ANALYSIS OF TWO 2005 WAKE VORTEX ENCOUNTER INCIDENTS

Carsten W. Schwarz, Dietrich Fischenberg
German Aerospace Center DLR, Institute of Flight Systems
Braunschweig, Germany

Keywords: *wake vortex evolution, wake vortex encounter, incident analysis*

Abstract

Two potential wake vortex encounter incidents which were reported in 2005 in Germany are subject to investigation regarding wake vortices as the possible cause. In both cases a heavy category aircraft was preceding a medium category aircraft. The analysis is based on radar data, FDR data and meteo data. The behavior of the leading aircraft's wake vortex is simulated in order to determine the closest distance between the follower aircraft and the wake vortex as well as the corresponding vortex strength. Although in both cases the required minimum separation between the aircraft was obeyed, analysis and simulation results indicate that most likely a wake vortex with considerable strength was encountered.

Nomenclature

a	acceleration
b	wing span
b'	distance between vortices
C	aerodynamic coefficient
δ_a	aileron deflection
g	standard gravity
Γ	circulation
H	altitude
L	rolling moment
n_z	vertical load factor
N^*	normalized Brunt-Väisälä frequency
p	roll rate
ρ	air density
r	distance from vortex center
t	time
V	velocity
w	velocity component in z-direction
W	weight
x,y,z	coordinates

subscripts

0	initial value
l	rolling moment
L	leader aircraft
max	maximum
WV	wake vortex

abbreviations

AP	autopilot
BFU	German Federal Bureau of Aircraft Accidents Investigation *(Bundesstelle für Flugunfalluntersuchung)*
DLR	German Aerospace Center *(Deutsches Zentrum für Luft- und Raumfahrt)*
FAF	final approach fix
FDR	flight data recorder
FRA	Frankfurt International Airport (IATA airport code)
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ILS	instrument landing system
MTOW	maximum takeoff weight
OEW	operating empty weight
P2P	probabilistic two phase model (DLR wake vortex evolution model)
RCR	roll control ratio
RWY	runway

1 Introduction

In the year 2005 the German Federal Bureau of Aircraft Accidents Investigation ("BFU") reported two incidents of medium category[1] air-

[1] ICAO wake turbulence category [1]

craft behind heavy aircraft during the landing approach phase. The question is whether the reason for the incidents is the encounter of wake turbulence and if the required minimum wake vortex separations [1] were violated. In order to investigate the incidents the radar data of both involved aircraft and the FDR data of the follower aircraft are analyzed. The flight tracks of the involved aircraft are compared in order to determine the actual aircraft separation. Wind speed and direction are estimated based on meteo data and FDR data. The wake vortex behavior is simulated regarding evolution of vortex strength and position considering wind and the self-induced downdraft. This way the closest distance of the follower aircraft to the wake vortex can be estimated as well as the corresponding vortex strength.

2 Scenario

2.1 General Scenario

Both incidents under investigation took place during final approach on Frankfurt International Airport (FRA) in the area of the final approach fix (FAF). In both cases the autopilot was initially engaged and then disengaged during the incident and the approach was continued manually with the landing without any damage to aircraft or persons.

An overview over the main parameters of the two cases is given in Tab. 1. The first incident involves a Boeing 737 behind a Boeing 747 approaching parallel runways [2]. The autopilot disengaged due to the disturbance at 820 m altitude. Pilot reporting was 30° bank to the right and 80° bank to the left. FDR data exhibits maximum bank angles of +27° and -62°, respectively. The maximum vertical accelerations are also significant.

The second case is an Airbus A320 also behind a Boeing 747 approaching the same runway [3]. Here the autopilot disengagement altitude is 1160 m. Bank angle according to pilot reporting was more than 45°. FDR data yields a maximum bank angle of 26° and significant load factor deviations.

2.2 Flight Tracks

Radar data of the aircraft positions of all involved aircraft are available in time steps of approximately 5 s. The 3D overview over the entire approach sequence as well as the ground tracks of the incident situation are shown for the two cases in Figs. 1 and 2 with the last 11 NM of the leading aircraft ILS reference track depicted in black. For case 1 the location of the incident which is characterized by a significant flight path deviation is at the beginning of the final approach shortly after the final approach fix, which is marked with a black hexagram at the end of the ILS reference track (Fig. 1).

In the case of the A320 behind a B747 the incident is located directly before the final approach fix (shortly before glide slope intercept, Fig. 2). The exact positions of the incidents are determined and plotted in section 5.

Tab. 1. Scenario overview

parameter	**case 1**	**case 2**
follower aircraft	Boeing 737 (ICAO category medium)	Airbus A320 (ICAO category medium)
leader aircraft	Boeing 747 (ICAO category heavy)	Boeing 747 (ICAO category heavy)
location	FRA (Frankfurt International Airport)	FRA (Frankfurt International Airport)
flight phase	approach (autopilot engaged)	approach (autopilot engaged)
incident altitude	820 m	1160 m
pilot report bank angle	30°/ -80°	>45°
max. bank angle FDR	+27°/ -62°	26°
vertical acceleration	max. +1.68 g/ min. +0.58 g	max. +1.36 g/ min. +0.35 g
runway setting	parallel RWY	single RWY
autopilot	autopilot disengagement	autopilot disengagement
pilot action	approach continued manually with landing	approach continued manually with landing
damage	no damage to aircraft/persons	no damage to aircraft/persons

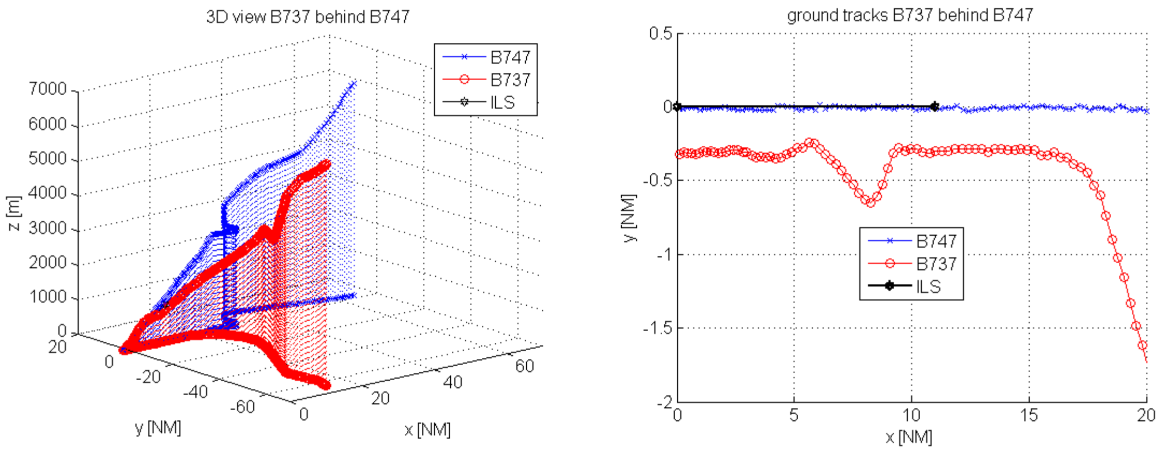

Fig. 1. Case 1 flight tracks, B737 (red **o**) behind B747 (blue **x**) 3D overview (left) and ground tracks (right) incident situation (leader ILS reference track in black with the final approach fix marked with a black hexagram)

3 Aircraft Data

3.1 Separation Distance and Vortex Age Determination

The distance between the two aircraft can be calculated from the radar data. When the autopilot of the B737 disengaged the separation was 4.6 NM and approximately 6 NM when the encountered wake vortex was generated. In the A320 case the autopilot disengaged at 6.2 NM and the encountered wake was generated with approximately 8 NM separation. The corresponding ICAO radar separation minimum of 5 NM for medium category aircraft behind heavy aircraft [1] was approximately obeyed (Fig. 3).

3.2 Leader Speed and Vortex Generation Altitude Determination

In both cases no FDR data are available for the preceding aircraft. Therefore the altitude of vortex generation is determined based on radar altitude. The speed is estimated by differentiating the radar positions. In case 1 the wake vortex to be encountered is generated at an altitude of 1000 m with an (inertial) speed of 90 m/s and in case 2 at 1500 m also with 90 m/s (Fig. 4). The speed information is used to estimate the initial wake vortex strength.

3.3 Wake Vortex Strength

The initial vortex circulation for both cases is estimated under the assumption of a B747 with

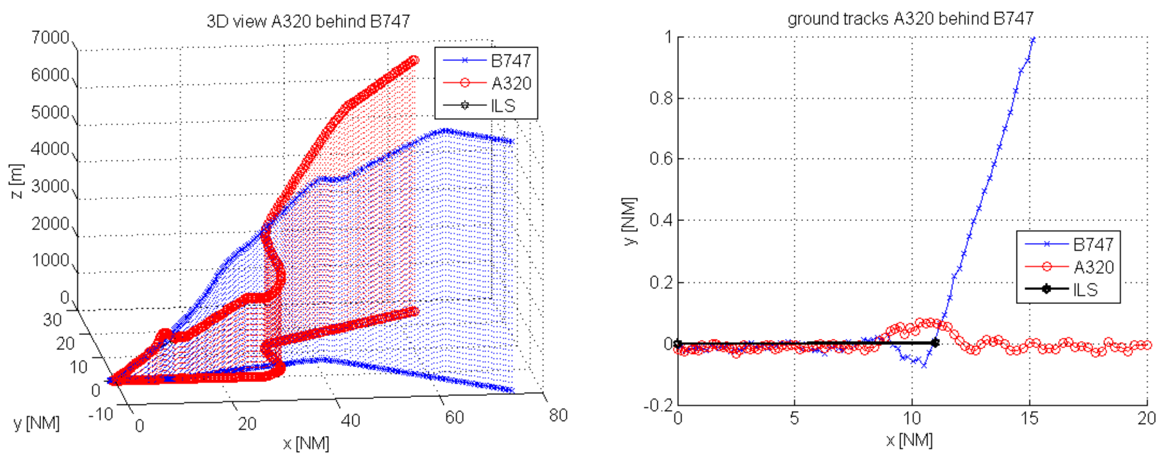

Fig. 2. Case 2 flight tracks, A320 (red **o**) behind B747 (blue **x**) 3D overview (left) and ground tracks (right) incident situation (ILS reference track in black with the final approach fix marked with a black hexagram)

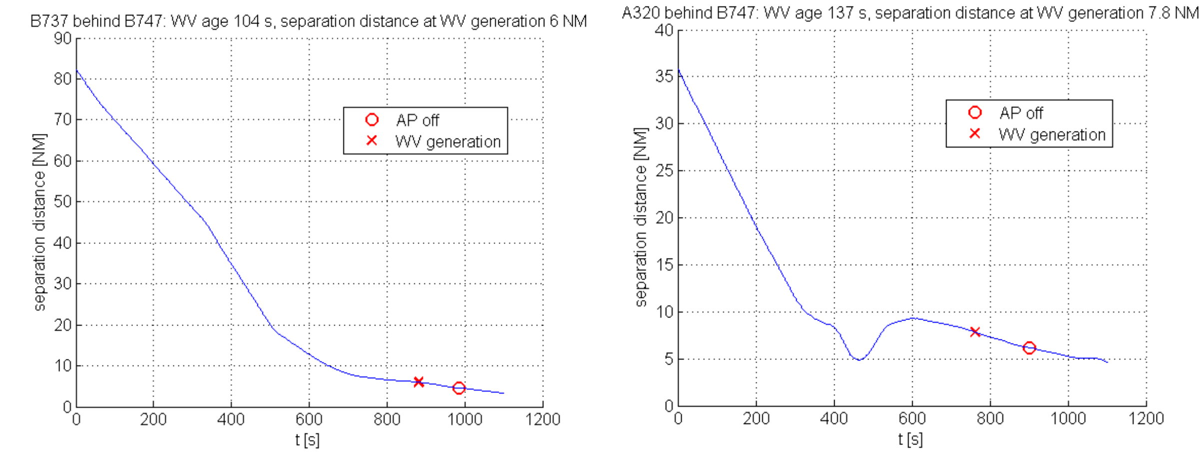

Fig. 3. Separation distance case 1 B737 behind B747 (left) and case 2 A320 behind B747 (right)

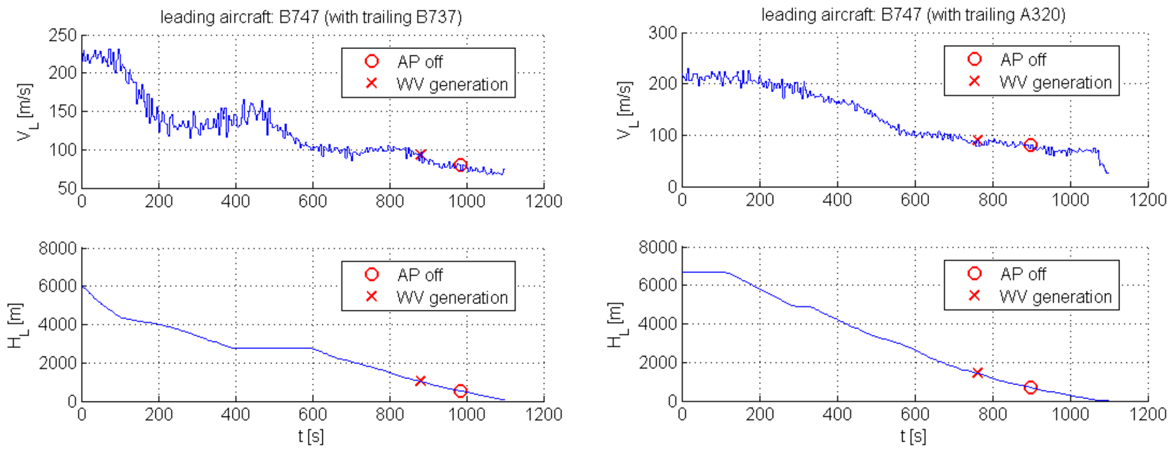

Fig. 4. Leading aircraft speed and altitude B747 case 1 (left) and B747 case 2 (right)

an approach mass of 180 t OEW, maximum payload of 64 t and 34 t fuel (20% of the maximum fuel). With the approach speed of 90 m/s the initial circulation calculates to 490 m²/s according to the equation of KUTTA-JOUKOWSKY.

$$\Gamma_0 = \frac{W_L}{\rho V_L b'} \tag{1}$$

The separation of the two vortices, b', with the leading aircraft wing span, b_L, is (for the reference case of elliptical lift distribution [8])

$$b' = b_L \frac{\pi}{4} \tag{2}$$

The validated DLR wake vortex evolution model P2P [4]-[6] (probabilistic two phase model) predicts vortex position and strength. In this case only the strength is calculated with P2P for a case of no atmospheric turbulence (worst case with high vortex strength) and with typical atmospheric turbulence (horizontal rms velocities of 0.38 m/s and 0.21 m/s vertical) and stratification (normalized Brunt-Väisälä frequency $N^* = 0.35$) (worst case with low vortex descent velocity) (Fig. 5). This gives an estimation of the encountered vortex strength for a given vortex age t_{WV}.

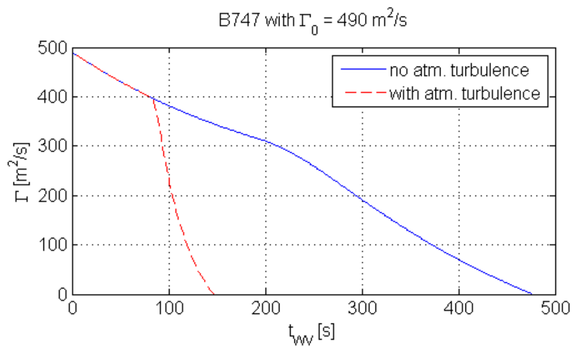

Fig. 5. Estimated wake vortex strength of B747 in approach phase for assumed approach weight with and without atmospheric turbulence

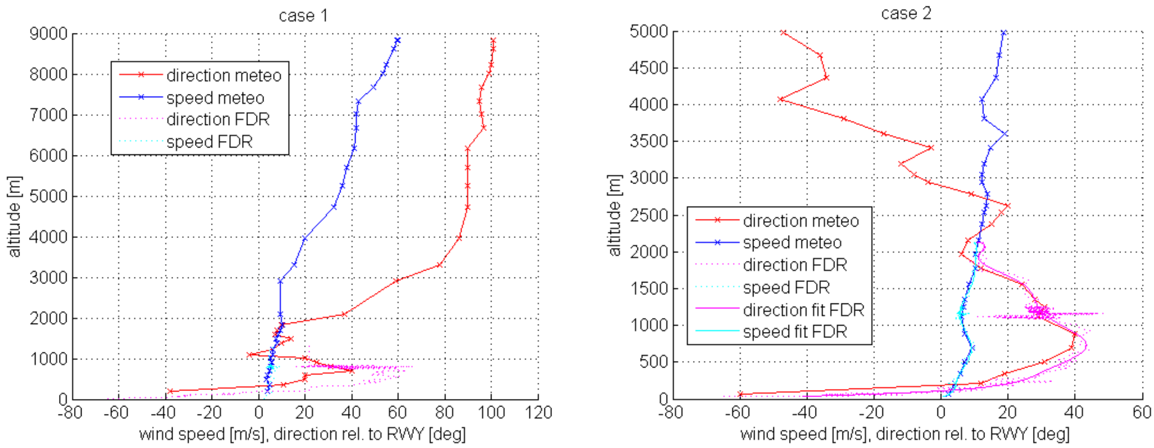

Fig. 6. Altitude profiles of wind speed and direction from FDR and meteo data case 1 (left) and case 2 (right)

4 Meteorological Parameters

Wind data (wind speed and direction) are available from meteo and FDR data (Fig. 6). The latter one is only available for this study below a certain altitude (case 1 1300 m, case 2 2100 m) and has lots of scatter. For both cases the incidences in the respective altitudes are marked by high-frequency peaks in the FDR wind speed and direction data. Such peaks are typically observed for wake vortex encounters (e.g. wake vortex measurement flight tests [7]) and indicate the presence of at least some sort of atmospheric disturbance. In principle the meteo data for both cases are verified with FDR data and hence the meteo data are used for the wake vortex simulation since they are available over a larger altitude range.

5 Wake Vortex Simulation

The wake vortex behavior is simulated based on the leader aircraft radar positions considering vortex decay (using the P2P model) and transport considering wind and the self-induced downdraft. The principal effect for vortex sinking (w_{WV}) is the mutual self-induced downdraft [8], which is depending on the wake vortex tangential velocity V_{WV} which is a function of the actual vortex strength (according to section 3.3, Fig. 5)

$$V_{WV} = \frac{\Gamma(t)}{2\pi r} \tag{3}$$

and the separation of the two vortices, with $r = b'$, eq. (2)

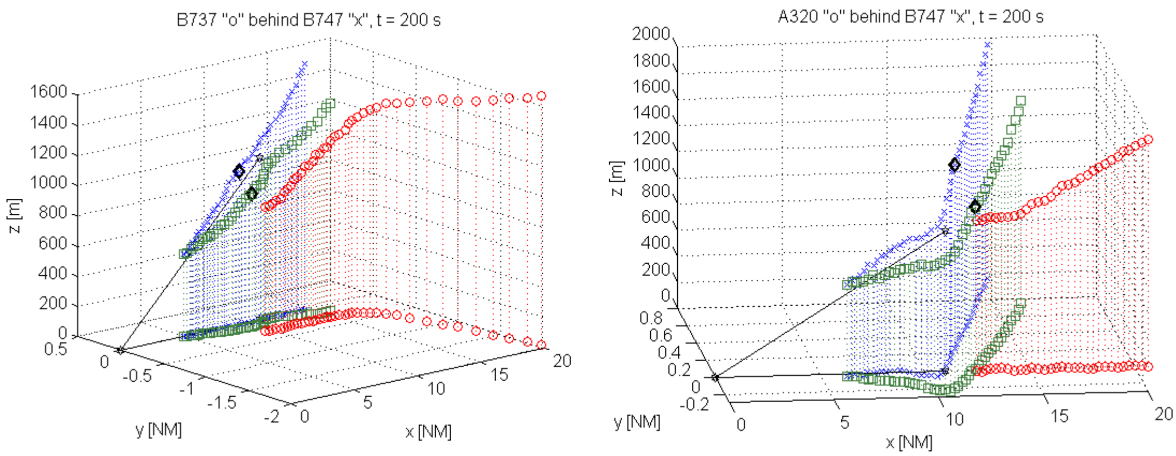

Fig. 7. 3D flight paths and wake vortex positions for encounter situation case 1 (left) and case 2 (right) (leading aircraft (blue **x**), following aircraft (red **o**), wake vortex (green square), closest wake vortex part to follower at AP disengagement in black ◊, leader ILS reference track in black)

$$w_{WV} = \frac{2\Gamma(t)}{\pi^2 b_L} \quad (4)$$

Wind speed and direction are taken into account using the meteo data for the respective altitude (section 4).

Fig. 7 shows the 3D flight paths of the involved aircraft for the incident situation up to the moment of autopilot disengagement. The wake vortex is shown in green. The corresponding side view and ground tracks are depicted in Figs. 8 and 9. The part of the wake vortex which is closest to the following aircraft at the moment of autopilot disengagement is marked by a black diamond "◊" and also the position along the leader aircraft flight track, where this part of the wake vortex was created.

In case 1 the wake vortex is drifted by the wind towards the flight track of the following aircraft on the parallel downwind runway. Due to the higher altitude of the leading aircraft (above the ILS) the vortex pair is sinking towards the flight path of the follower aircraft which is intercepting the glide slope from below the ILS. For vortex decay with no atmospheric turbulence (Fig. 5) the distance between wake vortex and follower for the instant of autopilot disengagement is estimated by the simulation to be 48 m (51 m with typical atmospheric turbulence) vertically and 273 m laterally. The estimated wake vortex circulation for a vortex age of 99 s at this moment is 380 m²/s (245 m²/s) (Fig. 5). This represents a (relatively) strong wake vortex for a following medium category aircraft if encountered within a short distance as discussed in the following.

In order to analyze the expected aircraft reaction for the encountering aircraft the normalized wake vortex induced vertical acceleration and rolling moment are useful parameters. The normalized wake vortex induced vertical acceleration is the change in the vertical load factor due to the wake vortex.

$$\Delta n_z = \frac{a_{z,WV}}{g} \quad (5)$$

The wake vortex induced rolling moment $C_{l,WV}$ normalized by the maximum available roll control power $C_l(\delta_{a,max})$ is called RCR and is a commonly accepted measure for wake vortex encounter evaluations [9-15].

$$RCR = \frac{C_{l,WV}}{C_l(\delta_{a,max})} \quad (6)$$

Fig. 10 shows the wake vortex induced normalized rolling moment/roll control ratio RCR (right half of plot) and vertical acceleration/load factor (left half of plot) estimated depending on the position of the following aircraft in the cross section behind the vortex generating aircraft (with indicated generator wing and vortex cores in black). The wake vortex is generated by a B747 with a reference circulation of 370 m²/s,

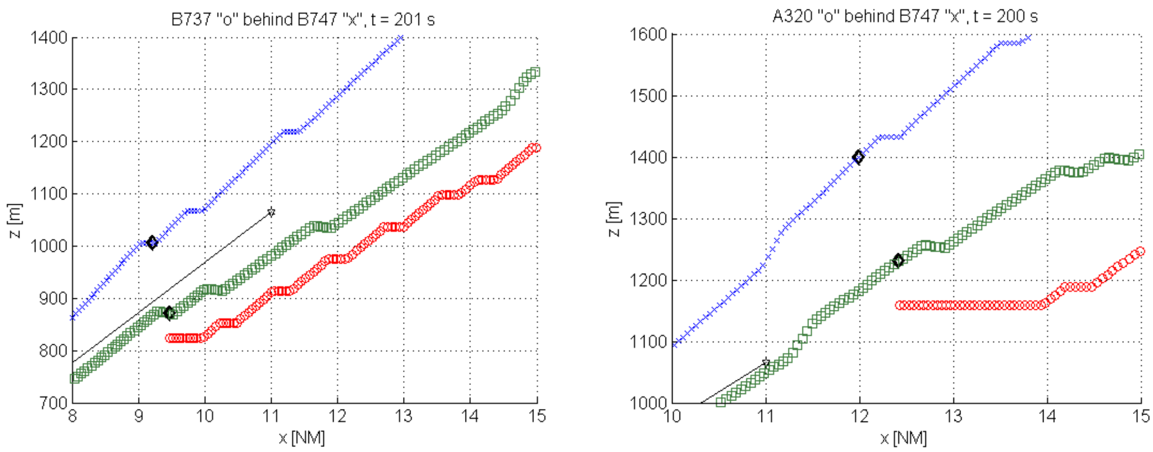

Fig. 8. Flight path and wake vortex position side view for encounter situation case 1 (left) and case 2 (right) (leading aircraft (blue **x**), following aircraft (red **o**), wake vortex (green square), closest wake vortex part to follower at AP disengagement in black ◊, leader ILS reference track in black)

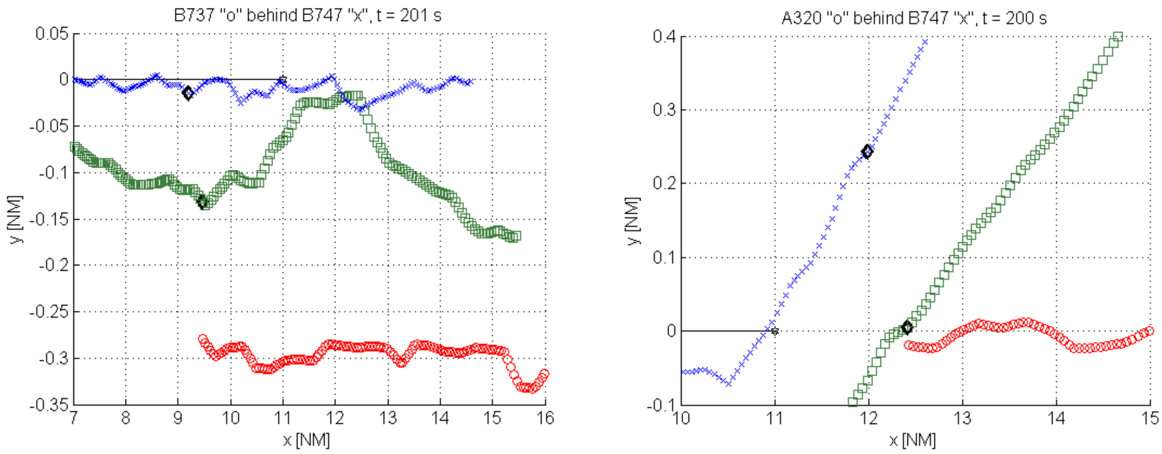

Fig. 9. Ground tracks of aircraft flight paths and wake vortex positions for encounter situation case 1 (left) and case 2 (right) (leading aircraft (blue **x**), following aircraft (red **o**), wake vortex (green square), closest wake vortex part to follower at AP disengagement in black ◊, leader ILS reference track in black)

which is chosen to approximately represent both cases (with no atmospheric turbulence assumed). The following aircraft is an A320, which is providing results which are comparable to a following B737 due to roughly similar size and weight. It can be concluded that for an aircraft pairing and a circulation like this encounters with around 40 m and less distance to the vortices (both vertically and laterally) can result in significant aircraft reactions.

The estimated lateral encounter distance in case 1 would not cause a significant aircraft reaction. However it has to be taken into account that the simulation results are based on several estimates and rely on wind data with limited precision. For a wind speed error of 1 m/s and a vortex age of e.g. 120 s the position error would be 120 m. Hence the nevertheless relatively small distance between the aircraft and the wake vortex respectively and the general tendency of the wake moving towards the follower flight path make a wake vortex encounter likely.

In case 2 the leader is also flying above the follower flight track and the wake vortex is sinking towards the follower aircraft (Fig. 8). In this case the leader is intercepting the localizer from the upwind side whereas the follower is already established on the localizer. Hence the wake is drifted towards the follower with the cross wind (Fig. 9). For vortex decay with no atmospheric turbulence the distance between wake vortex and follower for the instant of autopilot disengagement is estimated by the simulation to be 72 m (97 m with typical atmospheric turbulence) vertically and 44 m laterally. The estimated wake vortex circulation for a vortex age of 129 s at this moment is 360 m²/s (56 m²/s) (Fig. 5). For the case without atmospheric turbulence this represents a strong wake vortex for an encountering medium category aircraft, but not for the other case. This estimated encounter distance is close to the region in which a following medium category aircraft is impacted significantly by a wake vortex of a strength of about 360 m²/s. Hence in this case it is also likely that a wake vortex encounter took place.

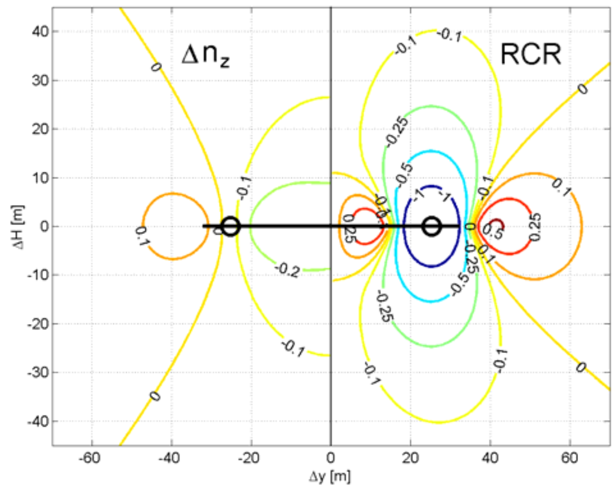

Fig. 10. Wake vortex induced normalized rolling moment/roll control ratio RCR (right half of plot) and normalized vertical acceleration Δn_z (left half of plot) estimated depending on the position of the following A320 as reference aircraft in the cross section behind the vortex generating B747 for a reference circulation of 370 m²/s (with indicated generator wing and vortex cores in black)

6 Conclusions

In both investigated cases of potential wake vortex encounters the possibility of a wake encounter is suggested simply by the relative flight tracks of the involved aircraft in combination with the prevailing wind direction. The detailed analysis of both cases is based on radar data, FDR data and meteo data. Simulating the wake vortex behavior using basic physical equations and a validated vortex behavior model shows that in both cases a wake vortex was likely encountered considering that the simulation results represent estimations based on several assumptions and wind data with limited precision. The probable wake vortex encounters took place although in both cases the required minimum separation between the aircraft was obeyed. Finally it can be concluded that despite the uncertainties of the underlying data the analysis method described here seems to be suitable for analyzing cases with reported potential wake vortex encounters with regard to the likely development of an encounter situation.

7 References

[1] International Civil Aviation Organization (ICAO), Doc 4444-ATM/501, Procedures for Air Navigation Services - Air Traffic Management, 14th Edition – 2001.

[2] BFU Bulletin, Accidents and serious incidents of civil aircraft (“Unfälle und schwere Störungen beim Betrieb ziviler Luftfahrzeuge”), German Federal Bureau of Aircraft Accidents Investigation, Braunschweig, Germany, September 2005.

[3] BFU Bulletin, Accidents and serious incidents of civil aircraft (“Unfälle und schwere Störungen beim Betrieb ziviler Luftfahrzeuge”), German Federal Bureau of Aircraft Accidents Investigation, Braunschweig, Germany, November 2005.

[4] Holzäpfel F. "Probabilistic two-phase wake vortex decay and transport model", *Journal of Aircraft*, Vol. 40, No. 2, March - April 2003, 2003.

[5] Holzäpfel F, Robins R E. "Probabilistic two-phase aircraft wake vortex model: application and assessment", *Journal of Aircraft*, Vol. 41, No. 5, 2004.

[6] Holzäpfel F. “Probabilistic two-phase aircraft wake-vortex model: further development and assessment”, *Journal of Aircraft*, Vol. 43, No. 3, pp. 700-708, 2006.

[7] Fischenberg D. “A method to validate wake vortex encounter models from flight test data”, to be published in proceedings of 27th International Congress of Aeronautical Sciences (ICAS), Nice (France), 19-24 September 2010.

[8] Gerz T, Holzäpfel F, Darracq D. Aircraft wake vortices – a position paper, deliverable of the European thematic network on wake vortex –WakeNet, 2001.

[9] Rossow 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.

[10] Stewart E C. A piloted simulation study of wake turbulence on final approach, AIAA Paper 98-4339, Atmospheric Flight Mechanics, 10-12 Aug. 1998, Boston, MA, United States, 1998.

[11] Luckner R, Höhne G, Fuhrmann M. Hazard criteria for wake vortex encounters during approach, *Aerospace Science and Technology*, Vol. 8, No. 8 (673–687), DOI 10.1016/j.ast.2004.06.008, 2004.

[12] Höhne G, Reinke A, Verbeek M. Wake vortex encounter flight simulation: metrics, hazard criteria, and influence of cockpit motions, Technical Note EU project S-Wake TN-320-1-v1, Airbus Deutschland, 2002.

[13] Schwarz C, Hahn K-U. Full-flight simulator study for wake vortex hazard area investigation, *Aerospace Science and Technology*, 10 (2), Elsevier, p. 136 – 143, DOI 10.1016/j.ast.2005.09.005, March 2006.

[14] Hahn 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*, p. 732.1-732.14, 2002.

[15] Hahn K-U, Schwarz C, Friehmelt H. "A simplified hazard area prediction (SHAPe) model for wake vortex encounter avoidance", 24th International Congress of Aeronautical Sciences, Yokohama (Japan), 29 August - 3 September 2004, *ICAS, 24th International Congress of Aeronautical Sciences Proceedings*, 2004.

8 Contact Author Email Address

carsten.schwarz@dlr.de

9 Copyright Statement