Flight simulator study on the influence of vortex curvature on wake encounter hazard using LES wind fields

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ABSTRACT

A flight simulator study has been carried out to evaluate the performance of modern flight control systems encountering curved wake vortices. During the decay process the shape of wake vortices alters significantly which has an influence on the encounter characteristics and thus on the encounter hazard. To analyse most realistic wake encounters, flow fields of matured vortices have been generated with large-eddy-simulations. These were used for the determination of induced force and moment histories during the encounter. The force and moment histories have been implemented into the equations of motions of a 6 DoF flight simulation. For the sake of comparison encounters have also been simulated with straight vortices as they were mostly used for many other investigations. The most important goal of the study was to analyse the difference between these ideally straight vortices and vortices with a more realistic shape regarding encounter acceptance. The simulator study was conducted in an A330 motion-based full-flight simulator with pilots-in-the-loop. The analysed scenario was a wake encounter during final approach. The encounter conditions corresponded to a heavy-behind-heavy situation for Instrument Flight Rules (IFR) operations. The aircraft was flown either manually (in normal law) or with autopilot engaged. Altogether 93 encounters have been simulated, 38 with straight and 55 encounters with curved vortices. For encounters under manual control the simulator study revealed a potential risk of pilot induced oscillations (PIO) during encounters with curved vortices. With autopilot engaged not even one encounter with curved vortices was classified to be unacceptable. Although significant aircraft response was experienced the autopilot never disengaged automatically in any encounter. Altogether about 12 percent of the encounters were not accepted by the pilots. This is indeed a significant number, especially as the analysed scenarios can be regarded to be realistic situations which can occur in reality even if the applicable separation distances are applied.

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NOMENCLATURE

b	wing span
r	radial distance from vortex
r_c	vortex core radius
t	time
u	longitudinal velocity component
v	lateral velocity component
w	vertical velocity component
x	longitudinal position in vortex axis
y	lateral position in vortex axis
z	vertical position in vortex axis
C_l	rolling moment coefficient
N	Brunt-Väisälä-frequency
V_T	tangential velocity
ε	eddy-dissipation-rate
ε^*	normalised eddy-dissipation-rate
Γ	vortex circulation
Γ_{5-15}	radii averaged circulation
Φ	bank angle
AIM	aerodynamic interaction model
ATTAS	Advanced Technology Testing Aircraft System
DoF	degrees of freedom
IFR	instrument flight rules
ILS	instrument landing system
IMC	instrument meteorological conditions
LES	large-eddy-simulation
PIO	pilot induced oscillations
RCR	roll control ratio
VFR	visual flight rules
VMC	visual meteorological conditions
ZFB	Centre of Flight Simulation Berlin

1.0 INTRODUCTION

Wake vortices pose a considerable threat to aviation. Especially during approach when aircraft fly on almost the same flight path the risk of encountering wake vortices from a preceding aircraft is high. To ensure that a trailing aircraft is not upset by wake vortices from a preceding aircraft, separation distances between different classes of aircraft have been defined for flights under instrument meteorological conditions (IMC). These separation distances were chosen large enough to ensure that the vortices from a preceding aircraft are decayed enough to prevent a follower aircraft from possibly hazardous wake impact.

As the air traffic increased considerably during the last decades these separation distances limit airport capacities[1]. Especially compared to the possible capacity under visual meteorological conditions (VMC) when the separation has to be maintained by the pilots themselves these separations are a limiting factor. To increase airport capacities without the necessity to build additional infrastructure one possible approach could be to decrease the separation distances. This

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could be achieved by applying more appropriate and flexible separation procedures considering specific aircraft related information and environmental conditions. Since adverse effects on flight safety cannot be accepted the revised separation distances must not lead to an increase of (hazardous) wake encounters.

1.1 Motivation

In the past a lot of knowledge was gained in the area of wake encounter hazard assessment[8,23,24,27]. But in most investigations only very simple wake vortex models were used in simulations to evaluate encounter hazards. Generally the wake vortices have been simplified by straight vortex filaments. In reality wake vortices are nearly straight only during a short period after their creation. Depending on various atmospheric conditions like e.g. turbulence and temperature stratification the shape of the vortices alters significantly during the decay process. The so-called Crow instability[2] leads to a growing nearly sinusoidal shape until the vortices link at intervals to form a train of vortex rings.

Indeed the shapes of the vortex lines have an influence on the encounter characteristics. Therefore vortex curvature has to be taken into account for wake encounter hazard assessment or evaluation of encounter acceptance. The simulator campaign presented here was conducted to evaluate the effect of vortex curvature on the encounter acceptance. Therefore simulations were performed in a full-flight-simulator with pilots-in-the-loop. The simulated encounters include either straight vortices and realistically perturbed vortices which were generated by large-eddy-simulations[15]. Another issue which was covered by the campaign is the capability of the autopilot and modern controller-augmented flight control systems to cope with the impact of wake vortices.

1.2 Previous investigations

In the last decades extensive research has been carried out to investigate on wake vortex development and wake encounter hazard. A variety of wake vortex models have been developed for flight simulations. Flight simulator studies showed a great potential to investigate encounter acceptance with pilots-in-the-loop safely and with modest costs. NASA Ames and Langley Research Centres have carried out various wake encounter simulator tests in the 1970s and 1980s to analyse the wake vortex impact and hazard. Luckner *et al*[3,4] give a good overview on the use of flight tests and flight simulations for wake vortex research.

Since the late 1990s DLR Institute of Flight Systems has carried out various simulator studies and in-flight simulations with the DLR research aircraft ATTAS[8,13,24] to evaluate wake encounter hazard and acceptance for manual flight without any controller assistance. Thus, the results of these investigations are only applicable to aircraft with conventional controls. Further more, in these investigations only straight vortices have been considered.

In 2004, Loucel and Crouch[5] were the first who analysed perturbed vortices in flight simulator tests. Until their investigation all previous wake encounter simulations used analytical models of straight vortices. In the study of Loucel and Crouch an analytical vortex model was used which takes the perturbed shape of maturing vortices into account. For the early stage of the vortex decay the vortices were modelled as a wavy vortex filament. For later stages, after portions of left and right vortices have linked sequentially, the structure of the vortex lines is modelled by a chain of rings. For a wide range of encounter angles Loucel and Crouch showed a significant reduction of the resulting maximum bank angle during the encounter due to vortex curvature and the formation of vortex ring structures. The respective wake encounters were carried out with a B737 simulator flying with autopilot engaged.

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Spence *et al*[6] implemented vortex flow fields from large-eddy-simulations (LES) in a flight simulator in 2007. The vortex flow fields were calculated, recorded, and stored into a database so that they can be loaded into the simulation in real-time. As this implementation of the vortex flow fields in the real-time simulation needs extensive computational resources they had to develop a complex dataset management for a research simulator at the University of Sheffield.

In 2010 Allerton and Spence[7] published results of a simulator study conducted using the simulation described in previously mentioned paper[6]. This study was performed to analyse the effects of wake encounters on the vertical stabiliser loads.

1.3 Simplified hazard area concept

Various approaches exist to quantify the hazard of a wake encounter[23,24,27]. As the encounter hazard depends on a great variety of conditions and parameters the DLR Institute of Flight Systems has defined Simplified Hazard Areas (SHA) which are determined to guarantee an undisturbed flight operation outside its boundaries. The SHA is based on simplifying assumptions[8].

Most encounters occur in flight phases when the flight paths of the wake generating aircraft and the encountering aircraft are nearly parallel. In these cases the most dominant impact of the wake vortices on an aircraft is a rolling moment induced by their rotational flow. Therefore, the simplified hazard area concept is based on the dimensionless roll control ratio. This value is the ratio of the wake induced rolling moment and the maximum rolling moment which can be achieved by means of the roll control surfaces;

$$RCR = \left| \frac{C_{l,ind}}{C_{l,max}} \right| \quad \ldots (1)$$

In other words, a roll control ratio of RCR = 1 means that theoretically the induced rolling moment could be counteracted by a full deflection of the roll control surfaces. The boundaries of the hazard areas are defined by a nominal roll control ratio which is the maximum theoretical value for quasi stationary flight outside the simplified hazard area. This means that for every point outside the hazard area the roll control ratio has to be smaller than the nominal roll control ratio.

$$RCR < RCR_{nom} \quad \ldots (2)$$

The nominal roll control ratio has to be chosen in such a way that it also covers all other impacts and risks of the wake vortices. Previous investigations on wake encounter limits for undisturbed flight operations at DLR Institute of Flight Systems performed with pilots-in-the-loop revealed an acceptance threshold of RCR = 0·2[9]. In this case the hazard area was defined to be a rectangular area surrounding the vortices outside which only a maximum of RCR = 0·2 can occur. Figure 1 shows the hazard area for this case. It should be noted that the hazard area does not necessarily need to be defined as a rectangular area. It can also be defined to be a circle or an ellipse. For reasons of simplification in this study the hazard area is defined to be a rectangle.

The above mentioned acceptance threshold of RCR = 0·2 has been identified using straight vortices and aircraft with conventional controls. The aim of the presented simulator study was to analyse how vortex curvature and modern flight control systems influence the encounter acceptance and thus the hazard area boundaries.

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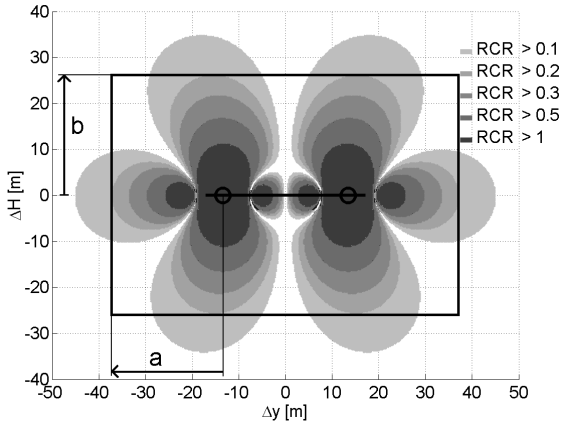


Figure 1. Simplified hazard area.

2.0 A330-FULL-FLIGHT-SIMULATOR

For the investigation on the influence of vortex curvature on wake encounter hazard a simulator was needed which (1) gave the pilots a very realistic impression during the encounter, and (2) provided the opportunity to implement the wake. The A330/A340 full-flight motion simulator of the Centre of Flight Simulation Berlin (ZFB) perfectly matched the requirements as it consisted of two separate simulation hosts. One is certified for training after the JAA standard for flight simulators STD 1A and the other identical one being fully adaptable for research needs including the possibility to implement wake encounter forces and moments. Additionally, this simulator perfectly represents modern controller augmented aircraft as it comprises an original Airbus flight control system.

Figure 2 shows the CAE A330/A340 full flight simulator cockpit operated by the ZFB[10].



Figure 2. Cockpit A330/340 simulator. (Photo: ZFB)

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The simulator flight deck is identical to the real A330/A340 flight deck and is easily convertible between both aircraft types. On Fig. 2 the instructor station can be seen on the left hand side behind the captain's seat. This station allows the changing of general aircraft settings, simulation parameters such as weather conditions and the activation of system failures. The initialisation and control of the wake encounter simulation is performed via network by connecting a usual laptop in the simulator.

The digital motion system provides six degree of freedom motion. The motion system generates realistic cues to the flight compartment using six servo actuators, supplied by a hydraulic power unit.

The computers certified for flight training are not available for research. An Ethernet-switch provides the possibility to use the research computers instead of the training hosts. The Scientific Research Facility (SRF) host computer is of the identical make as the training computers. This guarantees that the scientific simulation has the same accuracy as the certified training simulation.

3.0 VORTEX FLOWFIELDS AND ENCOUNTER GEOMETRY

For reasons of comparison the encounters were simulated with straight and curved vortices as well. The vortex generator aircraft is an A340-300 in approach configuration with a constant gross weight of 190t and a true airspeed of 72ms^{-1}. The vortex age is t_{age} = 108s, which corresponds quite well to the heavy behind heavy approach separation under IFR operations of 4NM. Thus the analysed encounter scenario represents normal IFR airport operations.

3.1 Straight vortices models

The encounters with straight vortices were based on an analytical vortex model with a Burnham-Hallock[11] respectively Rosenhead[12] radial velocity distribution. The induced velocities during the encounter were calculated by superimposing two single straight and infinite vortices. Thus the induced velocity components $[u,v,w]$ at a specific spatial point are only a function of the radial distance from each vortex so that;

$$[u, v, w] = f(y, z). \quad \ldots (3)$$

This analytical vortex model was used at DLR Institute of Flight Systems for various wake encounter simulations and showed a good conformity to vortex flow fields measured in-situ[13]. The tangential velocity is calculated by;

$$V_T = \frac{\Gamma}{2\pi} \frac{r}{r^2 + r_c^2} \quad \ldots (4)$$

Fischenberg[13] identified the core radius r_c to be 0·04 · b . The circulation of each vortex at the defined vortex age is .Γ = 338·3m^2/s.

3.2 Curved vortices models

The flow-fields of the curved vortices were generated with large-eddy-simulations (LES) by the DLR Institute of Atmospheric Physics[14,15]. The LES were conducted with the numerical code LESTUF which is a 2nd order space and time finite differences code using a staggered grid with a modified Smagorinsky closure scheme. In advance to the actual large-eddy-simulations simulation runs are

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performed to adjust the ambient turbulence. When the actual vortex simulation is started the turbulence field is fully developed with a constant dissipation rate and a spectral inertia range following the $k^{-5/3}$-distribution after Kolmogorov. The curved vortices have been initialised with a Lamb-Oseen vortex model[17] which comprises the following equation for the tangential velocity;

$$V_T = \frac{\Gamma}{2\pi r}\left(1 - e^{-1.2544\frac{r^2}{r_c^2}}\right) \quad \ldots (5)$$

The mean circulation of the vortices at this vortex age is $\Gamma_{5-15} = 339{\cdot}5\text{m}^2/\text{s}$.

As mentioned above the straight vortices were modelled with a Burnham-Hallock radial velocity distribution. The Burnham-Hallock model and the Lamb-Oseen model slightly differ in the radial velocity distribution. For the same core radius the two models have a different maximum tangential velocity and alternatively to have the same maximum velocity the core radius differs between both models. However, during the decay process both vortex models conform to each other after some time. Therefore the comparison of both vortex models is valid for the analysed vortex age.

The LES were performed independently from the work described in the presented paper. Outputs of the LES as they were used in the simulator study are 4D flow fields. For each time step the three velocity components $[u,v,w]$ are given on a 3D grid with a grid width of 1m. It applies;

$$[u,\ v,\ w] = f(\mathrm{x}, y, z). \quad \ldots (6)$$

Figure 3 shows the iso-surface of an absolute flow speed of 5ms^{-1} for the vortex pair at the age of 108s. At this age the flow-field represents the vortices before linking. With a normalised eddy-dissipation-rate of $\varepsilon^* = 0{\cdot}23$ (non-normalised eddy-dissipation-rate $\varepsilon = 1{\cdot}10^{-3}\ \text{m}^2/\text{s}^3$) and a Brunt-Väisälä-frequency of $N = 0$ the atmospheric conditions which the LES was based on, were moderate turbulence and neutral temperature stratification. These are typical values for the lower layer of the atmosphere[16]. On the figure the sinusoidal shape of the vortices at that stage of the decay can easily be recognised. A few seconds later the vortices will link at their nearest point and form ring structures.

Due to numerical reasons, the flow field matrices have a length of 400m in flight direction with periodic boundaries in all three dimensions. This length is sufficient for the large-eddy-simulations as it covers one wavelength of the Crow-instability. The Crow-instability represents one of the dominant mechanisms for vortex decay. However, this length is not sufficient for wake encounter flight simulations. Therefore, for the simulator study the flow field of one vortex age is connected in series so that in flight direction of the generator aircraft an infinitely long flow field is formed with the repeated shape of the oscillating LES vortices.

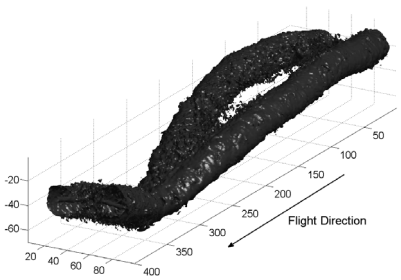


Figure 3. Iso-surface of absolute velocity of 5ms^{-1} for vortex age of 108s.

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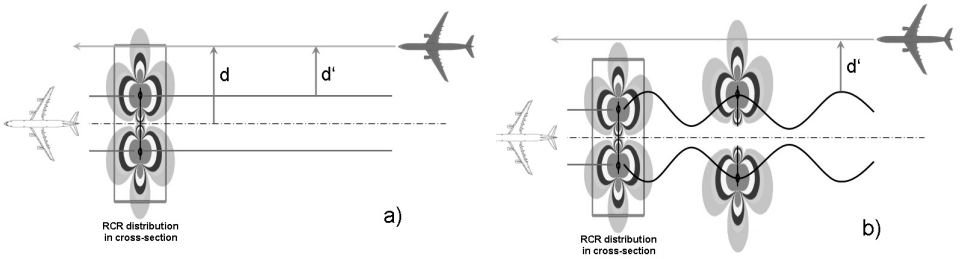


Figure 4. Encounter geometry for a) straight and b) curved vortices.

3.3 Encounter geometry

The encounter geometry follows the simplified hazard area concept. The encounters were performed by flying along the boundaries of the hazard area either on the left or right side as well as on top or below the hazard area. Flying along the hazard area boundary ensures that the maximum roll control ratio which occurred during the encounter corresponds to the envisaged nominal roll control ratio from the hazard area assessment. Encounters with various nominal RCR values between 0·1 and 1·2 were considered to find the acceptance threshold.

As the dimensions of the simplified hazard areas are calculated using straight vortices these dimensions cannot be applied to the curved vortices. Due to the curvature, the lateral spread of the curved vortices is larger compared to straight vortices. Thus, to have comparable encounters, the relative lateral distance between vortex and flight path must be increased in case of curved vortices. Fig. 4 shows the encounter geometry for lateral encounters.

The figure shows the roll control ratio distribution in the cross section behind the generator aircraft (see. Fig. 1) and the hazard area boundaries for a specific nominal roll control ratio. Figure 4(a) shows the flight path for lateral encounters with straight vortices along the lateral boundary of the hazard area. Figure 4(b) shows the equivalent conditions for encounters with curved vortices. Due to the wider lateral spread of the curved vortices an encountering aircraft would experience much higher induced rolling moments if it flew through the vortex at the same distance d to the centreline as in case a). Investigations prior the simulator study showed that the aircraft reaction is significantly higher in this case. Therefore, the distance d' between the vortex core and the lateral hazard area boundary for straight vortices is added to the widest lateral position of the curved vortices.

Figure 4(b) illustrates that on the flight path through the curved vortices the encountering aircraft experiences a comparable maximum roll control ratio as along the hazard are boundary in Fig. 4(a).

This also means that the wider lateral spread of realistically perturbed vortices must be taken into account for the hazard area assessment. The evaluation of a vortex age dependent lateral offset which takes vortex curvature into account is not the issue of this simulator study. Here, this offset is solely evaluated to ensure comparable encounters for straight and curved vortices.

3.4 Implementation of wake vortices in the simulator

The technique to hit the wake in a reproducible way used in this simulator study is called 'time-fixed' encounter. This is a method to expose the aircraft to a wake vortex upset which uses pre-recorded or pre-computed force and moment histories for a defined flight path. These time histories are used in the simulation instead of calculating them in real-time depending on the relative position to the vortex (so-called 'space-fixed' encounters).

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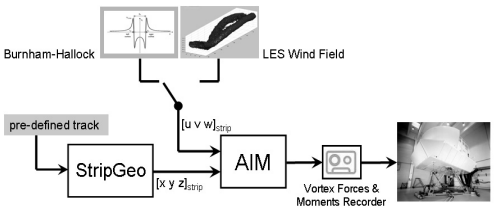


Figure 5. Methodology of vortex force and moment generation.

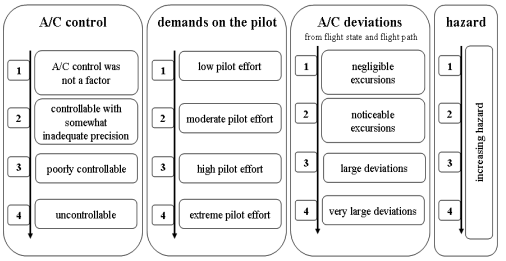


Figure 6. Encounter Rating Scale[22,23].

The advantage of this method is that the disturbance is fixed no matter what the pilot does so any scatter in the aircraft reactions can only be due to variation in the control inputs. This is especially useful when comparing the control inputs of different pilots on the same defined disturbance. The error made by using time-fixed vortices is small as long as deviations between the predefined track and the track flown in the experiment are small.

For the computation of vortex forces and moments no aircraft simulation was used. An aerodynamic interaction model (AIM) calculates the incremental forces and moments for the specific aircraft type using the strip method[28]. Here the lift and side-force generating surfaces are subdivided into sections for which the vortex influence is determined. For each strip an additional angle of attack and an additional angle of sideslip due to the vortex flow-field are calculated. By means of aerodynamic derivatives the resulting three additional forces and with the respective lever arm of each strip the resulting three moments are calculated. This method was deemed feasible by Barrows[18], verified against wind tunnel tests by de Bruin[19] and validated using real flight test data by Fischenberg[20] and Jategaonkar[21].

To record the vortex forces and moments the AIM was carried out on different pre-defined tracks through the vortex flow field. Depending on the envisaged nominal roll control ratio the dimensions of the hazard area differ. The track for the recording was either a three degrees descent left or right of the hazard area or with a ten degrees different azimuth a horizontal path on top or below the hazard area. Figure 5 illustrates the generation of forces and moment histories and the implementation in the simulator. The strip geometry calculation computes the spatial position of each strip along the desired flight path. With the respective velocity components from the vortex flow field the AIM calculates the resulting forces and moments.

The pre-recorded force and moment histories were implemented in the simulator software. Depending on a specific activation altitude the force and moment histories were played back in the simulation. Twenty three encounter force and moment histories using curved vortices and 21 using straight vortices were recorded. The playback heights were in the range between 400ft and 1,300ft above ground.

4.0 PILOTED SIMULATOR CAMPAIGN

The simulator sessions were performed with four airline pilots and a DLR test pilot as well as. Each approach was flown by two pilots but only the pilot-flying acted as the experimental pilot. The pilot-non-flying just acted as a co-pilot like in real flight. This means that the pilot-non-flying performed configuration changes, callouts, etc. whilst the pilot-flying performed the flying task and rated the encounter.

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4.1 Scenario

The analysed scenario was a wake encounter during final approach at EDDF Frankfurt/Main runway 25R. Each simulation started at 10NM final on the localizer but below the glide-slope at 2,000ft above ground. The pilots' task was to intercept the glide-slope and perform an ILS-landing under visual meteorological condition (VMC). The approaches had to be performed either under manual control or with autopilot engaged. The pilots had to act like in real flight including all procedures, call-outs, go-around decisions if necessary etc. Each encounter was initialised at a specific pre-defined playback altitude. After reaching this altitude the playback of the pre-recorded vortex force and moment histories was started and the pilots were asked to counteract the wake encounter like in real flight. If a go-around was initiated the simulation was stopped after the aircraft was stabilised again with a positive climb rate. If the pilots were able to counteract the encounter the simulation was finished after touch-down at the runway. After each encounter the pilot-flying had to rate the encounter by means of a special encounter rating scale as described in the following section.

4.2 Encounter rating scale

After completion of each simulation run the encounter was rated by the pilot-flying by means of a subjective encounter rating scale. This scale follows an approach of Sammonds and Stinnett[22] but was adapted[23,24] to comments from DLR test pilots (see Fig. 6).

The rating scale comprises the four items A/C control, Demands on pilot, A/C deviations and Hazard. All items can be rated from '1' to '4' where '1' means 'negligible' and '4' means 'unacceptable'. The rating is purely subjective. If a go-around was performed the aircraft deviations from the flight state and flight path had to be rated with '4'. It was defined that if any of the items was rated with '4' the encounter was unaccepted. The encounter hazard is to be treated independently from the other ratings. This means that although the demands on the pilot might be high and considerable aircraft excursions occur, the pilot might not feel unsafe and therefore the corresponding subjective feeling of a threat might be low. For example, a go-around is not necessarily considered to be a hazardous situation as it is a safe standard procedure.

The encounter rating scale is used at DLR Institute of Flight Systems for wake encounter rating since many years and was deemed appropriate for encounter rating in many piloted studies[9,23].

5.0 RESULT

Altogether 93 encounters have been simulated and rated by the 5 pilots. These encounters were either flown under manual control (50 encounters) or with autopilot engaged (43 encounters). 38 encounters have been simulated with straight vortices and 55 encounters with LES-generated flow fields. 11 of the total 93 encounters were not accepted by the pilots (12%). The percentage of unaccepted encounters with curved and straight vortices is in the same range. Five encounters with straight vortices were not accepted (~13%) and 6 encounters with curved vortices were not accepted (~11%). As the vortex age corresponds to the heavy-behind-heavy separation distance of 4NM the percentage of unaccepted encounters is considerable. But please note that in the simulator study every approach was designed to end up in a wake vortex encounter. In reality the overall probability to hit a wake is much smaller due to the effects of sinking and drifting of the vortices.

Figure 7 and Fig. 8 show the actual height during the encounter at which the maximum roll control ratio occurred versus the maximum roll control ratio which occurred during the encounter.

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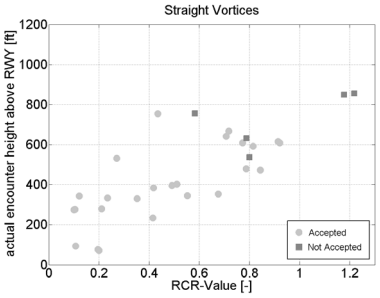


Figure 7. Acceptance with straight vortices.

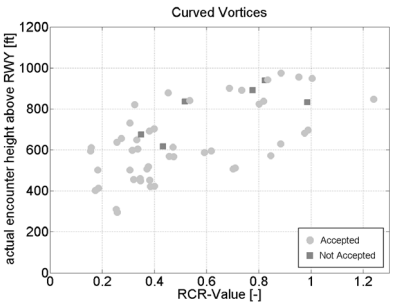


Figure 8. Acceptance with curved vortices.

Figure 7 depicts those encounters with straight vortices whereas Fig. 8 gives the results of those with curved vortices. Accepted encounters are presented with bright circles and unaccepted encounters with dark squares. Both figures include encounters under manual control and with autopilot engaged.

As the ratio between manual and automatic flights is the same for straight and curved vortices both figures can be compared concerning the overall encounter acceptance.

Although, the statistical basis of the different approach scenarios is not very high a general conclusion seems to be evident. Figures 7 and 8 depict a considerable difference in the acceptance threshold for straight and curved vortices. Following a conservative approach one can observe that for the straight vortices there are no unaccepted encounters below a maximum roll control ratio of 0·55 whilst for the curved vortices no unaccepted encounters occurred below 0·35.

Based on the same conservative approach previous investigations at DLR Institute of Flight Systems revealed an acceptance threshold of RCR = 0·2[9]. These investigations were conducted with aircraft with conventional flight controls using solely straight vortices. Obviously the controller augmented fly-by-wire flight control system of the A330 assists the pilot during the wake encounter in a way that the acceptance threshold moves towards larger acceptable roll control ratios. This can be seen in Fig. 7 which shows the encounters with straight vortices. The only difference to the previous investigations is in these cases the flight control system.

The influence of the vortex curvature on the encounter acceptance can be taken from Fig. 8. Vortex curvature seems to decrease the acceptance threshold significantly. This outcome is not surprising since the characteristics of encounters with curved vortices create repeating aircraft response stimulations which are more difficult for the pilots to handle.

5.1 Comparison between encounters with curved and straight vortices

The following results apply for manually and automatically flown encounters. It should be noted that in all flight phases with manual control the normal laws of the fly-by-wire control system were active, and thus the pilot was permanently assisted by automated control system. The major concern the simulator study revealed is a potential risk of pilot induced oscillations (PIO) which may occur during manually flown encounters with curved vortices. Due to the vortex curvature the aircraft may hit the vortices more than only once which then results in multiple impacts by the vortices. The induced rolling moment of the curved vortices, as the major vortex impact, changes rapidly. This can lead to PIO when the pilots' control inputs interfere with the control commands of the flight control system.

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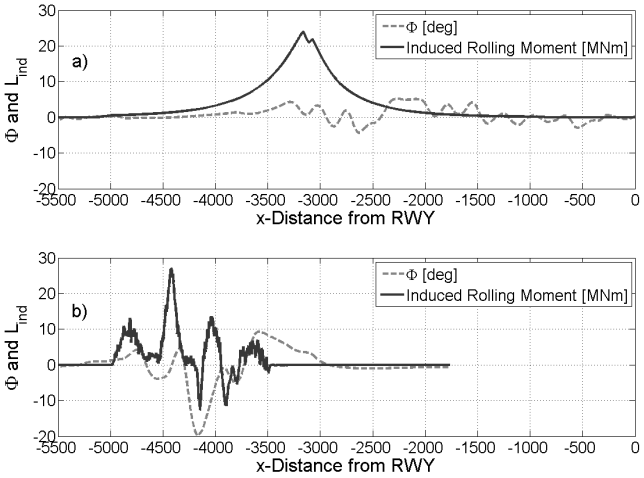


Figure 9. Encounters with (a) straight and (b) curved vortices (manual control).

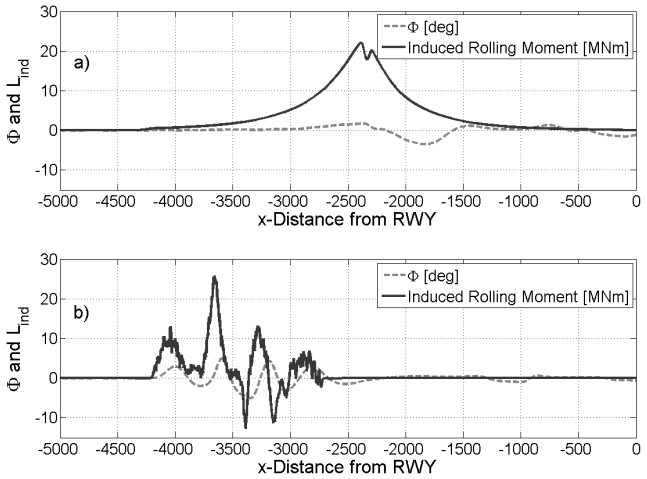


Figure 10. Encounters with (a) straight and (b) curved vortices (autopilot engaged).

Those encounters with straight vortices which were flown under manual control do not show this PIO tendency. The force and moment histories of straight vortices contain lower frequencies disturbances and thus do not lead to rapid alternating aircraft response. Figure 9 shows exemplarily two encounters of the same strength (nominal RCR = 1·0) under manual control. The encounters were simulated along the left boundary of the hazard area with the same azimuth but a 3° different flight path angle between the vortices and the aircraft flight path angle. The figure illustrates the induced rolling moment (solid line) and the resulting bank angle (dashed line) versus the distance from the runway.

The encounter with the straight vortices is given in Figure 9(a)). One can see the slowly increasing rolling moment which firstly can be counteracted accurately by the normal law of the flight control system. In the region of the maximum induced rolling moment the pilot corrects some of the residual bank angle but during the whole encounter the bank angle does not exceed 5°. The average rating of this encounter is 2·5 and the hazard was rated 2.

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Figure 9(b)) shows an encounter with curved vortices having a comparable maximum roll control ratio. However, compared to Fig.9(a)) the evolution of the rolling moment during the encounter is totally different.

Although in this case the duration of the encounter with curved vortices is much shorter the very rapid changes in rolling moment with even differing sign lead to bank angles up to 20°. The average rating of this encounter is 3·3. Finally this encounter leads to a go-around so that this encounter has to be classified as not acceptable. The hazard of this encounter was rated 3.

The analysis of the manually flown encounters also showed a correlation between pilot ratings and pilot's experience. Indeed this outcome is not surprising but although all pilots are professional airline pilots it shows deficiencies in the handling of wake encounters by pilots without extensive flight hours. The observed PIO tendency decreased in the simulator study with increasing experience of the pilot on this specific aircraft. The deficiencies in handling wake encounters and the capability of less experienced pilots to cope with an encounter could possibly be improved by including wake vortex encounters in pilot's simulator trainings.

Of course the PIO tendency observed during the manually flown encounters does not exist when the encounters were executed with the autopilot engaged. In these cases the aircraft response was comparable for straight and curved vortices. Nevertheless the pilot ratings were better for those encounters with curved vortices. This outcome supports the results of Loucel and Crouch[5].

Figure 10 shows again the induced rolling moment and the bank angle versus the distance from the runway. Both encounters were simulated with autopilot engaged and a same nominal roll control ration of 0·8. Figure 10(a)) depicts the encounter with the straight and Figure 10(b)) that with the curved vortices.

In both cases the autopilot was able to keep the bank angle below ±5°. The deviations from the desired flight path are marginal and also the slightly oscillating bank angle during the encounter with curved vortices did not result in worse pilot ratings. Contrary to the encounter with straight vortices, the encounter with the curved vortices was rated better. The average rating of the encounter with the straight vortices was 2·25 whilst the average rating of encounters with the curved vortices was 1·25. Besides the subjective perception of the pilot these different ratings might also be caused by the fact that the duration of the encounter with straight vortices is longer. Both types of encounter have the same activation altitude. But in the case of the straight vortices the most considerable aircraft motion occurs later and thus at lower altitude. As encounters at lower altitude are normally more disliked by pilots this might also cause the worse pilot ratings.

5.2 Comparison between encounters under manual control and with autopilot engaged

Several encounters were simulated under the same conditions with either autopilot engaged or under manual control. These simulations were mainly conducted to evaluate the capability of the autopilot to cope with the vortex impact especially against the background of vortex curvature. In those cases with autopilot engaged the pilots were allowed to disengage the autopilot and take over control during the encounter like in real flight. Except for one encounter during which the bank angle slightly exceeded 10° the autopilot was able to keep the bank angle below 10° during all encounters simulated with autopilot engaged. Also, the autopilot did not automatically disengage during any encounter. Although the bank angle was not crucial during any of the automatically flown encounters there are three unaccepted encounters which were all based on straight vortices. All encounters with curved vortices with autopilot engaged were acceptable.

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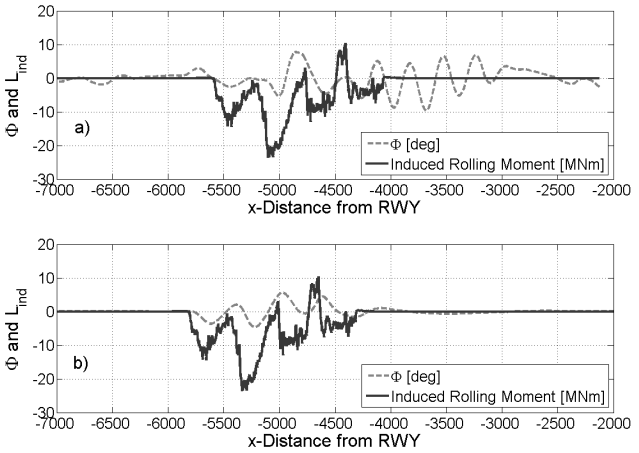


Figure 11. Encounters with curved vortices (a) under manual control and (b) with autopilot engaged.

Figure 11 shows two encounters with the same wake vortex force and moment histories. Again the induced rolling moment (solid line) and the bank angle (dashed line) are shown versus the distance from the runway. The nominal RCR of both encounters was 0·9. Figure 11(a)) shows the encounter under manual control whereas Figure 11(b)) shows the encounter with autopilot engaged.

In both cases no excessive bank angles occur. But in Fig. 11(a) PIO can be observed which are initialised by the wake encounter but still persist afterwards. These PIO lead to a go-around and thus the encounter was not accepted. Although predominantly the bank angle is the most important factor for the pilot's rating in this case it was not the only factor for non-acceptance. The dynamic interference between the pilot's control inputs and the control commands of the flight control system are the most crucial factor for non-acceptance. The average rating of this encounter is 3·75 and the hazard was rated 3.

Figure 11(b) shows the same encounter with autopilot engaged. In this case the autopilot was able to keep the bank angle within +/–5°. Astonishingly the average rating of this encounter is 1·25 with a hazard rating of 1. This comparison of identical encounters clearly shows how significantly different the encounter hazard can be if the encounter is flown manually or with autopilot engaged.

This outcome of the simulator study corresponds to the Airbus recommendation[25,26] that in case of a wake encounter with autopilot engaged the pilots should keep the autopilot engaged unless it disengages by itself. In case of manual flight the pilots are recommended to act as less as possible and to avoid abrupt actions on the stick. The simulator campaign showed that especially overreaction is crucial when encountering wake vortices with controller-augmented aircraft.

6.0 CONCLUSION

The simulator study revealed various effects which are influenced by the vortex curvature. Another important factor to cope with wake vortex encounters is the flight control system itself and its interaction with the pilots control inputs.

Some analysis prior the simulator study showed that the wider lateral spread of the curved vortices in comparison to straight vortices must be taken into account for the hazard area assessment. If the hazard area is solely determined with straight vortices, disregarding the effect of vortex curvature, the encounter is significantly stronger.

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The total percentage of unaccepted encounters of 12% appears to be relatively high, especially as the analysed vortex age corresponds to the heavy-behind-heavy separation distance for IFR operations. But the reader should keep in mind that every encounter in this simulator study was forced to end up in a wake encounter. The total probability of such wake encounters is much lower in reality due to the drift and sinking of the wake vortices.

For encounters with straight vortices there are no unaccepted encounters below a maximum roll control ratio RCR of 0·58. Encounters with curved vortices were all accepted below an RCR of 0·35. This shows that vortex curvature results in encounter characteristics which are more demanding for the pilots in manual flight.

Those encounters simulated with curved vortices showed a potential risk of pilot induced oscillations under manual control. This PIO tendency of some pilots seems to correlate with the pilot's experience on the specific aircraft. Taking into account this result it can be assumed that wake vortex encounter simulator trainings would probably improve the pilots' capability to cope with the phenomenon.

With autopilot engaged the pilot ratings were better for the curved vortices. The autopilot could very well counteract the wake impact and kept the aircraft on the desired flight path with only small deviations. With autopilot engaged no go-around was conducted for curved vortices and hazard ratings were never worse than '2' (referred to a maximum rating of 4) even with a maximum RCR up to 1·3.

It can be concluded that the results of the simulator study support recommendations given by Airbus. If the autopilot is engaged it should remain engaged in case of a wake encounter unless it disengages by itself. If the encounter occurs under manual control the pilots should avoid abrupt and alternating stick inputs and should try not to overreact.

For the future it is planned to continue simulator studies like described in the present paper. Those future studies should focus on 'space-fixed' encounters. This would allow analysing a more realistic behaviour of the aircraft during the encounter. In that case the aircraft is not exposed to pre-recorded forces and moments but to the forces an moments resulting from the respective encounter flight path. Further more, the effect of vortex deformation variation should be investigated in more detail. This will include encounters with vortex rings like they exist after the vortex linking. The main goal of these studies will focus on the reliable characterization of conditions (vortex age and deformation) for which the vortex' impact on the encountering aircraft can be neglected.

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