27TH INTERNATIONAL CONGRESS OF THE AERONAUTICAL SCIENCES

ANALYSIS OF TWO 2005 WAKE VORTEX ENCOUNTER INCIDENTS

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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
- $\delta_a$: aileron deflection
- $g$: standard gravity
- $\Gamma$: circulation
- $H$: altitude
- $L$: rolling moment
- $n_z$: vertical load factor
- $N^*$: normalized Brunt-Väisälä frequency
- $p$: roll rate
- $\rho$: 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
- $\text{max}$: 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-
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.

<table>
<thead>
<tr>
<th>parameter</th>
<th>case 1</th>
<th>case 2</th>
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</thead>
<tbody>
<tr>
<td>follower aircraft</td>
<td>Boeing 737 (ICAO category medium)</td>
<td>Airbus A320 (ICAO category medium)</td>
</tr>
<tr>
<td>leader aircraft</td>
<td>Boeing 747 (ICAO category heavy)</td>
<td>Boeing 747 (ICAO category heavy)</td>
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<td>location</td>
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<td>FRA (Frankfurt International Airport)</td>
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<td>flight phase</td>
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<td>approach (autopilot engaged)</td>
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<td>1160 m</td>
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<td>&gt;45°</td>
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<td>max. bank angle FDR</td>
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<td>26°</td>
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<td>max. +1.36 g/ min. +0.35 g</td>
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<tr>
<td>damage</td>
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<td>no damage to aircraft/persons</td>
</tr>
</tbody>
</table>
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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
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.

\[ \Gamma_0 = \frac{W_L}{\rho V_L b^l} \]  

(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])

\[ b' = b_L \frac{\pi}{4} \]  

(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 \( t_{WV} \).
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)

\[
V_{WV} = \frac{\Gamma(t)}{2\pi r}
\]

and the separation of the two vortices, with \( r = b^* \), eq. (2)
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.

\[
\Delta n_z = \frac{a_{z,WV}}{g}
\]  

(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].

\[
RCR = \frac{C_{l,WV}}{C_l(\delta_{a,max})}
\]  

(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,
which is chosen to approximately represent both
cases (with no atmospheric turbulence as-
sumed). 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 air-
craft pairing and a circulation like this encoun-
ters 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 re-
action. 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 atmos-
pheric turbulence) vertically and 44 m laterally.
The estimated wake vortex circulation for a vor-
tex age of 129 s at this moment is 360 m²/s
(56 m²/s) (Fig. 5). For the case without atmos-
pheric turbulence this represents a strong wake
vortex for an encountering medium category
aircraft, but not for the other case. This esti-
minated 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. 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 o, leader ILS reference track in black)

Fig. 10. Wake vortex induced normalized rolling
moment/roll control ratio RCR (right half of plot)
and normalized vertical acceleration $\Delta n_z$ (left half of
plot) estimated depending on the position of the fol-
lowing A320 as reference aircraft in the cross sec-
tion behind the vortex generating B747 for a refer-
ce circulation of 370 m²/s (with indicated genera-
tor 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


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