schwarz, C., Wake Vortex Avoidance Versus Landing Capacity, *AIAA Guidance Navigation and Control Conference*, Keystone, CO, August 2006
- ³⁸Gerz, T., et al., "Atmospheric Impact on Wake Vortex Development", *European Congress on Computational Methods in Applied Sciences and Engineering*, ECCOMAS 2004, Jyväskylä, Finland, 24—28 July 2004.
- ³⁹Schwarz, C.; Hahn, K.-U., Impact of Individual and Dynamic Wake Vortex Separations on Airport Capacity, *International Congress of Aeronautical Sciences*, ICAS, 25th International Congress of Aeronautical Sciences Proceedings, Hamburg (Germany), 3-8 September 2006.
- ⁴⁰Hahn, K.-U., Schwarz, C., Kloidt, S., Full-Flight Simulatorstudie zur Verifizierung von Wirbelschleppen-Gefährdungsraumgrenzen, DLR IB 111-2004/42, DLR Institute of Flight Systems, Braunschweig, 2004
- ⁴¹Schwarz, C., Hahn, K.-U., Automated Pilot Assistance for Wake Vortex Encounters, First CEAS European Air and Space Conference, 09/10/2007 – 09/13/2007, Berlin, Germany