1. A simulation case-study on the influence of plate lines on the severity of wake vortex encounters in ground proximity

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Close to ground the behaviour of wake vortices changes in comparison to out of ground effect. Whilst vortices descend in free air due to their mutual induced velocities, they are hindered in sinking in presence of ground. This also changes the risk to encounter the wake of a preceding aircraft. Furthermore, wake encounters in ground effect are especially critical due to the nearness of the ground. Recent studies showed that vortex decay in ground proximity can be accelerated by installing a series of plates in lines perpendicular to the flight direction (so-called plate lines). This study analyses whether the accelerated vortex decay also results in lesser encounter severity in terms of aircraft reaction and pilot acceptance. Flow fields were generated by coupled RANS-LES simulations of an A340-sized aircraft in ground effect with light crosswind with and without plate lines for different vortex ages were implemented in a six-degrees-of-freedom aircraft simulation of an A320-sized aircraft. Offline simulations with autopilot engaged in autoland-mode showed a significant reduction of the aircraft response during the wake encounter with the plate lines. This reduction is indeed more pronounced with younger vortices but is still noticeable with old vortices. Simulations with pilots-in-the-loop in a full-flight simulator applying the same simulation model for the encountering aircraft also show a reduction of the aircraft response during manual landing as well as improved subjective pilot acceptance. Plate lines are therefore considered an effective means for either increasing flight safety with current minimum separations or maintaining the same level of safety in case that the minimum separations are reduced in the future.

Introduction

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 [1,2]. 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, due to the same sign as the crosswind shear, and attenuates it at the luff (upwind) vortex, due to the opposite sign of the crosswind shear. Secondly, the primary vortices redistribute vorticity of the crosswind shear with which they mutually induce transport velocities [3]. These effects lead to an earlier and higher rebound and a more rapid decay of the lee vortex.

An increase in encounter probability close to ground was shown by various simulations [4-6]. Those results are confirmed by an increased encounter occurrence close to ground shown by pilot reports [7-10]. A potentially most dangerous situation for following aircraft arises if the longer-living luff vortex hovers above the runway because the self-induced lateral propagation speed of the luff vortex is just compensated by the crosswind. Numerical simulations [3] and lidar measurements conducted at Frankfurt airport [11] 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 is the induced lateral vortex speed. In this study, with a generator aircraft of the ICAO HEAVY category, a crosswind of about 3 knots at a height of one initial vortex separation is chosen in order to compensate lateral vortex drift immediately before touchdown.

Recent studies showed that vortex decay in ground proximity can be accelerated by installing a series of plates in lines perpendicular to the flight direction (so-called plate lines) [35]. Plate lines [12] trigger the early detachment of strong Ω-shaped secondary vortices that actively approach the wake vortices and subsequently propagate along the primary vortices. These secondary vortices lead to an accelerated wake vortex decay independent from natural external disturbances [1,2]. Lidar measurements confirm the functionality of the plate line [3]. The benefits of the plate line are obvious 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 on the glide path, plate lines may substantially reduce vortex lifetimes and thus increase safety.

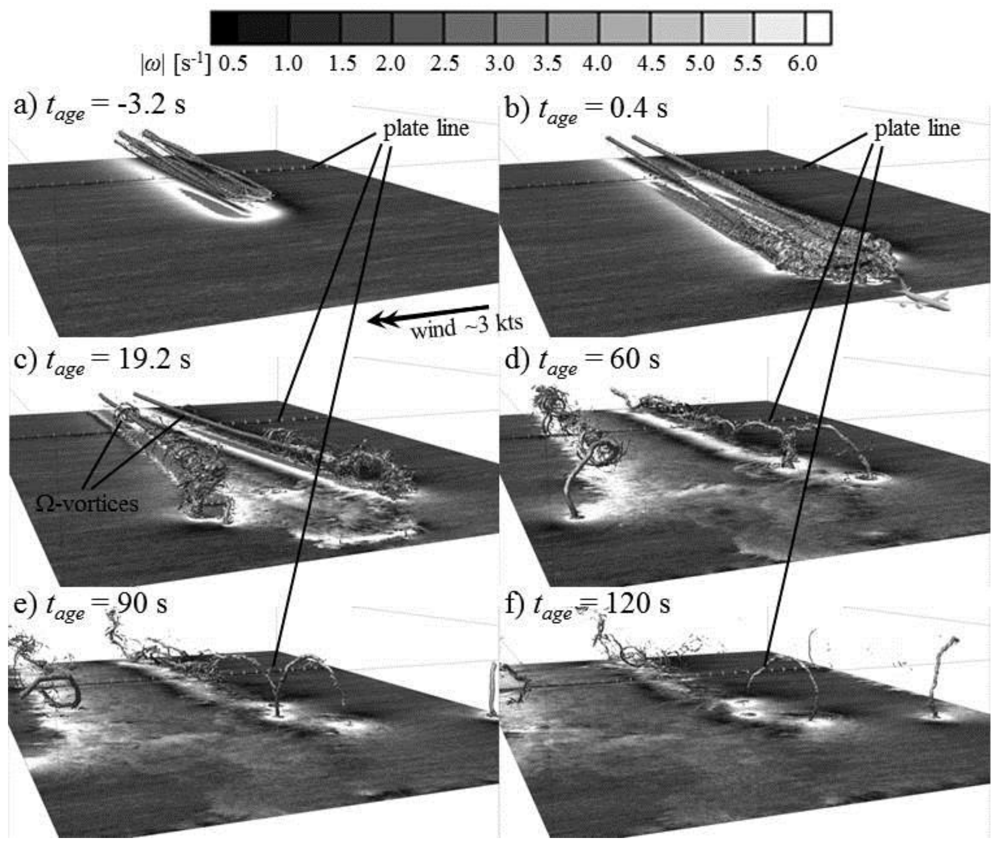

Figure 1 General overview on the simulation of wake vortex evolution of a landing aircraft at weak crosswind with plate line (iso-surfaces show vorticity of $|\omega| = 3.3\ \mathrm{s}^{-1}$, ground shaded by vorticity magnitude) [13].

The purpose of the simulations presented here is to analyse whether the accelerated vortex decay due to the plate line also affects the reaction of the encountering aircraft and the subjective hazard perception of pilots near ground. A more detailed analysis of the offline-simulations can be found in [13].

Aircraft Model

The DLR research aircraft A320 ATRA (Advanced Technologies Testing Aircraft) was chosen as encountering aircraft. For this aircraft a comprehensive simulation model exists at the DLR Institute of

Flight Systems [14] usable for offline-simulations on usual desktop computers as well as for the motion-based full-flight simulator AVES [15]. The analysed 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.

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 aerodynamic 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. The aerodynamic model is validated by means of flight test data from ATRA within the flight envelope for normal operations. Besides this, the aircraft simulation model includes models of the V2500 engines, landing gear, control surface actuators and sensors (air data, navigation etc.), which are not yet validated by means of flight test data but which were adapted in a way to represent an A320. The sensor models for inertial and air data consider a specific time delay for each sensor and additionally the wind vanes for angle of attack and sideslip angle are modelled as PT2-system. The local influence of the vortex flow field on the wind vanes is considered in the sensor models as well (s. next section). However, as the angle of attack is not used for the flight control laws but only for engaging the high angle of attack protection (alpha-floor) the effect of the vortex flow field on the wind vanes is less relevant. Engagement of the high angle of attack protection did not occur during any simulation. The ATRA model incorporates a flight control system designed in analogy to the Airbus flight control architecture. The flight control system model of the ATRA simulation consists of an autopilot / auto-thrust system and provides a typical normal law with rate command / attitude hold control for manual flight.

One issue to keep in mind is that the reaction of the simulated flight control system to an external disturbance is difficult to validate. Whilst the response of the flight control system to control inputs shows a good conformity to the behaviour of the original flight control system of ATRA, its reaction to 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. All parameters, which are relevant for representing the flight dynamics of an aircraft correctly, are within the tolerances for Level-D-simulations [14,16]. Hence, the accuracy of the simulation model can be considered sufficient for scientific purposes. Also, even if the maximum aircraft response may be different from the response of the original A320 flight control system on the same external disturbance it can be assumed that relative assessment between cases with and without plate lines shows the correct tendency. For this reason the outcomes of the present simulation study can be considered as meaningful.

Generation of vortex flow fields and modelling of the aerodynamic interaction

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 [12]. 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) solution through the domain, which enables to simulate wake vortex evolution from generation until final decay [17]. Compared to the method used in previous studies [22,27], where fully rolled-up vortices were introduced in the LES-domain, this method considers all physical effects from the very creation and roll-up of the vortices right behind the generator aircraft and thus gives a much more realistic start point for the further simulation of the vortex evolution. Validation with data from windtunnel-measurements showed a very high accuracy of the simulation results [17].

The simulations are performed for an ICAO HEAVY transport aircraft of A340-size in high-lift configuration with deployed flaps and slats without landing gear. A landing mass of m = 190,000 kg, a wingspan of b = 60.3 m and a true airspeed of 75 m/s was employed, leading to an initial circulation of Γ_0 = 435 m^2/s and an initial vortex descent speed of w_0 = 1.46 m/s. The RANS flow field, which has been established before with the DLR TAU code [18], serves as a forcing term or inner boundary in the LES domain. The LES code MGLET from the TU Munich [19] calculates the flow in the ground fixed domain, incorporating a Lagrangian dynamic subgrid-scale model [20]. The LES are conducted with and without one plate line. A turbulent crosswind with a wind speed of 3 knots at a height of one initial vortex separation is allowed to develop prior to the wake initialization [21]. It is assumed that the encounter duration is short so that during an encounter the vortex age does not alter significantly. For this reason vortex flow fields for one specific vortex age are used for the entire encounter simulation.

The numerical results of the coupled RANS-LES simulations for three specific vortex ages (60 s, 90 s, 120 s) were transformed into three-dimensional look-up tables. These look-up tables were implemented in the simulation model of the encountering aircraft with a linear interpolation in order to give the velocity components in the three spatial directions (u,v,w) at a given position in space (x,y,z). The dimensions of these flow fields can be taken from Figure 2 which shows the shape of the vortices at three vortex ages with and without plate line. The plots in Figure 2 show the iso-surfaces of an absolute flow velocity of 5 m/s including the wind velocity. 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 centreline) 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.

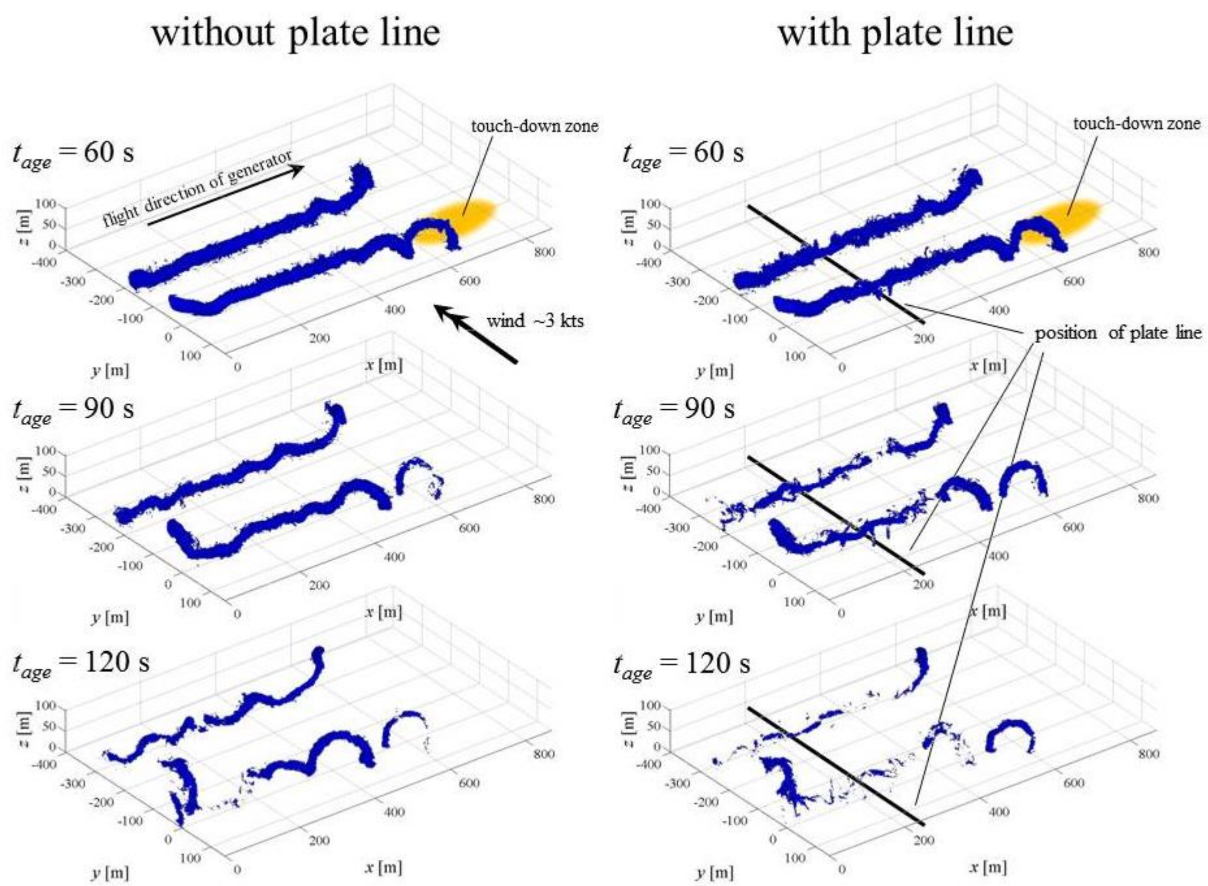

Figure 2 Vortex shapes (iso-surface of $|V| = 5\,\mathrm{m/s}$) for the investigated ages with and without plate line under light crosswind [13].

In order to simulate wake encounters with a dynamic aircraft simulation, an aerodynamic interaction model (AIM) is needed which calculates the vortex induced forces and moments acting on the encountering aircraft as a function of the aircraft position and attitude. 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 approach used for the AIM is the so-called strip method which divides the lift and side force generating surfaces of the aircraft (including wings, horizontal and vertical tail plane and fuselage) into single strips (see Figure 3).

For each strip an additional angle of attack (for wings and horizontal stabilizer) or angle of sideslip (for the fuselage and the 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 moments as well. For the wings and the horizontal stabilizer an elliptical lift distribution is assumed and the resulting forces of each strip are weighed accordingly. Each strip is positioned according to the aircraft's geometry relative to the aircraft's centre of gravity. The forces and moments are assumed to apply at 25% of the strip's chord length. No dedicated stall model is included, instead for large angles of attack at the strips (>20°) the angle of attack is kept constant in order to prevent unrealistically high resulting forces. The forces and moments of all strips are 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.

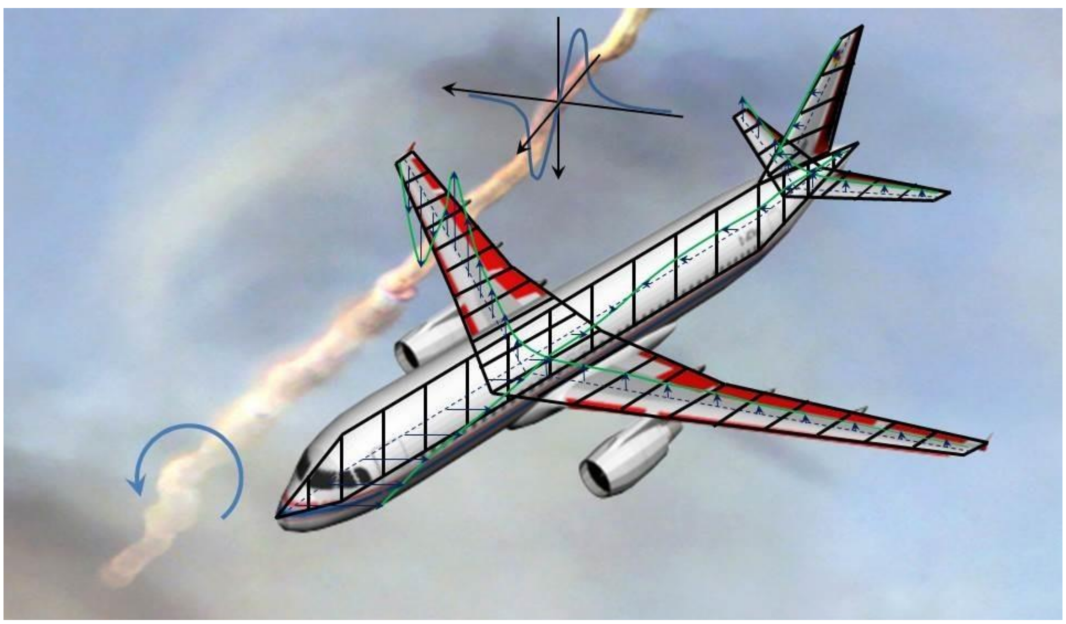

Figure 3 Depiction of the strip method with an exemplary lift distribution (green line) for each strip (black rectangles) [22].

This method was deemed feasible by Barrows [23], verified against wind tunnel tests by de Bruin [24], and further validated using flight test data by Fischenberg [25] and Jategaonkar [26]. The method was applied in various studies in the past [22,27-29] and is accepted to provide vortex induced forces and moments of acceptable accuracy.

As mentioned above, the vortex flow fields are not only used for the calculation of the forces and moments acting on the encountering aircraft, but also to calculate the influence of the wake encounter on the air data probes and vanes.

AVES Motion-Based Flight Simulator

The AVES (Air VEhicle Simulator) simulator centre was established by DLR Institute of Flight Systems in 2013 [15]. The simulator centre comprises a fixed-based and a motion-based simulator with variable cockpits. Figure 4 (left-hand side) shows the motion-based simulator of the AVES simulator centre from outside. As a major part one can observe the large dome which allows an enormously large visual projection area of 240° in horizontal and 95° in vertical direction. The large vertical expansion of the visual projection area is a requirement from the helicopter simulation, as helicopters require a much larger outside view as fixed-wing aircraft. Another detail of the motion-based simulator in Figure 4 is the motion system, which consists of an electrical hexapod-system. Figure 4 (right-hand side) shows the inside view of the A320 cockpit of AVES. The cockpit is a replica of the A320 cockpit, which represents the original in almost all details. In the aft part of the cockpit (not visible in Figure 4) an operator station is located, which allows full control of the simulation.

Figure 4 The AVES motion-based flight simulator

The whole software of the AVES was developed by DLR Institute of Flight Systems except the control of the motion platform. The flight simulation including the flight control system, autopilot, flight management system, flight warning computer, systems simulation as well as the simulator control software and the visual software was also developed by DLR Institute of Flight Systems. This guarantees highest flexibility for scientific purposes. Although the simulator is not certified for pilot training following JAA STD 1A [16], the simulation accuracy is considered to be well appropriate for scientific investigations.

Severity Assessment

For the assessment of the severity or hazard of a wake encounter suitable metrics are needed. During approach and landing aircraft usually fly the same nominal flight path, for which reason wake encounters typically occur under small encounter angles during this flight phase. As under small encounter angles the rolling moment induced by the vortices is the predominant disturbance acting on the encountering aircraft [30], it is reasonable to choose a metric that uses the rolling moment impact. An appropriate parameter is the so-called Roll Control Ratio *RCR*, i.e. the ratio between the vortex induced rolling moment coefficient $C_{\ell,ind}$ and the coefficient of the maximum rolling moment which can be generated by all roll control surfaces $C_{\ell,CTRL,\max}$ [31,32]

$$RCR = \frac{C_{\ell,ind}}{C_{\ell,CTRL,\max}}. \quad (1)$$

Consequently, an *RCR* greater than 1 means that the induced rolling moment cannot be fully compensated by the roll controls of the encountering aircraft. One important hazard metric used here is the maximum absolute *RCR* which occurred during the encounter $|RCR|_{\max}$. Other parameters used as metric represent the aircraft motion, e.g. the maximum bank angle Φ_{max}. Such metrics are useful when comparing different encounters or rating encounters on an objective level without any subjective pilot rating. However, a disadvantage of metrics like the maximum bank angle is that these values depend on the control inputs from the pilot or autopilot. The $|\mathrm{RCR}|_{\max}$ is independent from control inputs and can be interpreted as the potential maximum impact on the encountering aircraft. 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.

As the encounter scenario analysed here is close to ground, some additional criteria for non-acceptance are defined for the offline simulations, where no pilot rating on the encounter acceptance can be obtained. These additional criteria are based on the A320 geometry: a) wing strike (if $\Phi > 4.1872°/\mathrm{m} \cdot H + 19°$), b) tail strike (if $\Theta > 12°$ and $H < 20$ m), and c) hard landing (if $n_z \geq 2.6$ g [33]). A violation of any of these criteria in the offline simulations is rated as hazardous and therefore as unacceptable.

For the pilot-in-the-loop simulations a rating scale is needed which quantifies the subjective hazard perception of the pilot. For this reason a dedicated wake encounter rating scale was developed [34] (s. Figure 5). Right after each encounter the pilot has to rate the four items “aircraft control”, “demands on the pilot”, “aircraft deviations from flight state and flight path” and overall “hazard” on a scale from 1 to 4. These ratings are purely subjective and can therefore differ from pilot to pilot. In case that any rating item is rated with “4” the encounter is unacceptable by definition. Also, even as go-arounds may not inevitably be hazardous but should be prevented, the encounter is to be rated as unacceptable in case the pilot performs a go-around. In case of a go-around the aircraft deviations have to be rated with “4” by definition in order to numerically identify the encounter as unacceptable afterwards.

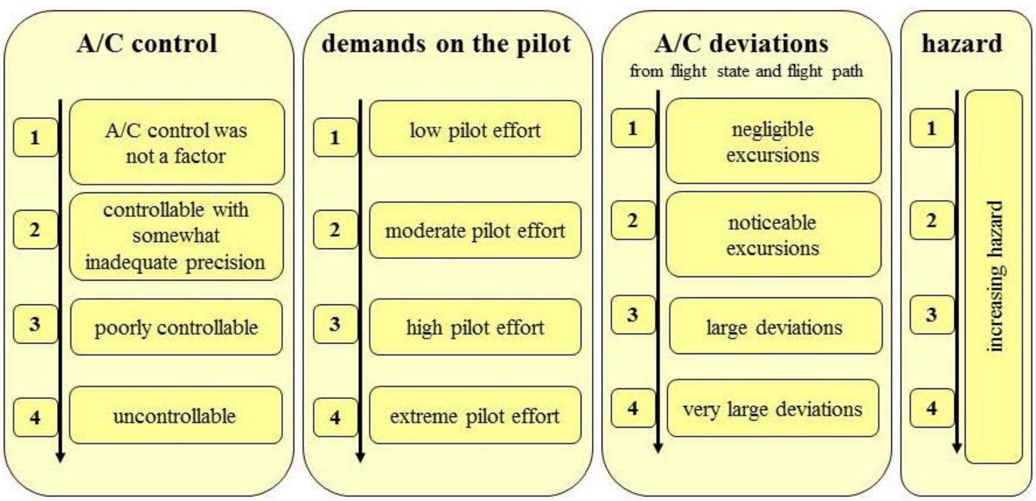

Figure 5 The wake encounter rating scale [34]

For the interpretation of the pilot ratings the practical experience from the experiments showed that if the average over all four rating items is below or equal “2” the encounter can be regarded as harmless. In this case the impact of the wake cannot be distinguished from other acceptable atmospheric disturbances such as light turbulence or gusts. On the other hand side the encounter has to be rated as unacceptable if one rating item is rated with “4” regardless from the other three rating items. Those encounters, which are not unacceptable by definition but with an average rating greater than “2” are indeed acceptable but cannot be regarded as harmless.

Offline Simulations

Offline simulations were conducted for analysis of the influence of plate lines on the aircraft reaction under variation of the encounter parameters. A more detailed analysis of the offline simulations described here is given in [13].

In all simulations the aircraft mass of the encountering A320 was 54 tons with a centre-of-gravity location of 25% of the mean aerodynamic chord (MAC). The aircraft is always fully configured with slats and flaps fully extended (slats at 27° and flaps at 40° deflection angle) and gear down. At simulation start the aircraft is trimmed with an approach speed of 137 kts true airspeed. The aircraft always lands in the autoland mode of the autopilot with glideslope and localizer hold engaged. In order to analyse different relative flight paths through the vortex flow field, the position of the flow field is varied in lateral and in longitudinal direction. This variation was performed between -500 m and 500 m in longitudinal direction (with a general step size of 100 m and a smaller step size of 20 m between -200 m and 200 m) and between -100 m and 100 m in lateral direction (with a general step size of 10 m and a smaller step size of 5 m between -50 m and 50 m). Altogether 868 encounters were simulated with different relative flightpaths through the vortex flow field, each with and without plate lines.

Table 1 shows the number of criterion violations with and without plate line as well as the relative improvement. Interestingly, no encounter at any of the analysed vortex ages resulted in a wing strike, neither with nor without plate line. One can observe that tail strikes occur 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. The table shows a significantly lower number of criterion violations with the plate line. The only slight increase is for hard landings at vortex ages of 90 s, when the criterion violations rise from 36 without plate line to 37 with plate line. However, this is a statistical issue at the boundaries of the investigated parameter space. All other criterion violations are significantly reduced.

	without plate line		
t_{age} [s]	wing strike	tail strike	hard ldg
60	0	38	110
90	0	0	36
120	0	0	0
	with plate line		
	wing strike	tail strike	hard ldg
60	0	7	95
90	0	0	37
120	0	0	0
	relative improvement		
	wing strike	tail strike	hard ldg
60	-	82 %	14 %
90	-	-	-3 %
120	-	-	-

Table 1 Number of criterion violations with and without plate line

Figure 6 shows the vortex impact, represented by $|RCR|_{max}$, and the aircraft reaction in the roll axis for all three investigated vortex ages. Comparing the vortex rolling impact in terms of $|RCR|_{max}$ 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 scenarios with the highest $|RCR|_{max}$ values are not always those with the maximum aircraft reaction. 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 smaller the aircraft reaction can evolve. Hence, the maximum bank angles did not occur in the scenarios with the highest $|RCR|_{max}$ values of almost 2, but in those with smaller but longer-lasting rolling impact and $|RCR|_{max}$ 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 about 20°. However, those events occurred at heights at which the wing could not hit the ground. Nevertheless, such large bank angles at very low altitude would be unacceptable for the pilot in reality and would most likely lead to a go-around.

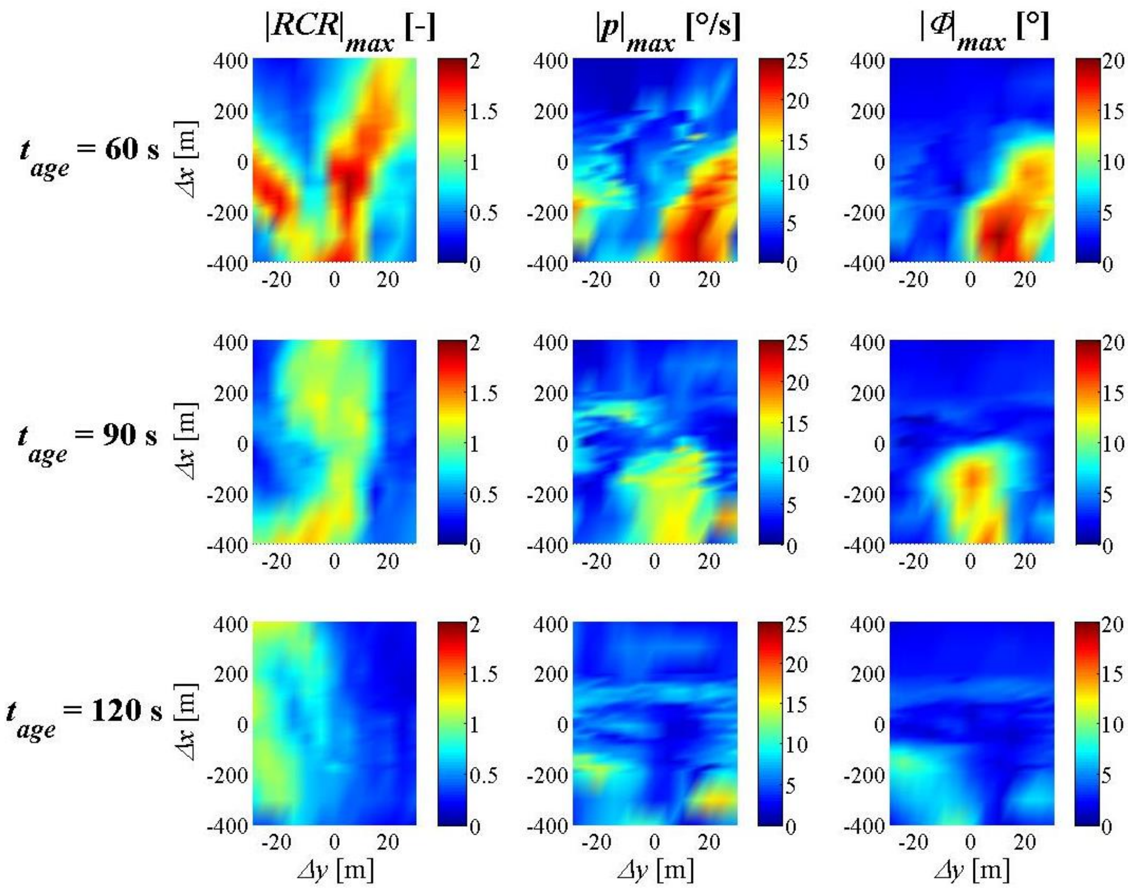

Figure 6 Distribution of $|RCR|_{max}$ and aircraft reaction in the rolling axis without plate line as a function of the relative longitudinal (Δx) and lateral (Δy) flow field position.

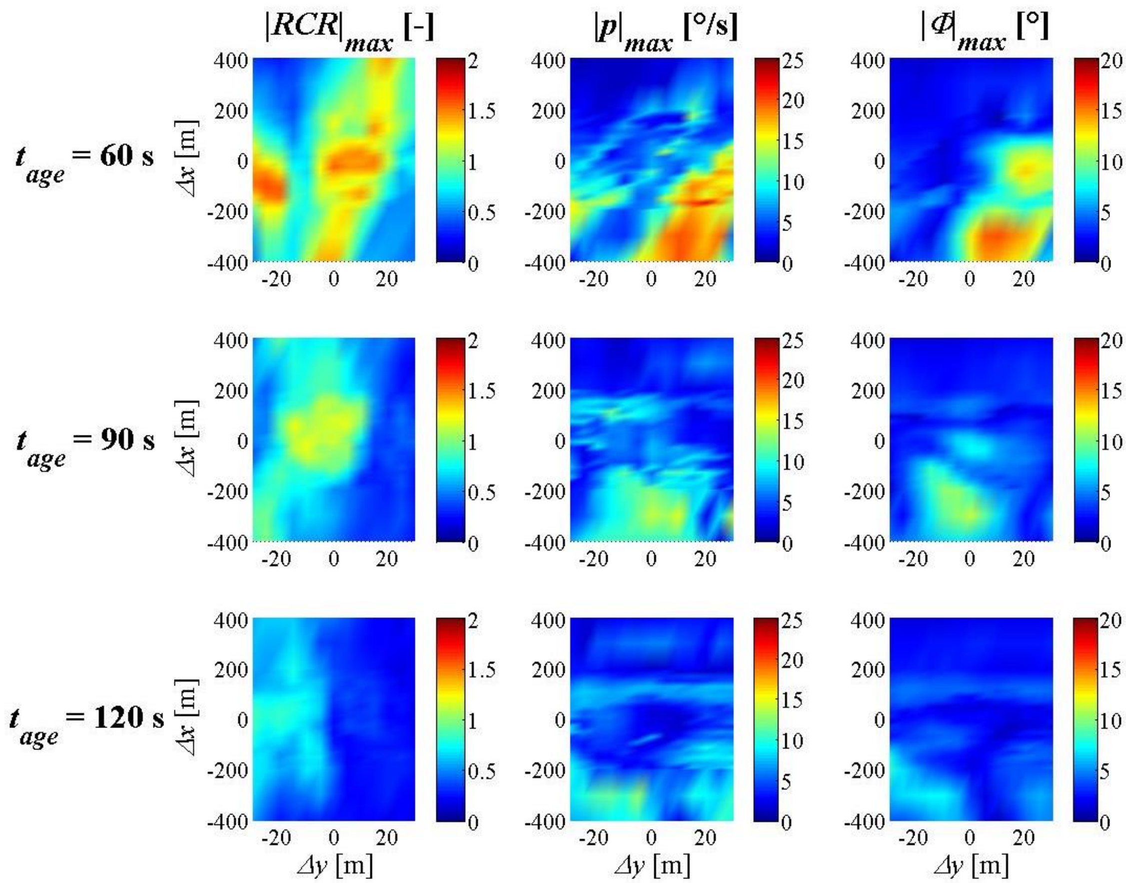

Figure 7 Distribution of $|RCR|_{max}$ and aircraft reaction in the roll axis with plate line as a function of the relative longitudinal (Δx) and lateral (Δy) flow field position.

The analysis of the simulation results with plate line reveals similar general effects as without plate line. However, due to the lower vortex circulation as a result of the plate line the vortex impact is reduced. Again, Figure 7 shows the vortex impact represented by $|RCR|_{max}$ and the aircraft reaction in the roll axis for the simulations with plate line. In the figure the areas with relatively large aircraft reactions have a similar size, but the magnitudes of the aircraft reactions are significantly reduced in comparison to the case without plate line (s. Figure 6).

Table 2 depicts the maximum and mean values of the $|RCR|_{max}$ and maximum bank angle $|\Phi|_{max}$, as well as the maximum values of the maximum vertical load factor $n_{z,max}$ and the maximum pitch angle Θ_{max} that occurred during all encounters as well as the relative improvement with the plate line. Interestingly, the positive effect of the plate line is more obvious for the younger vortices. Regarding the maximum $|RCR|_{max}$, one can observe that the values are significantly lower with plate line, especially for the old vortices. Nevertheless, this lower maximum impact in the roll axis does not result in the same reduction of aircraft reaction in terms of maximum bank angle $|\Phi|_{max}$ (~30% reduction in $|RCR|_{max}$ compared to ~16% reduction in $|\Phi|_{max}$ and ~2% in $|\Phi|_{max}$ at t_{age} = 120 s). This implies that the duration of the maximum rolling impact is short, whereas the amount of smaller, 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 figure indeed.

	without plate line					
t_{age} [s]	max. $\|RCR\|_{max}$ [-]	mean $\|RCR\|_{max}$ [-]	max. $\|\Phi\|_{max}$ [°]	mean $\|\Phi\|_{max}$ [°]	max. $n_{z,max}$ [-]	max. Θ_{max} [°]
60	1.90	0.64	19.7	4.6	17.0	17.3
90	1.36	0.49	15.5	3.8	5.1	10.4
120	1.21	0.42	9.5	3.3	2.5	9.4
	with plate line					
t_{age} [s]	max. $\|RCR\|_{max}$ [-]	mean $\|RCR\|_{max}$ [-]	max. $\|\Phi\|_{max}$ [°]	mean $\|\Phi\|_{max}$ [°]	max. $n_{z,max}$ [-]	max. Θ_{max} [°]
60	1.59	0.62	15.6	4.2	15.5	14.0
90	1.19	0.46	11.2	3.6	5.0	10.2
120	0.86	0.38	8.0	3.2	2.2	9.3
	relative improvement					
t_{age} [s]	max. $\|RCR\|_{max}$ [-]	mean $\|RCR\|_{max}$ [-]	max. $\|\Phi\|_{max}$ [°]	mean $\|\Phi\|_{max}$ [°]	max. $n_{z,max}$ [-]	max. Θ_{max} [°]
60	16.3 %	3.3 %	20.8 %	8.7 %	8.8 %	19.1 %
90	12.5 %	6.1 %	27.7 %	5.8 %	2.0 %	1.9 %
120	28.9 %	10.6 %	15.8 %	2.3 %	12.0 %	1.1 %

Table 2 Maximum rolling impact and maximum aircraft reactions (with and without plate line) and their relative improvement

The very large numbers for the maximal $n_{z,max}$ at a vortex age of 60 s is assumed to be mainly from the modelling of the landing gear as a spring-damper-combination without modelling damping effects of the tire and a modelling of the aircraft as rigid-body. These large numbers would probably not occur at this magnitude in reality.

The significant reduction of $|RCR|_{max}$ is in accordance with the results of the WakeOP flight campaign [3], where Lidar measurements showed a reduction of the vortex circulation due to the plate line. As, for a given aircraft pairing, the vortex induced rolling moment, hence the *RCR*, is mainly influenced by the vortex circulation, the vortex separation and the encounter geometry, a lower circulation is directly connected to a lower $|RCR|_{max}$ if all other influencing factors are kept the same.

All in all the results show a considerable influence of the plate line on the severity of wake encounters. Both the number of criterion violations and the magnitude of the aircraft reaction can be reduced by the plates.

Pilot-in-the-loop simulations

In addition to the offline simulations with autopilot engaged pilot-in-the-loop simulations were conducted in the AVES motion-based simulator for analysis of the influence of plate lines on the subjective hazard perception of pilots.

The analysed scenario was IFR approach under VMC at Frankfurt/Main airport (Germany). At simulation start the aircraft was trimmed at the final approach fix REDGO of runway 25C with an indicated airspeed of 180 kts in Config 2 (slats 22° / flaps 15°) with gear up. Initially, the autopilot was engaged in glideslope and localizer hold mode. The pilots were allowed to disengage the autopilot at their own discretion with the only limitation that the autopilot had to be disengaged below a height above ground of 500 ft in order to assure that the wake encounter was flown manually. During the approach the pilots had to configure the aircraft like in real flight and should perform a landing. In case that they decided to perform a go-around because of the wake encounter, they were allowed to do so. Same as for the offline simulations, the position of the flow field was varied in lateral and in longitudinal direction in order to analyse different relative flight paths through the vortex flow field. However, due to the limited number of possible simulation runs in the flight simulator, the variation was performed in a narrower range than in the offline simulations. In lateral direction the discrete positions y = (-25 m, 0 m, 25 m) and in longitudinal direction x = (-100 m, 0 m, 100 m) were applied. In the simulation campaign three DLR-internal pilots performed 55 encounters at the three vortex ages, each at the aforementioned flow field positions with and without plate lines.

The analysis of the encounters and pilot ratings shows that the pilot ratings correlate best with the aircraft reaction in the roll axis (Φ_{max} and p_{max}) and the maximum sink rate (or mathematically minimum vertical speed). These were also the main factors for the rating mostly mentioned by the pilots during the experiment. No correlations between the pilot ratings and other parameters, such as yaw rate, sideslip angle, load factors, etc. are found. Most unaccepted encounters were not accepted due to large bank angles. However, the data analysis shows that at very low heights above ground unacceptable bank angles means $\Phi > 5°$. Another reason for unacceptance was excessive sink rates.

All unaccepted encounters resulted in go-arounds. However, not every unaccepted encounter can be clearly explained by large bank angles or sink rates. Few unaccepted encounters show no excessive aircraft reaction but nevertheless resulted in a go-around. In some cases the pilots stated right after the encounter that they did not feel comfortable and that, although the aircraft reaction was not excessive, they decided to go-around as they could not anticipate how the encounter will evolve. Such ratings, which cannot be explained by quantitative figures, show the subjectivity of this kind of analysis. Such effects can only be handled through statistics, for which reason the limited database presented here can only outline preliminary results. More simulation trials with more pilots are planned in the future in order to increase the statistical basis by more encounters. However, the current campaign already shows interesting results concerning the influence of the plate line.

Figure 8 shows the maximum bank angle as a function of $|RCR|_{max}$ for the three vortex ages with and without plates. Figure 9 shows the same for the maximum roll rate.

One can clearly observe in both figures that with and without plate line the average of Φ_{max} and p_{max} decreases with increasing vortex age. What is also obvious is that the number of unaccepted encounters decreases with increasing vortex age, both for cases with and without plate line. However, in direct comparison between the cases with and without plates for one single vortex age, one can observe that with the plate line the average value is usually lower than without plates. The same applies for the number of unaccepted encounters, which is always lower with plates than without.

The same tendency can be observed regarding the maximum sink rate during the encounter. Figure 10 depicts the minimum vertical speed (the maximum sink rate) again as a function of $|RCR|_{max}$ for the three vortex ages with and without plates.

Generally, Figure 10 shows higher maximum sink rates for younger vortices. In direct comparison for one vortex age, the average is in similar range with and without the plate line.

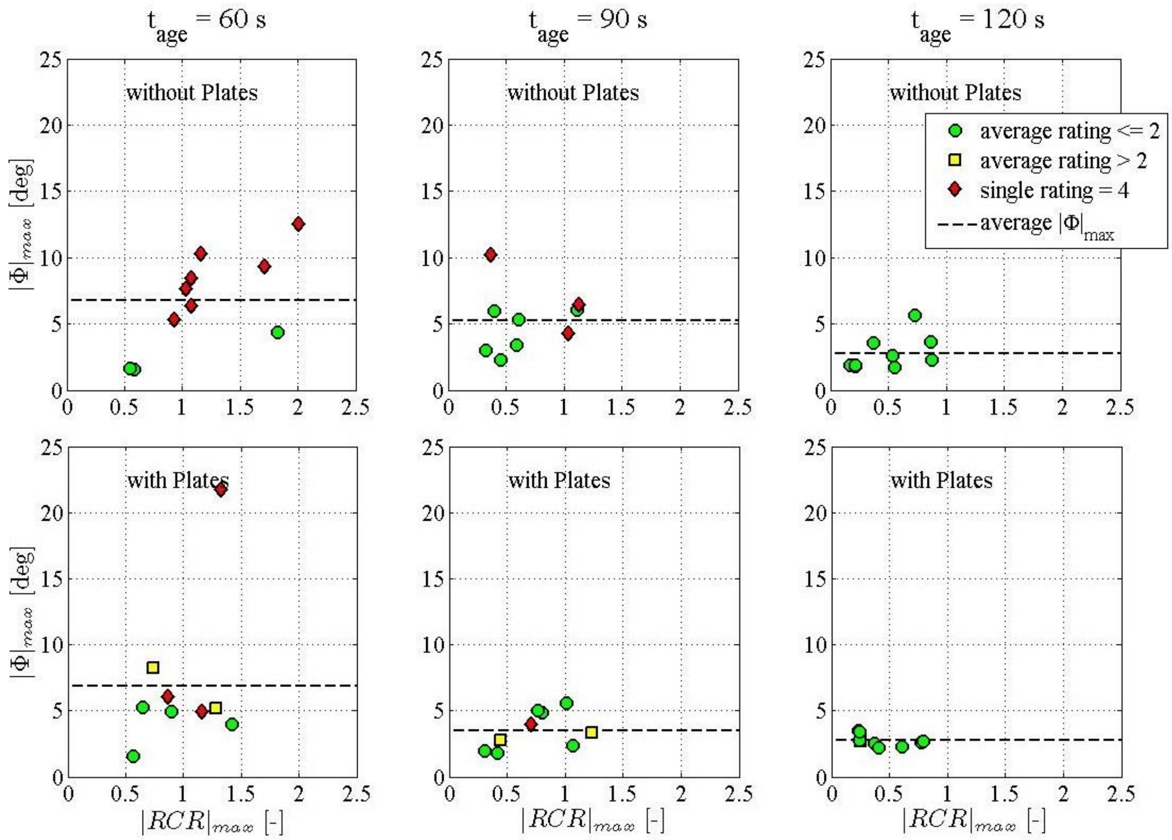

Figure 8 Maximum bank angles and pilot ratings as a function of $|RCR|_{max}$ with and without plate line

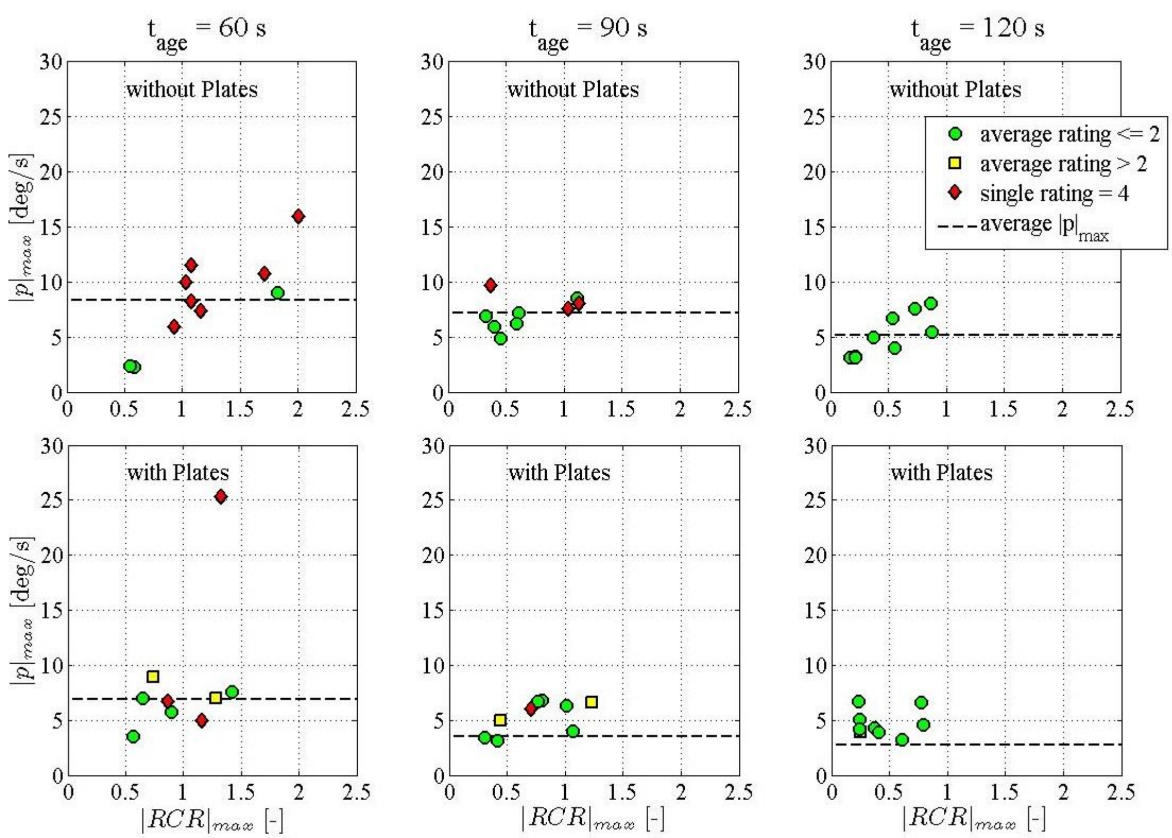

Figure 9 Maximum roll rates and pilot ratings as a function of $|RCR|_{max}$ with and without plate line

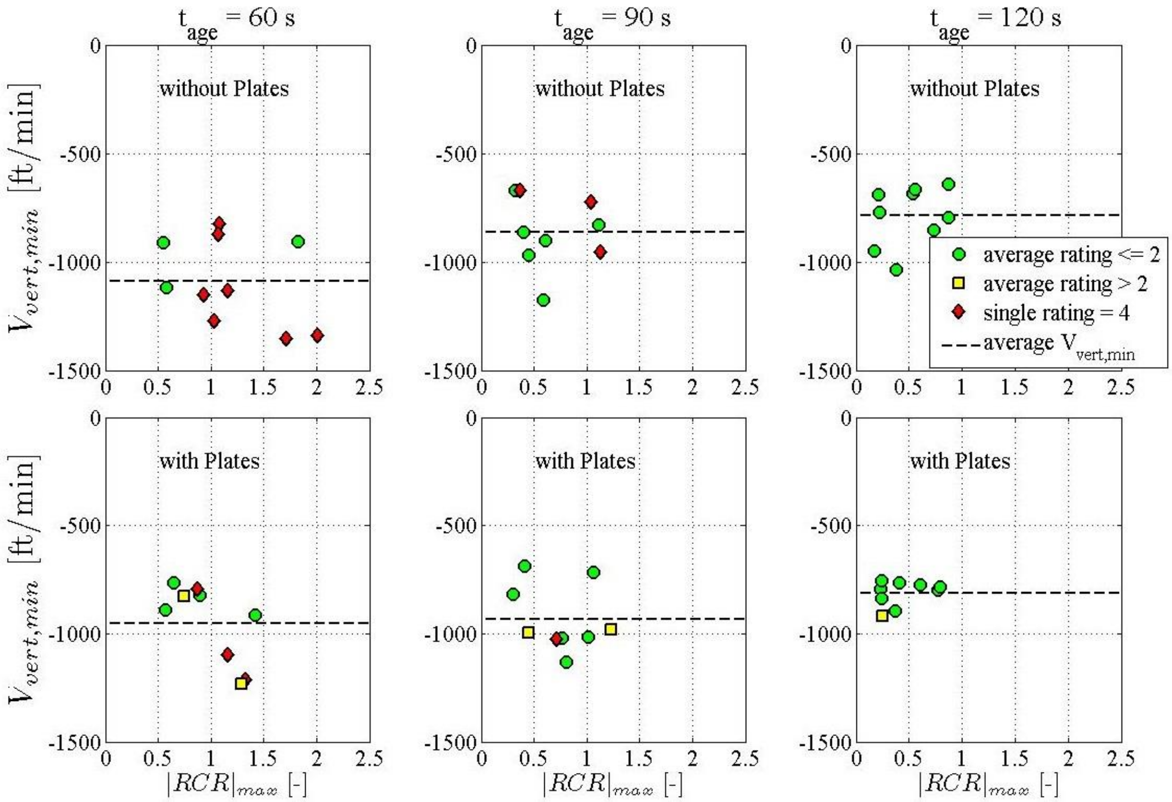

Figure 10 Minimum vertical speeds and pilot ratings as a function of $|RCR|_{max}$ with and without plate line

The simulator trials show the same tendency as the offline simulations, namely that the effect of the plate line to reduce the maximum vortex circulation also results in a reduction of the average aircraft response during the encounter and in an improved pilot acceptance. Obviously, the plate line is not able to fully eliminate unaccepted encounters; however, pilot acceptance is significantly improved due to the quicker vortex decay caused by the plates. Hence, the simulator trials also show that plate lines can be an effective means in order to reduce the severity of wake encounters close to ground.

Conclusions

A study with offline simulations and pilot-in-the-loop simulations in a motion-based full-flight simulator was performed for investigation of 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 shown to accelerate the vortex decay.

Wake vortex flow fields of an A340-sized aircraft were generated by coupling Reynolds-Averaged Navier-Stokes (RANS) simulations with Large-Eddy-Simulations (LES). With this method to simulate the evolution of wake vortices in ground proximity flow fields can be generated, which represent the special behaviour of wake vortices in ground effect very well. The accuracy of the simulation model of the encountering aircraft A320 is considered to be well acceptable for the present investigations. The aerodynamics model is validated by means of flight tests with the DLR research aircraft A320 ATRA. Other parts of the simulation model, such as landing gear, propulsion and the autopilot are not directly validated by flight test data, but were adapted in terms of their dynamics to represent an A320-size aircraft. The method to calculate the vortex induced forces and moments by using the so-called strip method has been widely used in the past and the confidence in the accuracy of this method is high. The autopilot and the control laws for manual flight used in this study were developed following the architecture of the original Airbus autopilot. However, only the behaviour of the autopilot on control inputs could be validated by means of real flight data. The flight control system's response on an external disturbance, such as wake vortices, could not be directly validated, but shows plausible results in counteracting external disturbances. The whole simulation framework can be considered accurate enough for representing wake encounters in ground proximity with autopilot of an A320-sized aircraft following an A340-sized one.

Both, the offline simulations and the trials in the flight simulator, showed a reduction of the aircraft reaction with the plate line. Especially for younger vortices the vortex impact and the aircraft reaction could be reduced considerably by the plates. Also, the piloted trials in the flight simulator revealed an improved pilot acceptance with the plate line. Hence, the dynamic encounter simulations showed that plate lines not only reduce the vortex circulation, as found out in previous studies, but also have a positive effect on the response of the encountering aircraft and the subjective hazard perception of the pilots.

The analysed aircraft pairing only represents A320-size MEDIUM aircraft following A340-size HEAVY aircraft. Other aircraft pairing were not investigated, which is why the results of the study cannot be generalized. However, it can be expected that the positive effect of the plate lines also applies to other categories of encountering aircraft as the plates generally accelerates the vortex decay.

Concluding, one can say that in case of a reduction of the separation minima plate lines could be an effective means in order to maintain safety. Also, there exist airports at which even with present separation procedures wake encounters occur more frequently than at other airports due to specific topographic, climatological or procedural reasons. Those encounters are mostly uncritical but nevertheless unwanted. For such airports plate lines could be a simple solution to reduce the encounter severity and thus increase flight safety.

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