On the severity and mitigation of wake encounters in ground proximity

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Wake vortex encounter reports as well as simulations show a significantly higher encounter risk in ground proximity. This is caused by the special behavior of wake vortices in ground effect. Nevertheless, hazardous wake encounters with adverse consequences are rarely reported in reality. In order to gain more insight in the mechanisms of wake encounters close to ground a realistic flow field around an aircraft of the HEAVY category is initialized using a high fidelity Reynolds-averaged Navier–Stokes solution. The further development of the vortical wake during final approach until touchdown is investigated by large-eddy-simulation until final decay. The resulting flow fields are used for a hazard analysis of wake encounters close to the ground. Encounter simulations are performed with a simulation model of the DLR research aircraft A320 ATRA with autopilot engaged. Different wind conditions and vortex ages are considered as well as the effect of a so-called plate line. Recent studies showed increased vortex decay in case that a series of plates is positioned in front of the runway threshold. Whether such a plate line also lowers the encounter risk or its severity is analyzed in this study.

Nomenclature

C_ℓ	=	rolling moment coefficient [-]
H	=	altitude [m]
n_z	=	vertical load factor [-]
p	=	roll rate [deg/s]

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RCR	=	roll control ratio [-]
t	=	time [s]
V/S	=	vertical speed [ft/min]
x,*y*,*z*	=	Cartesian co-ordinates [m]
Φ	=	bank angle [deg]
Θ	=	pitch angle [deg]

I. Introduction

WAKE vortices are an inevitable result of lift generation. Due to the pressure gradient between the upper and lower surface of the wing of a flying aircraft a shear layer is generated directly behind the wing that rolls up and forms two counter-rotating vortices. These vortices may persist for several minutes depending on the atmospheric conditions. Even a considerable time after their generation the vortices are able to impose excessive forces and moments on an aircraft encountering the flow field of the vortices. Therefore, wake vortices can generally pose a considerable threat to aircraft. In order to avoid hazardous wake encounters the ICAO (International Civil Aviation Organization) introduced special wake turbulence separation minima in the 1970s [1,2]. This separation scheme distinguishes between aircraft of mainly three different categories depending on their maximum takeoff weight. The A380 is treated as additional category with special separation minima. Besides the ICAO scheme some slightly adapted separation schemes exist worldwide, such as the FAA (Federal Aviation Authority) wake turbulence separation scheme and special schemes used at different airports.

All these separation schemes have proven to be sufficiently safe over the last decades. However, the separation minima limit airspace and airport capacity [3,4], for which reason they are currently at least partly under revision [5]. Any revision of separation minima, however, must not affect safety negatively. For this reason the threat posed to aircraft by wake vortices must be thoroughly known in order to assure the same level of safety in case that present regulations are changed. Research has gained a lot of insight in wake encounter hazard during the last decades, but still there are blank pages in the book of wake vortex understanding.

Monte-Carlo Simulations (e.g. with the simulation tool WakeScene [6] developed by the German Aerospace Center DLR) showed that the probability to encounter the wake of a preceding aircraft is significantly higher during approach at very low altitudes and shortly before landing, rather than during other flight phases [7,8]. This effect can be explained by the presence of ground. Usually vortices descend due to their mutually induced downwash, by which the risk of a wake encounter is reduced for a trailing aircraft flying the same flight path like the generator. However, in ground proximity the vortices are hindered to descend. Therefore, the vortices diverge and may subsequently rebound. Crosswind on the magnitude of the self-induced lateral velocity of the vortices is able to make the luff vortex hover over the runway [9]. This is a critical situation with a high risk for a following aircraft to encounter the vortex if it is not yet fully decayed.

This increase of encounter probability in ground vicinity indicated by simulations is confirmed by pilot's encounter reports. In 2002 the Flight Safety Digest [10] outlined data collected by NTSB (National Transportation Safety Board), FAA and via the NASA reporting system ASRS (Aviation Safety Reporting System) between 1983 and 2000. These data show that of all encounters that were reported in the approach and landing phase the vast majority occurred at low altitude, below 200 ft above ground. The encounters reported to NTSB occurred at 67% below 200 ft, whereas the FAA collected reports of encounters of which even 78% occurred below 200 ft. Another study, conducted by the British CAA (Civil Aviation Authority) in 1991, showed the same tendency [11]. Reported encounters at London Heathrow airport between 1982 and 1990 occurred mostly below an altitude of 500 ft. Furthermore, all databases indicate that most encounters at low altitude occurred during a light crosswind of only a few knots. This matches exactly the situation where weak crosswind keeps the luff vortex within the flightpath above the runway.

One may conclude that recent simulations represent reality in terms of reported encounters quite well. However, analysis of the ASRS wake reports shows that indeed most reported encounters occurred during approach and landing, but that most encounters classified as incident occurred during cruise flight [12]. This means, that the probability of a wake encounter near ground is indeed higher than during cruise flight, but the consequences of a wake encounter is mostly worse in cruise.

One possible reason for this may be that shortly prior to landing pilots are highly prepared to counteract any disturbance and everyone on board is seated with seatbelts fastened. During approach or in cruise flight this is not always the case, so that an unforeseeable, violent disturbance might easily result in injuries. Nevertheless, the low rate of reported incidents is surprising given the dramatic increase in encounter probability at very low altitude. This implies that potentially the simple vortex models used in previous simulations do not cover all relevant effects that occur during final approach. In ground effect wake vortices behave differently than out of ground effect, which might possibly cause a reduction of the encounter severity. Furthermore, some effects have been discovered recently that strongly influence the vortex decay in ground effect, namely so-called end-effects occurring in the moment when the lift of the aircraft breaks down immediately after touchdown. This disturbance efficiently leads to a quicker decay of the vortices than out of ground [13-15].

A similar effect can be generated artificially by placing so-called plate lines in front of the runway. These patented plates generate disturbances that result in a further increase of the vortex decay. This effect could be verified by means of laboratory experiments [16], numerical simulations [14] as well as real flight tests [15]. Lidar (light detection and ranging) measurements during flight trials with the DLR research aircraft HALO (a modified Gulfstream G550) showed a noticeable effect of the plate line on the vortex circulation. Whether this accelerated vortex decay also affects the encounter hazard near ground is analyzed through simulation in this paper.

The paper first introduces the reader to the specific behavior of wake vortices in ground effect and the method how the generation and decay of vortices in ground effect can be simulated realistically, including all relevant effects. Also the idea and the effect of the plate lines are presented to the reader. In the following the aircraft simulation is described. Finally, the results of the severity assessment of wake encounters in ground effect are presented.

II. Wake Vortices in Ground Proximity

The following subsections introduce the physics and the applied numerical simulation method of wake behavior in ground proximity with crosswind. Further the plate line concept to accelerate wake vortex decay by the installation of plate lines at airports is introduced.

A. Wake Vortex Behavior in Ground Proximity

Vortices in proximity to a solid surface induce a boundary layer (vorticity layer) at the surface which causes the vortices to move along the surface driven by mutual velocity induction. Counter-rotating vortex pairs diverge during their approach to the ground following the hyperbolic trajectory of classical inviscid theory. Because of an adverse pressure gradient the vorticity layer may separate from the surface leading to the formation of secondary vortices. The detached secondary vortices may orbit around the primary vortices and the newly formed unequal vortex pairs rebound [17,18].

In contrast to headwind crosswind causes asymmetric rebound characteristics. Firstly, the crosswind shear vorticity supports the formation of the secondary vorticity at the lee (downwind) vortex and attenuates it at the luff (upwind) vortex. Secondly, the primary vortices redistribute vorticity of the crosswind shear with which they mutually induce transport velocities [19]. These effects lead to an earlier and higher rebound and a more rapid decay of the lee vortex.

A potentially most dangerous situation for following aircraft arises from the longer-living luff vortex hovering above the runway because the self-induced lateral propagation speed of the luff vortex is just compensated by the crosswind. Numerical simulations [19] and lidar measurements conducted at Frankfurt airport [9] indicate that a crosswind of about half the initial vortex descent speed roughly compensates the vortex-induced propagation speed of wake vortices generated at a height of about one initial vortex separation. The lower the vortex generation height the higher the induced lateral vortex speeds. Therefore, in this study a crosswind of about 3 knots at a height of one initial vortex separation is chosen in order to compensate vortex drift immediately before touchdown.

B. Plate Lines

Vortex decay in ground proximity can be accelerated by installing a series of plates in lines perpendicular to the flight direction. The so-called plate lines trigger the early detachment of strong Ω-shaped secondary vortices that actively approach the wake vortices and subsequently propagate along the primary vortices. These dedicated secondary vortices lead to an accelerated wake vortex decay independent from natural external disturbances [14,16,18].

Lidar measurements accomplished during the WakeOP campaign at special airport Oberpfaffenhofen confirm the functionality of the plate line [19]. The benefits of the plate line appear very conclusive if the most safety relevant long-lived and strongest vortices are considered whose lifetime can be reduced by one third. It can be concluded that in potentially hazardous situations caused by persistent wake vortices within the glide path, plate lines may substantially reduce vortex lifetimes and thus increase safety. A respective patent entitled “Surface Structure on a Ground Surface for Accelerating Decay of Wake Turbulence in the Short Final of an Approach to a Runway” has been filed under number DE 10 2011 010 147.

C. Simulation of Wake Vortices in Ground Proximity

A new hybrid method for the simulation of wake vortex evolution from early roll-up until final decay is applied for approach and landing of an aircraft including touchdown [14]. The hybrid LES (Large Eddy Simulation) initializes a realistic aircraft wake in an LES domain by sweeping a high-fidelity RANS (Reynolds Averaged

Navier-Stokes) aircraft flow through the domain, which enables to simulate wake vortex evolution from generation until final decay [20]. The simulations are performed for a HEAVY transport aircraft in highlift configuration. The RANS flow field, which has been established before with the DLR TAU code, serves as a forcing term or inner boundary in the LES domain. LES are conducted either employing a calm atmosphere or a crosswind situation with and without one plate line. For the crosswind case prior to the wake initialization a turbulent crosswind with a wind speed of 3 knots at a height of one initial vortex separation is allowed to develop.

Figure 1 depicts the wake evolution in the crosswind situation with a plate line during approach and after touchdown at the times t_{age} = -3.2 s, 0.4 s, 19.2 s and 60 s, where the time stamp t_{age} = 0 s is assigned to the instant of touchdown.

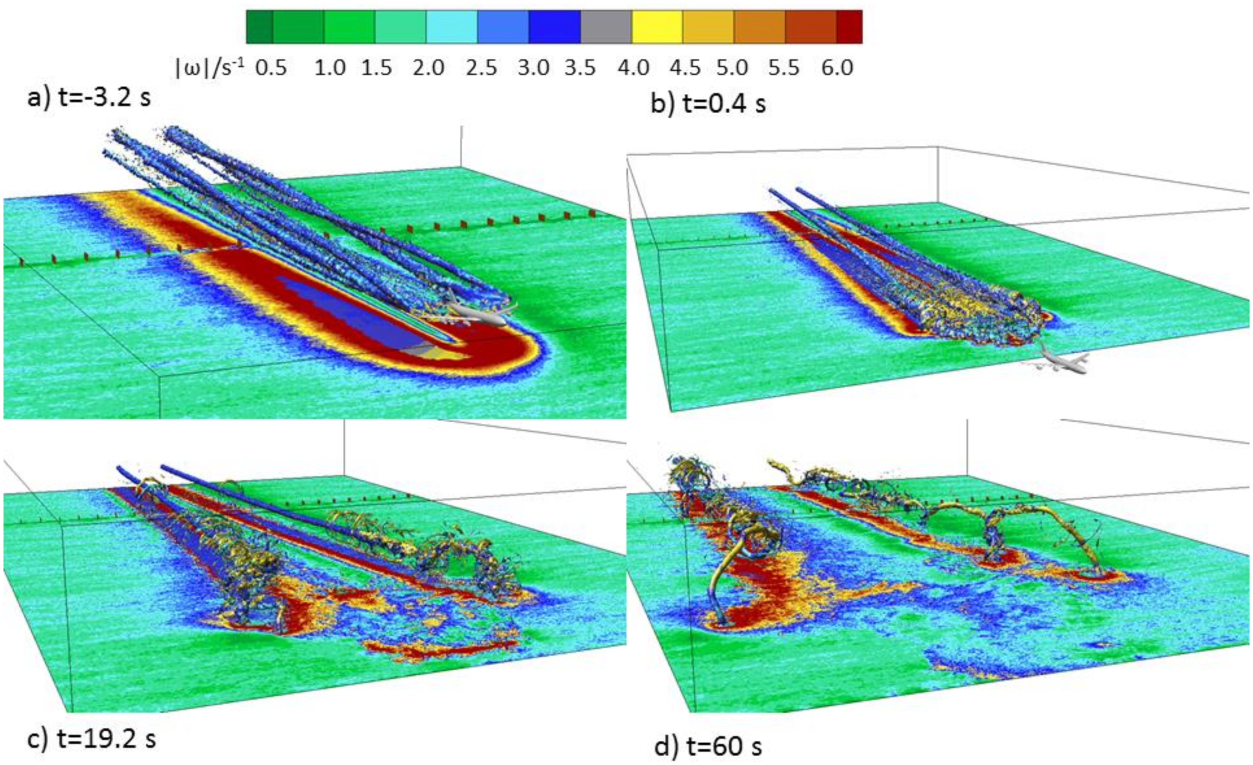

Fig. 1 Simulation of wake vortex evolution of a landing aircraft at weak crosswind.

Figure 1 displays the aircraft landing including touchdown with vortex roll-up, end effects, and the influence of a plate line in a turbulent crosswind situation. The iso-surface depicts the vorticity level of 3.3/s. The ground is colored by the vorticity magnitude. In Figure 1 top left the complex vorticity distribution emerging directly behind the aircraft and the subsequent vortex roll-up to a single counter-rotating vortex pair can be observed. In the near wake flow the outer flap-tip vortices, the wing-tip vortices, the inner engine-nacelle vortices, and the vortices detaching from the wing-fuselage junction can be distinguished.

The wake vortices as well as the bound vortex along the wing instantaneously induce a vorticity layer of opposite sign at the ground surface already at the initial flight altitude of z = 60 m. This vorticity layer is disturbed by the turbulence of the crosswind. At the lee side it is more pronounced as the vorticity of the wind is added, where it is suppressed at the luff vortex. This vorticity layer subsequently detaches from the ground and is wrapped around the primary vortices. Due to the small distance between the vortices and the ground surface this process starts with almost no delay at the point of touchdown (see Fig. 1 top right, t_{age} = 0.4 s). The turbulent wake of the fuselage is transported towards the ground by the downwash between the main vortices, where it additionally disturbs the vorticity layer at the ground surface. As a consequence, the secondary vorticity detaching from the ground is organized in Ω-shaped / hairpin vortices wrapping around the primary vortices (bottom left).

Further consequences of the low vortex generation altitude are the rapid divergence of the vortices reaching a maximum vortex separation of more than 5 initial vortex separations already at t_{age} = 19.2 s. At higher generation heights the vortices diverge later. In addition the vortices are advected by the crosswind. Immediately after touchdown the bound vortex vanishes and the unconnected ends of the wake vortices get highly disturbed. Due to the pressure imbalance between the core of the freely decaying vortex ends and their environment, an axial flow is induced within the vortex cores and a corresponding pressure disturbance is propagating against flight direction. Simultaneously, helical disturbances are wrapped around the vortices and are propagating along the wake as well. The pressure disturbances and the helical structures constitute the so-called end effects [13]. In accordance with the Helmholtz vortex theorem the free vortex ends cannot persist but connect rapidly with the ground (see Fig. 1 below) where they turn up vertically.

The first effect of the plate line can already be identified at t_{age} = -3.2 s via a small gap of the vorticity layer generated at the ground. Already at t_{age} = 19 s Ω-shaped secondary vortices have detached from the plates and approach the primary vortices driven by self-induction. This effect of the plate lines starts first at the downwind vortex and a few seconds later at the upwind vortex. A half vortex time scale later vigorous helical secondary vorticity structures have wrapped completely around the wake vortices and travel to either side of the plate line again driven by self-induction. The plate line concept exploits vortex dynamics by generating powerful secondary vortices that first actively approach the primary vortices and then actively propagate along the primary vortices finally leading to accelerated vortex decay. The crosswind transports the downwind vortex away from the runway, i.e. it is no longer relevant for following aircraft unless we consider closely-spaced parallel runways. However, the upwind vortex remains in the proximity of the touchdown zone, where it can potentially be dangerous to following aircraft. In weak crosswind situations with a potentially hazardous upwind vortex the plate line is aiming at relaxing that critical situation.

III. Wake Encounter Simulation

In this section the simulation models used for the encounter simulations are described. The simulation framework comprises the aircraft model including an electronic flight control system for manual flight and an autopilot as well as an aerodynamic interaction model for the calculation of vortex induced forces and moments acting on the encountering aircraft.

A. Aircraft Model

As encountering aircraft the DLR research aircraft A320 ATRA (Advanced Technologies Testing Aircraft) was chosen for the hazard assessment (see Fig. 2). For this aircraft a comprehensive and thoroughly validated simulation model exists, developed and continuously improved by the DLR Institute of Flight Systems [21]. The analyzed aircraft pairing of an aircraft of the ICAO MEDIUM category following a wake generator of the HEAVY category is considered to be especially relevant at most highly frequented airports for which wake related separation minima are a more limiting factor than for less frequented airports.

Fig. 2 The DLR research aircraft D-ATRA.

The simulation model of the ATRA comprises a two-point aerodynamics model for the longitudinal motion (wing and horizontal tail) and a one-point model for lateral motion. The aerodynamics model is based on stability and control derivatives identified from flight test data including nonlinear corrections for dynamic pressure, Mach number effect, stall, ground effect, etc. Furthermore, the aircraft simulation model comprises models of the V2500 engines, landing gear, control surface actuators and sensors (air data, navigation etc.). The model also incorporates a flight control system designed in analogy to the Airbus flight control architecture and design. The flight control system model of the ATRA simulation consists of an autopilot / auto-thrust system and for manual control a normal law, providing rate command / attitude hold control, as well as a direct law without any controller assistance and direct control of the control surfaces. The ATRA simulation is also used in the AVES motion-based full-flight simulator operated by DLR in Braunschweig [22].

One issue to keep in mind is that the behavior of the simulated flight control system on an external disturbance can hardly be validated. The behavior of the flight control system on control inputs indeed shows a good conformity with the behavior of the original flight control system of the real ATRA. Nevertheless, the behavior of the flight control system used in the simulations on an external disturbance such as wake turbulence is likely to differ from the original one. However, the aircraft reaction appears plausible and is comparable with the aircraft reaction of the real aircraft in terms of magnitude and agility of the aircraft reaction on an external disturbance.

Concluding, one can say that the accuracy of the simulation model is considered sufficient for scientific purposes [21] (as no pilot training is intended with this simulation model). Nevertheless, the model is continuously updated by means of flight test data of the real A320 ATRA.

B. Implementation of Vortex Flow Fields in the Aircraft Simulation and Aerodynamic Interaction Model

In order to simulate wake encounters with a dynamic aircraft simulation an aerodynamic interaction model (AIM) is needed that calculates the vortex induced forces and moments acting on the encountering aircraft as a function of the aircraft position and attitude in the vortex flow field. As described in section II the wake vortices were calculated with a coupled simulation of RANS (Reynolds Averaged Navier-Stokes) and LES (Large Eddy Simulations). The results of these vortex simulations as used in the aircraft simulation are three-dimensional flow fields for each vortex age that were implemented into the AIM.

The AIM used in this study is modelled as delta-aerodynamics model, which means that the basic aerodynamics model of the aircraft simulation is used for the calculation of the undisturbed flight, whereas the AIM solely calculates the additional forces and moments induced by the wake. The method used for the AIM is the so-called strip method. This method divides the lift and side force generating surfaces of the aircraft into single strips (see Fig. 3).

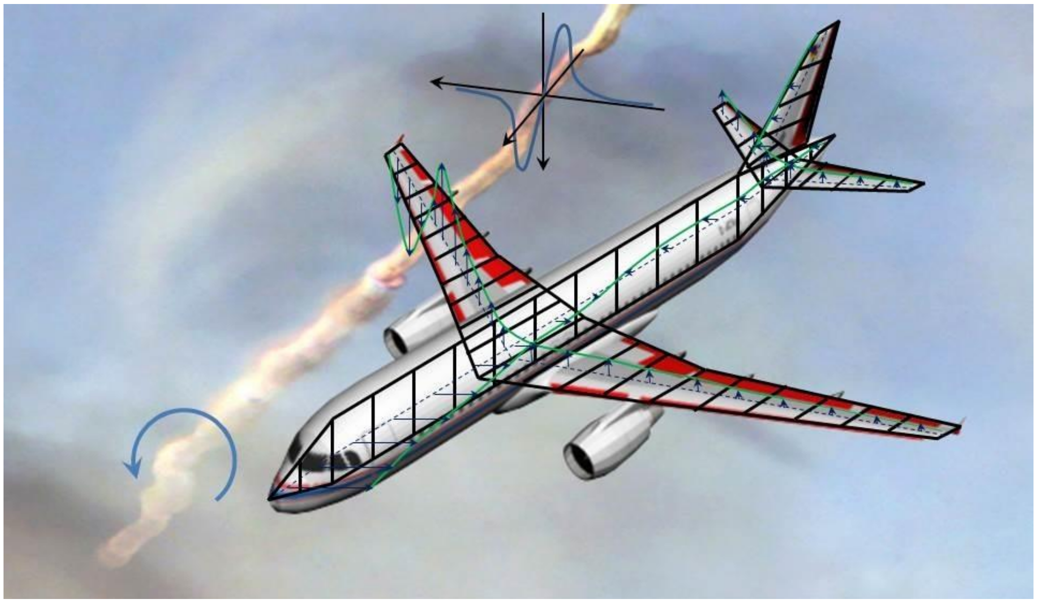

Fig. 3 The strip method [3].

For each strip an additional angle of attack (for lift generating surfaces such as wings and horizontal stabilizer) or angle of sideslip (for side force generating surfaces such as the fuselage and vertical stabilizer) is calculated by means of the flow velocities of the vortices at the respective strip position. With the additional angles of attack and sideslip angles the incremental lift and side forces are calculated for each strip and with the respective lever arm of each strip the resulting moment, too. The forces and moments of all strips are finally summed up to total induced forces and moments in all six degrees-of-freedom. These forces and moments are fed into the equations of motion of the aircraft simulation.

This method was deemed feasible by Barrows [23], verified against wind tunnel tests by de Bruin [24], and further validated using real flight test data by Fischenberg [25] and Jategaonkar [26]. The method was applied in various studies in the past [27-32] and is accepted to provide vortex induced forces and moments of acceptable accuracy.

The velocity components of the flow field at each strip position are evaluated by three-dimensional linear interpolation in the flow field lookup-tables for the different vortex ages. It is assumed that during an encounter the vortex age does not alter significantly. Therefore, the flow fields are positioned on ground at the runway so that the nominal touchdown positions of generator and encountering aircraft are the same. However, in order to be able to evaluate the effect of different landing positions of either generator or encountering aircraft or slight differences in the underlying wind conditions (hence, vortex drift), the encounterer's flight path through the wakes flow field is varied within a meaningful range in longitudinal and lateral runway direction.

IV. Severity Assessment

For the assessment of the severity or hazard of a wake encounter suitable metrics are needed. As under small encounter angles the rolling moment induced by the vortices is the predominant disturbance acting on the encountering aircraft [33], it is obvious to choose a metric that uses the rolling moment impact. A meaningful parameter is the so-called Roll Control Ratio RCR, that is the ratio between the vortex induced rolling moment coefficient and the coefficient of the maximum rolling moment that can be generated by all roll control surfaces.

$$RCR = \left| \frac{C_{\ell,ind}}{C_{\ell,CTRL,\max}} \right| \tag{1}$$

Obviously, an RCR greater than 1 means that the induced rolling moment cannot be fully compensated by the roll controls of the encountering aircraft. One parameter used here as hazard metric is the maximum RCR that occurred during the encounter. Other parameters used as metric represent the aircraft motion, e.g. the maximum bank angle etc. Such metrics are especially useful when comparing different encounters or rating encounters on an objective level without any subjective pilot rating. However, such metrics can only be used for a-posteriori analyses. RCR_{max} is also able to serve as a hazard metric in a-priori severity assessment as it can be predicted before an encounter happens.

Past hazard analyses showed that it is indeed useful to analyze both the aircraft motion and the RCR_{max}. For pilot-in-the-loop investigations with subjective pilot ratings as well as for offline simulation studies the RCR_{max} has proven to be a suitable metric. Recent studies showed that pilots accepted encounters below an RCR_{max} of 0.2 [28-31]. Below this value the impact of the wake was not distinguishable from ordinary atmospheric turbulence in all past analyses.

As the encounter scenario analyzed here is close to ground some additional criteria for non-acceptance are defined. These are a) wing strike ($f(H,\Phi)$), b) tail strike ($f(H,\Theta)$), c) hard landing ($n_z \geq 2{,}6$ [34]), and d) runway excursion ($f(y_{RWY})$). All these criteria are rated here as severe incident and encounters that result in at least one of the aforementioned consequences are treated as hazardous and therefore as unacceptable.

V. Encounter Simulations

A comprehensive simulation study was conducted for parameter variation. First of all, the case without any wind was analyzed. In this case both vortices diverge symmetrically in ground effect. It can be expected that this case is not the worst case. The worst case can be assumed as the one with a crosswind of the same magnitude as the velocity with which the vortices diverge on average. Under such wind conditions the luff vortex will inevitably remain above the runway, posing a far greater threat to a following aircraft as in calm air. This worst case was analyzed for different vortex ages. Furthermore, these simulations were performed with and without plate line in order to give on the one hand a sound understanding of the mechanisms of wake encounters in ground effect and on the other hand analyze the influence of plate lines on the encounter severity.

A. No Wind

In absence of wind both vortices diverge symmetrically in ground effect. Figure 4 gives an impression of the shape of a 60 seconds old vortex pair. The blue shape is the iso-surface of an absolute flow velocity of 5 m/s. Also shown in the figure are the contour of the runway and the flight path of the trailing aircraft. In this case the touchdown point of both, generator and follower aircraft, is the same and located approximately at x = 700 m in the figure.

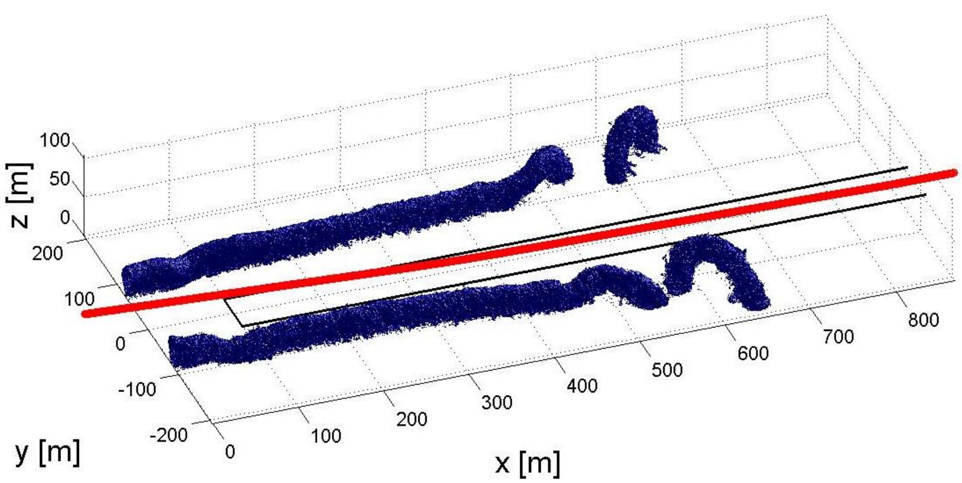

Fig. 4 Vortex shape and encounter flight path without wind.

As the case without wind can be expected not to be the worst case, only simulations without plate lines were considered. One can clearly observe in Fig. 4 that already after 60 s the distance between both vortices is large enough that a following aircraft can fly through them without any risk of encountering the vortices. Also, the downdraft between the vortices is not excessive because of the large distance between the vortices. Hence, within a meaningful range a variation of the touchdown point of generator and encountering aircraft does not lead to a significant aircraft reaction. Without any wind no unacceptable encounter occurred although the vortices were relatively young in this case with an age of 60 s, corresponding to a very small separation distance between generator and follower aircraft of only about 2.3 nm. Further increase of the vortex age would lead to an even more relaxed situation, as besides the further decay, the vortices also further diverge with increasing time, opening even more space for the follower aircraft to fly through.

Altogether, the simulations without wind showed that wake vortices do not pose a considerable threat to a following aircraft close to ground in absolute calm air. This outcome was also confirmed by Bitar [8]. However, weather conditions with absolute calm air can be regarded as relatively rare. It can be expected that under real flight conditions mostly at least light air or a light breeze would prevail. Such conditions are analyzed in the following.

B. Weak Crosswind

As mentioned before, the worst case wind condition is crosswind of the magnitude with which the vortices diverge in ground effect on average [9]. In such case the luff vortex is persisting above the runway resulting in a high risk for a follower aircraft to encounter the vortex unless it is fully decayed. Hence, weak crosswind of only a few knots is the most hazardous case for wake encounters close to ground. Under stronger crosswind even the luff vortex drifts leeward so that after some time a follower aircraft is not threatened by the vortex anymore. Figure 5 shows the shape of the vortices at the three considered vortex ages with and without plate line. The plots in Fig. 5 again show the iso-surfaces of an absolute flow velocity of 5 m/s. One can observe in the figure that in both cases (with and without plate line) the luff vortex remains nearly at a lateral position of y = 0 m (the runway centerline) throughout all vortex ages. Furthermore, the figure shows the quicker decay of the vortices due to the plate line located at a position of approximately x = 200 m. For greater vortex ages the contour of the vortices is much more diffuse, hence the flow velocities are smaller with the plate line.

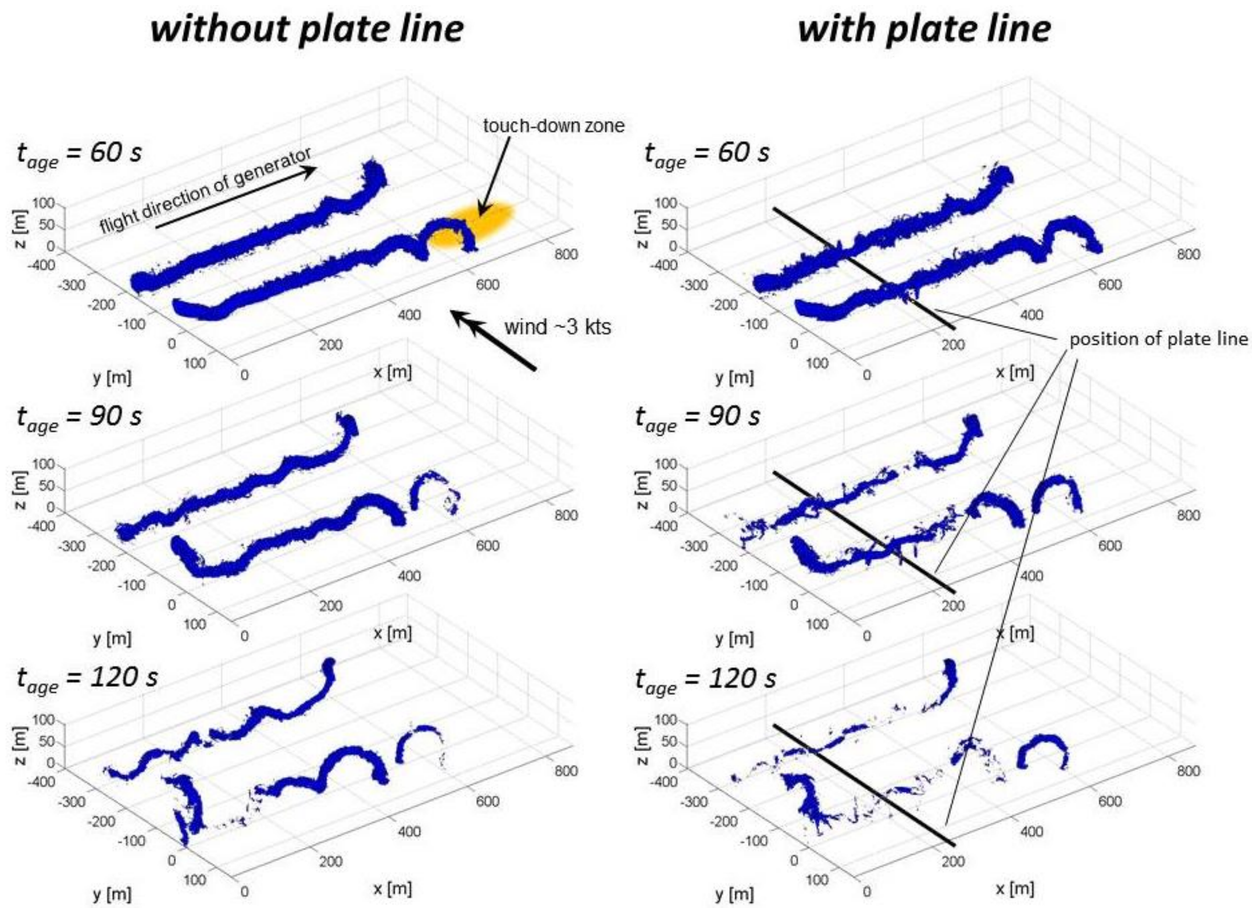

Fig. 5 Vortex shapes for different ages with and without plate line under light crosswind.

As mentioned above the position of the encountering aircraft's flight path through the vortex flow field was varied in the simulation study. This variation was performed in longitudinal and lateral direction within a meaningful range in order to represent different touchdown points of the encountering aircraft or little variations in wind speed. This way the encountering aircraft passes through the wake's wind field at different positions within a meaningful range.

For the interpretation of the results it must be emphasized that flight path and aircraft reaction also depend on the characteristics of the flight control system, which can only hardly be fully validated against the behavior on external disturbances (see explanation in section III. A.). Hence, the absolute numbers of incidents that occur in the simulation is not necessarily fully comparable to reality. The absolute results are likely to differ with a real A320. Nevertheless, relative assessments between different vortex ages or cases with and without plate line are indeed valid.

Interestingly, no encounter at any vortex age resulted in a wing strike, neither with nor without plate line. This issue will be discussed later on. Figure 6 shows the distribution of incidents without plate line as a function of the position of the touchdown point. One can observe that tail strikes occurred around the touchdown point of the generator aircraft (x = y = 0 m) only at a vortex age of 60 s. Hard landings occurred at vortex ages of 60 s and 90 s but not at 120 s. Runway excursions occurred at each vortex age. The analysis of the simulation results shows that runway excursions occurred due to a yawing impact shortly before touchdown, causing the aircraft to touchdown in a crabbed motion with an angular difference between aircraft and runway of about 10-15°. In those cases the autopilot in the simulation is not able to keep the aircraft on the runway. However, it is questionable whether this would also occur in reality. Probably the yawing impact could be manageable for the autopilot or pilot in reality. E.g. in case of strong crosswinds a touchdown in crabbed motion is not unusual as well and mostly does not lead to a runway excursion.

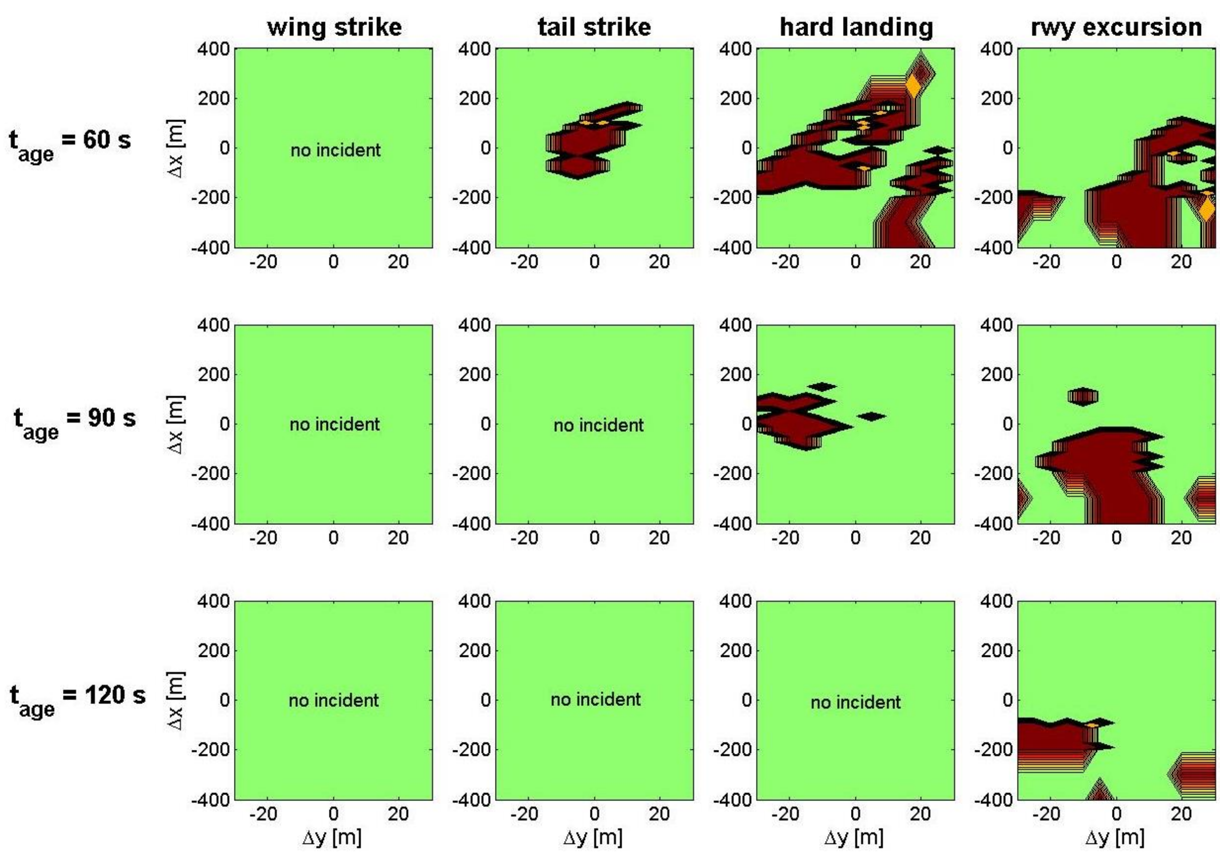

Fig. 6 Distribution of incidents without plate line under light crosswind.

Tail strikes and hard landings mostly occurred in the simulations due to up- or downwash beside the vortex centers. Both, tail strikes and hard landings, occurred due to large pitch angles as a result of the vortex downwash. As the autopilot tries to maintain the glideslope the pitch angle is increased in the downwash area of the vortex. This can either lead to a tail strike or if the aircraft subsequently leaves the downwash area, the high pitch angle can lead to a too high flare. A few meters above ground the engines are already in idle so that in such a case the airspeed rapidly drops resulting the aircraft to plunge down, eventually followed by a hard landing.

Figure 7 depicts such a case resulting in a maximum vertical load-factor of almost 3 at touchdown. Referring to the A320 maintenance manual [34] this is considered a severe hard landing (vertical acceleration equal or more than 2.86). Tail strikes and hard landings did not occur at a vortex age of 120 s, which is slightly less than the current ICAO minimum separation for MEDIUM behind HEAVY. Besides the possibly questionable runway excursions no further incidents occurred at that vortex age. This supports the initially mentioned general opinion that today's wake related separation schemes are sufficiently safe. However, the simulations reveal that in case that the separation shrinks the number of incidents increases considerably.

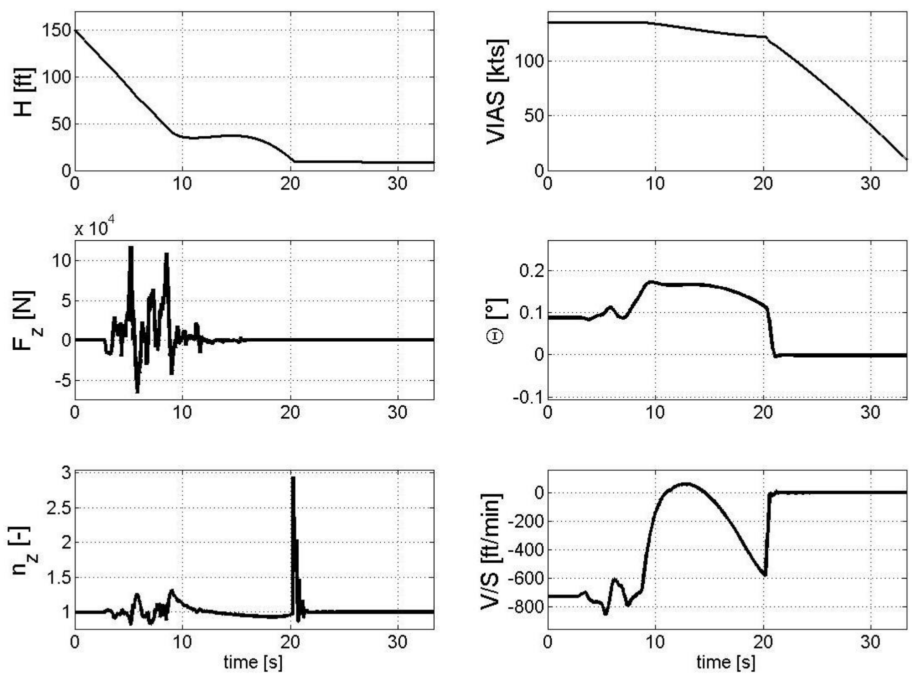

Fig. 7 Time histories of exemplary hard landing.

As mentioned above no wing strike occurred in the simulations although the roll axis is usually considered as the most relevant one for wake encounters under small encounter angles like during approach and landing.

Fig. 8 shows the vortex impact and aircraft reaction in the roll axis for all three vortex ages. Comparing the vortex rolling impact in terms of maximum RCR that occurred during the encounter and the aircraft reaction in terms of maximum roll rate, $|p|_{max}$, and maximum bank angle, $|\Phi|_{max}$, one can observe that the areas with the highest RCR_{max} values are not always the areas where the maximum aircraft reaction occurred. This fact is very obvious at t_{age} = 60 s and can be explained by the duration of the vortex impact. The shorter the impact, the lesser the aircraft reaction can evolve. Hence, the maximum bank angles did not occur in the area with the maximum RCR_{max} values of almost 2, but in those areas with RCR_{max} values in the range between approximately 0.5 and 0.8 (the lower right corner of the figures). The maximum bank angle that occurred during the encounter simulations is at about 20°. However, this maximum bank angle occurred indeed at a still sufficient height so that the wing did not hit the ground in those cases. Nevertheless, such large bank angles at very low altitude would most likely lead to a go-around initiated by the pilot.

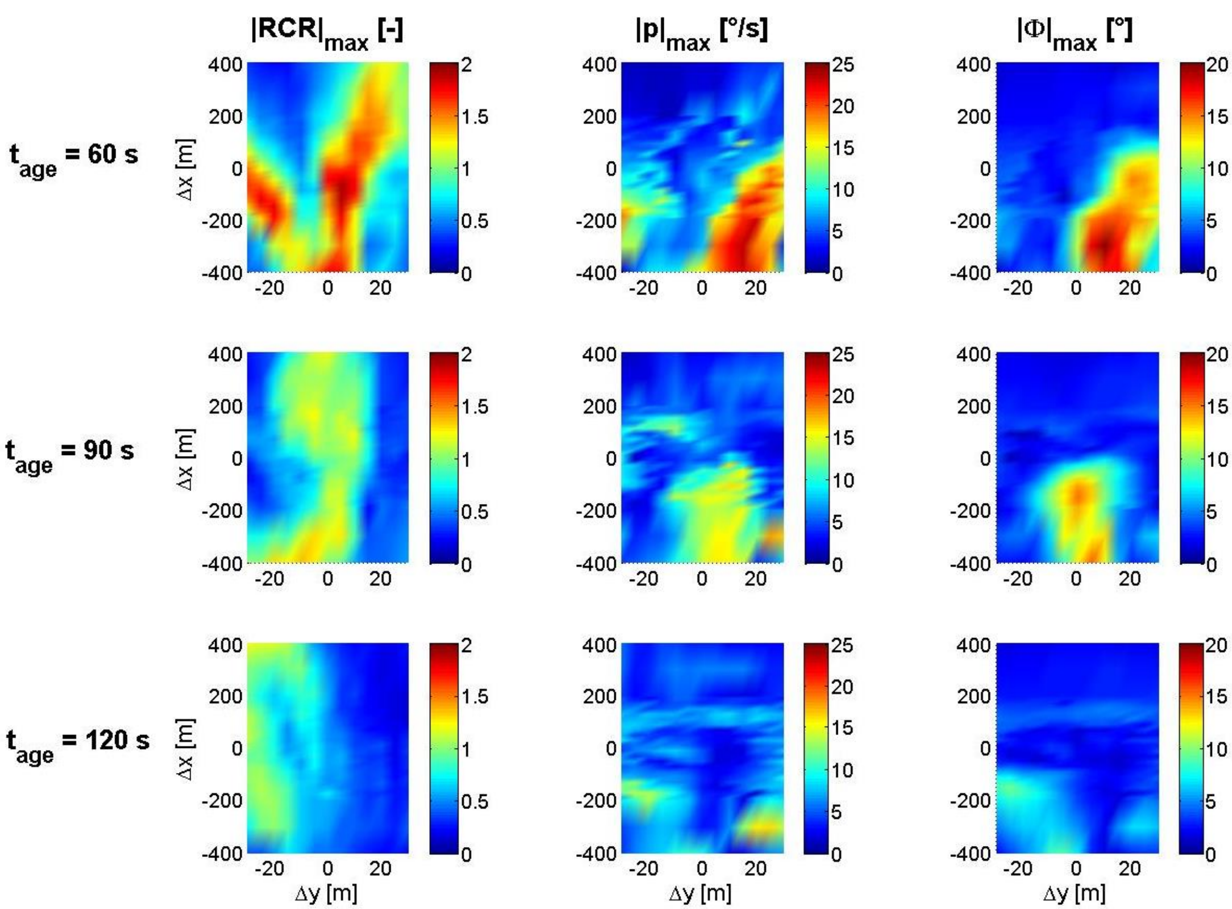

Fig. 8 Distribution of RCR_{max} and aircraft reaction in the rolling axis without plate line.

Similar to the encounter resulting in a hard landing shown in Fig. 7 the following Fig. 9 depicts an encounter with large bank angles, which, however, did not result in a wing strike but in a hard landing and a runway excursion.

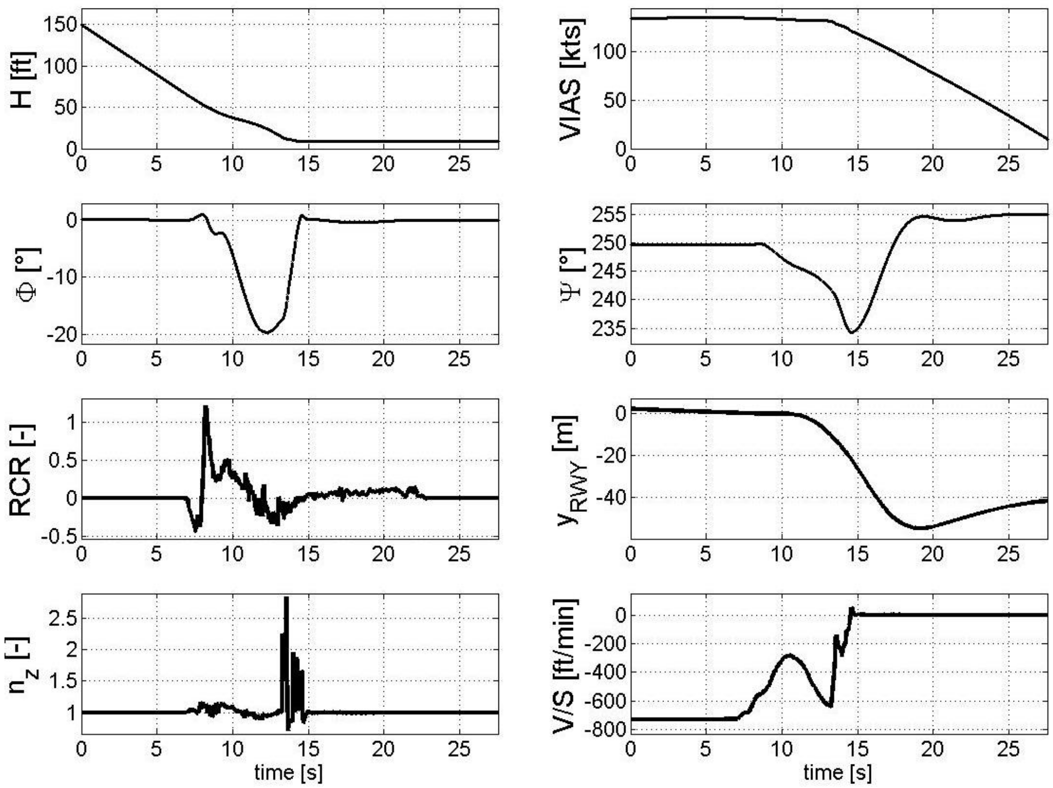

Fig. 9 Time histories of exemplary encounter with large bank angles.

One can observe in Fig. 9 that the maximum bank angle occurs at a height of about 20-30 ft. With a maximum bank angle of 19.7° and a height of the center of gravity of 7.3 m in that moment the wing-tip is only 1.6 m above the runway. Also, the yawing motion of 15° to the left during this violent roll to the left is critical. Even as this encounter does not result in a wing strike, it is rated as severe hard landing (n_z > 2.85 [34]) and leads to a runway excursion as well.

In order to accelerate vortex decay, hence hopefully lower the risk of a considerable impact by the wake on a trailing aircraft, a plate line as described in section II. B. is included in the simulation. Practically, this means that different vortex flow fields were used in the encounter simulation for the mentioned vortex ages including the effect of a plate line.

The analysis of the simulation results with plate line reveals similar general effects as without plate line. However, due to the lower vortex flow velocities the vortex impact is reduced. Figure 10 shows the vortex impact and aircraft reaction in the roll axis for the simulations with plate line. In the figure the areas with large aircraft reactions have similar extensions, but the magnitudes of the aircraft reactions are significantly reduced in comparison to the case without plate line (s. Fig. 8).

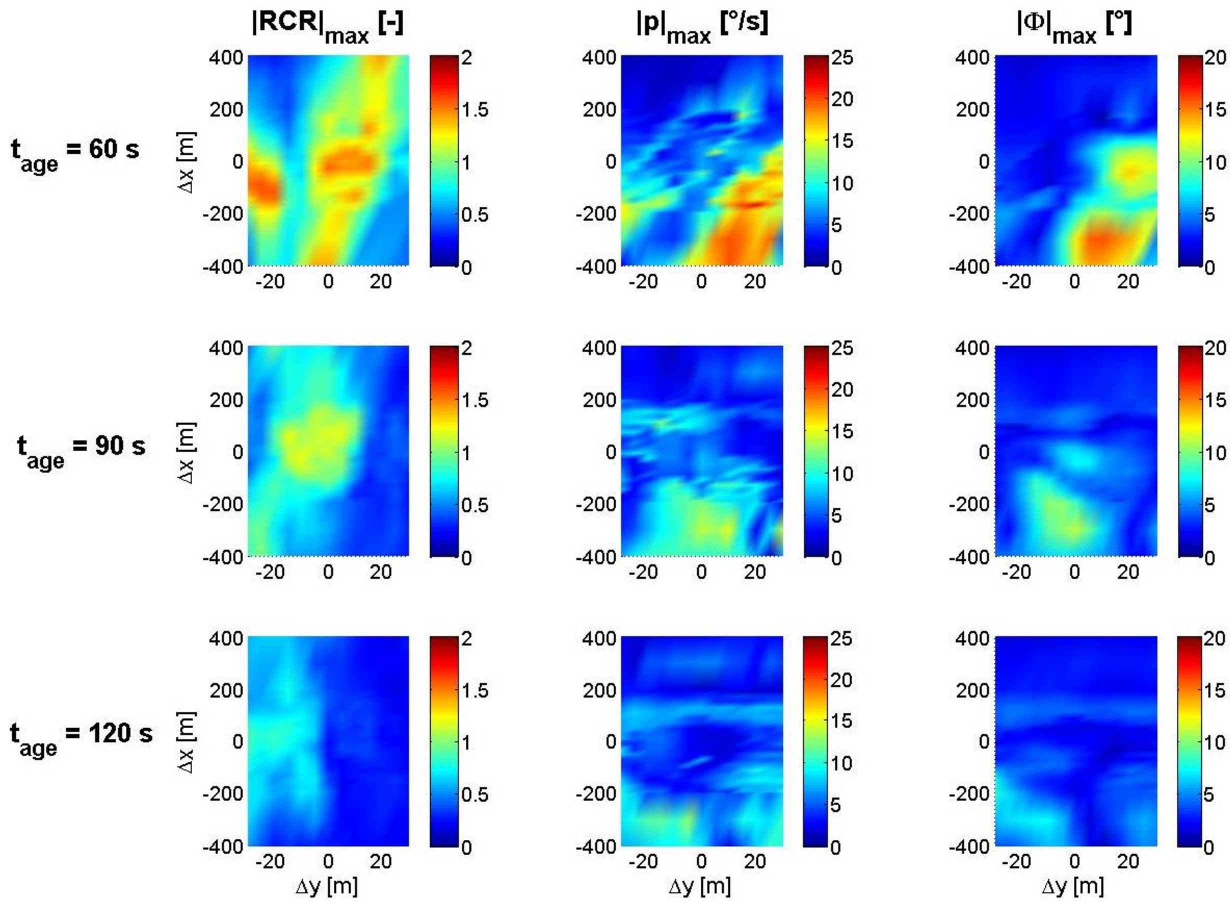

Fig. 10 Distribution of RCR_{max} and aircraft reaction in the roll axis with plate line.

For a quantitative overview Table 1 shows the number of incidents with and without plate line as well as the relative improvement. The table shows a significantly lower number of incidents with plate line. The only slight increase is for hard landings at vortex ages of 90 s, when the incidents rise from 36 without plate line to 37 with plate line. All other incidents are significantly reduced.

Table 1 Number of incidents with and without plate line

	without plate line			
vortex age [s]	wing strike	tail strike	hard ldg	rwy exc.
60	0	38	110	75
90	0	0	36	67
120	0	0	0	39
	with plate line			
	wing strike	tail strike	hard ldg	rwy exc.
60	0	7	95	57
90	0	0	37	44
120	0	0	0	11
	relative improvement			
	wing strike	tail strike	hard ldg	rwy exc.
60	-	82 %	14 %	24 %
90	-	-	-3 %	34 %
120	-	-	-	72 %

As Fig. 10 already depicts for the roll axis, the same outcome can be observed regarding the aircraft reaction that is reduced as well with plate lines. Table 2 depicts the maximum values of RCR, bank angle, vertical load factor and maximum pitch angle that occurred during all encounters as well as the relative improvement with plate line. Interestingly, in the roll axis the positive effect of the plate line is more obvious for the younger vortices. Regarding the maximum RCR one can observe that the values are significantly lower with plate line, especially for the old vortices. Nevertheless, these lower maximum rolling impacts do not result in the same reduction of aircraft reaction in terms of maximum bank angle Φ_{max} (~30% reduction in RCR_{max} compared to ~16% reduction in bank angle at t_{age} = 120 s). This implies that the duration of the maximum rolling impact is short, whereas the amount of lesser, but still considerable rolling impact that results in aircraft reaction is not lowered on a comparable level by the plate line. However, for t_{age} = 90 s the maximum bank angle could be reduced by almost 30% by the plate lines, which is a remarkable number indeed.

Table 2 Maximum rolling impact and aircraft reactions with and without plate line and relative improvement

	without plate line			
vortex age [s]	RCR_{max} [-]	$\lvert\Phi\rvert_{max}$ [°]	$n_{z,max}$ [-]	Θ_{max} [°]
60	1.90	19.7	17.0	17.3
90	1.36	15.5	5.1	10.4
120	1.21	9.5	2.5	9.4
	with plate line			
vortex age [s]	RCR_{max} [-]	$\lvert\Phi\rvert_{max}$ [°]	$n_{z,max}$ [-]	Θ_{max} [°]
60	1.59	15.6	15.5	14.0
90	1.19	11.2	5.0	10.2
120	0.86	8.0	2.2	9.3
	relative improvement			
vortex age [s]	RCR_{max}	$\lvert\Phi\rvert_{max}$	$n_{z,max}$	Θ_{max}
60	16.3 %	20.8 %	8.8 %	19.1 %
90	12.5 %	27.7 %	2.0 %	1.9 %
120	28.9 %	15.8 %	12.0 %	1.1 %

The significant reduction of the maximum RCR is in line with the results of the WakeOP flight campaign [19] mentioned in section II. B., where Lidar measurements showed a reduction of the vortex circulation due to the plate line. As the vortex induced rolling moment, hence the RCR, is mainly influenced by the vortex circulation, the vortex separation and the encountering aircraft's geometry, a lower circulation is directly connected to a lower RCR if all other influencing factors are kept the same. However, if the maximum rolling impact acts on the encountering aircraft only for short time so that only little aircraft reaction can evolve, a reduction of the maximum rolling moment does not affect the maximum aircraft reaction in the same manner.

Nevertheless, the results show a significant influence of the plate line on the severity of wake encounters. The number of incidents and the magnitude of the aircraft reaction can indeed be reduced by the plates. The simulations without plate line confirm that present minimum separation standards to avoid hazardous wake encounter are effective. With 120 s old vortices the most significant impact of the encounters was in the yawing axis. As described above it could be assumed, that this would be less a problem in reality. No tail strike, hard landing, or any wing strike occurred at this vortex age. However, in case of reduced minimum separations plate lines could possibly reduce the wake impact effectively; hence reduce the probability of hazardous wake encounters and increase flight safety.

VI. Conclusions

A simulation study was performed for hazard assessment of wake encounters in ground proximity and in order to investigate the influence of so-called plate lines on the encounter severity. Plate lines are a series of plates positioned in front of the runway that have proven to effectively accelerate the vortex decay.

Wake vortex flow fields of a wake generating aircraft of the HEAVY category were generated by coupling Reynolds-averaged Navier-Stokes (RANS) simulations with Large-Eddy-Simulations (LES). With this coupling a realistic behavior of the wake vortices of a landing aircraft in ground proximity could be simulated from wake generation until full decay. For the encounter simulations different flow fields were generated for two different wind situations as well as with and without a plate line. Simulations of an A320 encountering the wake at different vortex ages and at different positions were performed without wind and with the worst case wind scenario, namely light crosswind that makes the luff vortex hover above the runway unless it is fully decayed.

The simulations without wind showed that in this case the vortices pose no threat to a follower aircraft at operationally relevant vortex ages as the vortices quickly diverge, opening enough space for a follower to safely land in between.

With light crosswind of the magnitude of the velocity with which the vortices diverge (here 3 kts), the luff vortex remains above the runway posing a considerable threat to a follower aircraft for quite a long time. Vortex ages of 60 s, 90 s and 120 s were considered in this simulation study. The vortex age of 120 s roughly represents a separation distance between HEAVY generator and MEDIUM follower aircraft as prescribed with the current ICAO separation scheme.

The simulations with light crosswind and without plate line show no incidents with 120 s old vortices except some runway excursions that might be questionable and possibly be explained with an insufficient yaw control of the used autopilot on ground. With younger vortices a significant number of tail strikes and hard landings occurred besides an increased number of runway excursions. Although remarkable bank angles of about 20° were observed during some encounters, no wing strike occurred at any vortex age as the large bank angles occurred at altitudes still sufficient not to hit the runway with the wing. However, in reality such large bank angles at very low altitude would most likely lead to a go-around.

The simulations with light crosswind and plate line showed that the plate line effectively reduces the maximum rolling moment (or roll control ratio) acting on the encountering aircraft. This result is in line with measurements of previous studies showing an increased decay of the vortices due to the plate line. However, during the encounter the maximum values only occur for very short periods of time so that the aircraft reaction is not much affected by this impact. The aircraft reaction seems to be more affected by lower but longer lasting rolling moment impact that still exists also with plate line.

Nevertheless, the simulations showed a significant reduction of the aircraft reaction as well. Especially for younger vortices the vortex impact and the aircraft reaction could be effectively reduced by the plates.

Concluding, one can say, that the simulations showed that present separation minima can be considered as acceptably safe and that in case of a reduction of separation minima plate lines could be an effective mean in order to maintain the same level of safety.

The results of the simulation study presented here will be enhanced in the future by subjective hazard ratings of pilots. For this reason a simulator study is planned to be conducted in the AVES A320 full-flight-simulator of DLR Institute of Flight Systems.

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