WAKE VORTEX ENCOUNTER RISK ASSESSMENT USING HIGH-FIDELITY FLIGHT SIMULATION

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Abstract

Wake-turbulence related separations are becoming an increasingly limiting factor to airport capacity. Furthermore the increasing traffic density predicted for the coming decades will very likely lead to an increased frequency of wake turbulence related incidents not only in the airport vicinity, but also in other flight phases such as during cruise. Maintaining or even improving safety with respect to wake vortex encounters requires new appropriate separation schemes to be developed, that take into account not only parameters of the wake vortices themselves, but also the effect of the wakes on the encountering aircraft. The validation of such separation schemes (as planned e.g. during the European ATM research undertaking SESAR) requires adequate simulation tools to demonstrate their safety.

Airbus has developed such tools during several research projects and internal activities during the last years. These tools are based on a high-fidelity, dynamic aircraft wake encounter simulation called VESA (*Vortex Encounter Severity Assessment*) taking into account the interaction of the aircraft aerodynamics and flight dynamics with the vortices. Recent advances in the development of these tools, specifically during the recently finished EU research project CREDOS, will be presented. In this project the feasibility of an operational concept for reduction of departure separations under crosswind conditions was investigated. Airbus simulation tools together with new models for pilot behaviour, wake vortex simulation and severity assessment developed in the project were applied to perform a risk assessment regarding severe wake encounters during departure with reduced separations. The results that will be presented show the interactions between the wind conditions, the routing of the departing aircraft and their influence on the wake encounter risk.

1. INTRODUCTION

Research over the past years has shown how the transport and persistence of wake vortices depends on the weather conditions, and that for many situations the existing separation standards might be over-conservative. For single-runway operations for example, analyses [1,2] suggest that, above a certain crosswind threshold, vortices are blown out of the flight corridor and pose no further threat to following aircraft. The experience gained in earlier research projects (such as S-WAKE [1] or ATC-WAKE [3]) lead into definition of the CREDOS project (Crosswind-Reduced Separations for Departure Operations [4]). In this European Commission co-funded project, running from 2006-2009, the feasibility of a concept was investigated that allows suspension of wake-turbulence separations for Single Runway Operations under the condition that a sufficient crosswind is prevailing on the departure runway.

One of its work packages was tasked with developing and applying a wake encounter risk assessment to quantify the relative risk of significant wake encounters for different scenarios. In this work package the two tools WakeScene-D and VESA-D were developed, where D designates "Departure". WakeScene-D (Wake Vortex Scenarios Simulation Package for Departure), developed by DLR, estimates the probability to encounter wake vortices in different traffic and crosswind scenarios using Monte Carlo simulation. In cases with potential wake encounters all relevant parameters can be provided to VESA-D (Vortex Encounter Severity Assessment for Departure), developed by Airbus, which subsequently performs high-fidelity flight dynamics simulations of the encounters to assess their severity. Both results together allow an assessment of the wake encounter risk. This assessment has been applied to different potential scenarios of reduced separations with Frankfurt/Main airport as the baseline.

In Chapter 2 the simulation platform will be described, with an emphasis on the VESA-D tool. The essential sub-models that have been added during the CREDOS project will be described shortly as well as the connection of WakeScene-D and VESA-D simulations. Chapter 3 finally describes the simulations performed in the wake encounter risk assessment for CREDOS and presents some of the results while Chapter 4 concludes on the main findings.

2. DESCRIPTION OF SIMULATION PLATFORM

In the European Commission co-funded research project S-WAKE [1] running from 2000-2003 modeling tools were developed that were assembled into the wake vortex encounter simulation tool VESA (Vortex Encounter

Severity Assessment [5,6]) by Airbus, which was continuously further developed since then. The tool is able to simulate the effect of wake vortex encounters on the encountering aircraft by coupling a 6 degree-of-freedom flight simulation with an aerodynamic interaction model between wake vortices and aircraft aerodynamics. Using this approach it is possible to conduct wake vortex encounter severity analyses taking account the full dynamic reaction of the aircraft. Parametric studies can be performed using Monte Carlo-type simulations as well as identification of worst-case encounter conditions. The work in the S-WAKE project focused on the approach phase of flight, and the platform had only limited capabilities to be applied to other flight phases. Within the CREDOS project the capabilities were extended to the departure flight phase and existing sub-models were further refined. VESA-D is thus the extension of the tool VESA to the departure situation.

In parallel DLR extended the WakeScene simulation platform to the departure phase [7]. WakeScene is a tool that simulates the traffic and weather situation around the airport, including generation and evolution of wake vortices shed by the aircraft. It contains an aircraft trajectory model, a weather model based on realistic profiles of all relevant weather variables, a wake vortex prediction model to predict the evolution of the wakes and criteria to detect potential wake encounters. It allows running extensive Monte Carlo simulations under variation of several influence variables. Its purpose in the simulations described here is to determine those departures out of a large number of simulated ones which lead to a potential encounter. In WakeScene however no interaction between the vortices and an encountering aircraft is included. This part is simulated specifically in VESA-D, with high fidelity with respect to flight dynamics and the wake hazard to the encountering aircraft. VESA-D contains several sub-models which will be described in the following sub-sections.

2.1. Flight simulation

The flight simulation used in VESA-D is a simulation of an Airbus A320 aircraft, validated by Airbus for handling qualities investigations. It contains the aerodynamics, Fly-By-Wire control laws as well as Flight Management and Autopilot functionalities of an A320-200 series aircraft. The added wake vortex encounter functionality is designed such that these core elements do not need to be modified with respect to the validated version. The flight simulation is able to cover the complete flight from runway threshold to runway threshold, i.e. take-off run, climb, cruise as well as approach and landing can be simulated. Performance-related parameters such as the mass, configuration and thrust settings can be varied. The ambient atmospheric conditions are modeled according to the International Standard Atmosphere (ISA). The simulation takes into account wind influence on the aircraft (apart from the specific wake vortex encounter model, see sect. 2.2) either from a simplified uniform wind field, or a synthetical wind field. Additionally ambient turbulence can be introduced with variable gust wind speeds.

2.2. Wake Vortex Encounter simulation package

The Wake Vortex Encounter simulation package (or *WVE* package) consists itself of two elements – a so-called Aerodynamic Interaction Model (or *AIM*) and the representation of the wake vortices themselves. In VESA-D a strip method is usually used as the AIM to compute the vortex-induced forces and moments impacting the encountering aircraft (see FIG 1). The induced additional forces are computed at several discrete positions on the aircraft's wings, horizontal and vertical tail plane, yielding consequently the aerodynamic y- and z-forces, as well as pitch-, roll- and yaw moments. No impact on the drag force is considered however. This wake vortex interaction model was developed and validated mainly within the S-WAKE project [8]. It provides good modeling quality with little computational effort in comparison to higher detailed approaches like Lifting Surface Methods. The strip method takes as inputs the vortex-induced additional velocity components at each strips control point (25% chord length). From this the additional flow angles (angle of attack and sideslip) caused by the vortices are computed, which in turn generate additional forces on the aerodynamic surfaces.

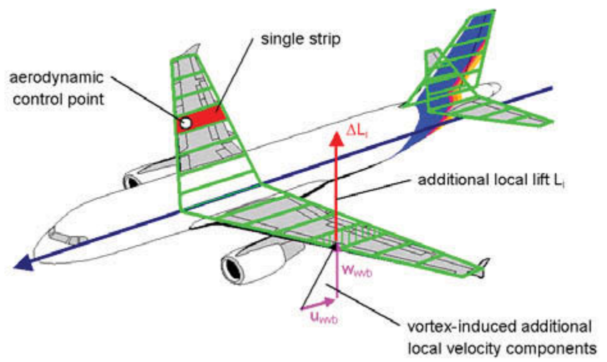

FIG 1. Strip method as Aerodynamic Interaction Model in VESA.

For the representation of the vortices in space several options are available in VESA. The simplest one is to represent the wakes as infinitely long, straight vortex tubes that can be oriented three-dimensionally in space to vary the wake intercept or *encounter angles* of the aircraft with the wake. This option is very useful for worst-case searches and parametric studies in Monte Carlo simulations. The vortex-induced velocity distribution is computed using a vortex velocity model in conjunction with the Biot-Savart law. Different vortex velocity models are available in VESA, e.g. after Lamb-Oseen, Winckelmans or Burnham-Hallock/Rosenhead. The so-computed velocity fields are usually constant in time. Results using this kind of modeling have been published e.g. in [5,6].

Here however another method shall be described in more detail, which has been added to VESA-D recently during the CREDOS project. In CREDOS the VESA-D platform was connected to WakeScene-D to assess the severity of potential encounters that are identified. WakeScene-D uses the deterministic version of the Two-Phase Wake Vortex Prediction Model D2P [9] to predict the behavior of vortices shed by aircraft. D2P computes the positions of the vortices and their strength (circulation) in and out of ground effect, taking into account meteorological conditions, in particular the wind. In WakeScene-D this model is executed in several so-called *control gates* which are created along the flight path of the wake-generating aircraft. These gates are oriented perpendicular to the flight path, that means they are inclined by the vortex-generating aircraft's heading and climb angle. In each gate the evolution of the shed vortex pair is computed until the vortices have decayed below a certain minimum circulation. From this data the vortex lines of both vortices can be reconstructed for each time step by assuming a straight vortex segment between the positions of the vortices in two adjacent control gates. The control gates between which the segments extend are created in intervals of 5 s by the vortex-generating aircraft. For a flight speed of 135 kt this results in a distance of approx. 350 m between each gate. The principle is shown in FIG 2.

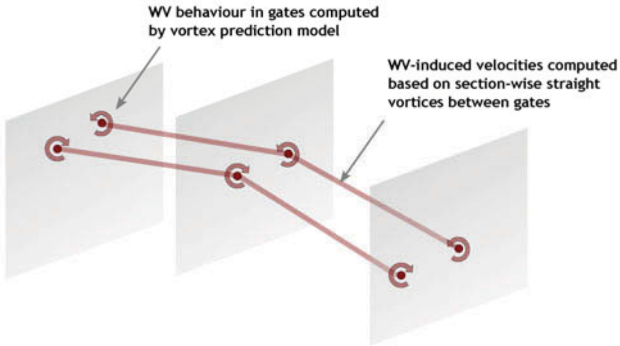

FIG 2. Schematic representation of three-dimensional vortices in VESA-D.

The next step is to compute the induced velocities needed for the AIM at each required point, using the law of Biot-Savart in combination with an appropriate vortex velocity model. Here a velocity model after Rosenhead has been chosen. The formulation of the induced velocity contribution of one vortex segment at one point is then the following (see FIG 3):

$$\vec{V}_{wv,seg} = \frac{\Gamma_{seg}}{4\pi} \frac{r}{r_c^2 + r^2} (\cos\alpha_1 - \cos\alpha_2) \frac{\vec{s}_{12} \times \vec{r}_1}{\left\| \vec{s}_{12} \times \vec{r}_1 \right\|} \quad (1)$$

with Γ_{seg} the circulation of the vortex segment and r_c the vortex segment core radius. Both are calculated as the mean values of those in the two adjacent control gates, giving a constant circulation per segment. Contributions of all segments are added up to give the total induced velocity at each point. Additionally in ground effect, secondary and tertiary vortices are generated in the D2P model, along with image vortices, that all contribute to the induced velocities. The computation is performed for each aerodynamic control point on the aircraft in each time step of the simulation, allowing the determination of the evolution of the induced forces and moments with time.

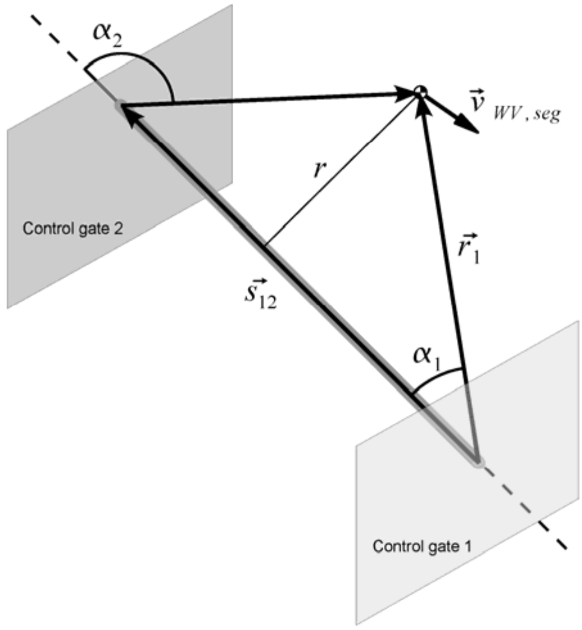

FIG 3. Computation of induced velocity for a vortex segment.

FIG 4 shows what the representation of the vortices looks like in VESA-D. It can be noted that kinks in the vortex lines due to the segment-wise reconstruction are only barely visible, as the curvature of the vortices is usually small, even during turns. Consequently no discontinuities in the velocities induced on the aircraft could be noticed either.

The advantage of such a vortex representation with respect to simple straight vortices is the better consideration of a curvature in the vortex lines as well as the variable circulation along the vortices. A full validation of the velocity field is however very difficult to perform. Field measurements of fully three-dimensional velocity fields which would be needed for comparison do not exist today. Even with a LiDAR system, which is very popular today for field measurements of real vortices, the best that can be achieved is the velocity profile in one scan plane covered by the LiDAR. So for the time being we rely on the assumption that the superposition of realistic velocity profiles of several vortices as described delivers velocity fields of sufficient accuracy for the envisaged application.

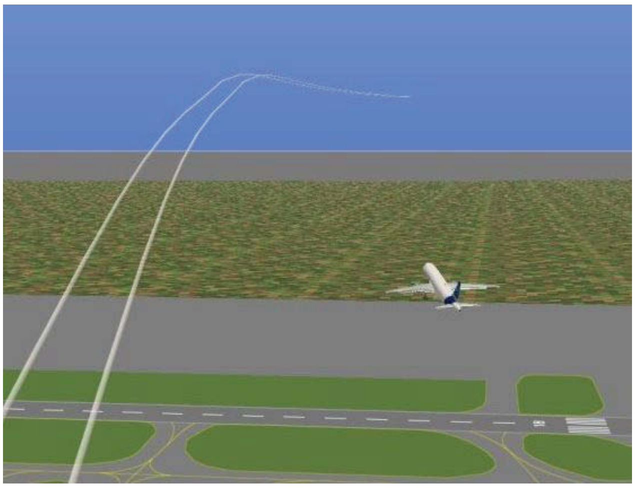

FIG 4. D2P vortex representation in VESA-D.

The position of the vortices as seen in FIG 4 can finally be fixed in time, or even evolve in time according to the prediction of the wake prediction model. For mass simulations however one fixed state of the wake is chosen, according to the instant of closest approach of the aircraft to the vortices, to limit the amount of necessary data to be transferred between WakeScene and VESA.

2.3. Pilot modeling

Another core element of VESA-D is the modeling of the pilot behavior. This is on the one hand required to guide the aircraft along its intended mission in offline simulations where no physical pilot is available, but also very important to generate realistic control input reactions to a wake encounter during offline simulations when performing manual flight. Earlier versions of VESA included a two-part pilot model designed to hold a steady glide slope on approach and in case of a wake encounter to return the aircraft to a wings-level attitude. Thus the wake encounter part of the model only acted on the roll axis, i.e. the side stick roll input, while the glide slope following part was only suited for approach simulations. To adapt VESA to departure simulations a new pilot model was developed by TU Berlin during the CREDOS project [10]. It is based on a neural net that has been trained to recorded pilot inputs during simulated wake encounters in an A320 development simulator at Airbus [11]. Similar to earlier models it is split into two parts. A low-gain part is responsible for the track following. It provides side stick roll and pitch inputs and follows a commanded pitch and bank angle, e.g. displayed by the Flight Director on the Primary Flight Display. As soon as a wake encounter is detected, the model switches to a high-gain part which has adapted weights in the roll axis, but still controls pitch and roll axis simultaneously. The model switches to the high-gain part as soon as a roll rate of p=7 deg/s is exceeded, and switches back when the roll rate falls below this threshold again for more then 2 seconds. Additionally the model has the capability to perform the take-off run on the runway, from setting the desired thrust level to rotation and capture of the Flight Director, and to set gear, flaps and thrust levers according to variable transition speeds. As long as on ground, the model will also compensate deviations from the runway centerline due to crosswinds by using the pedals. Once in the air, the pedals are no longer used to control the aircraft.

The model has been validated using extensive data collected during simulator sessions with a number of airline pilots, flying simulated wake encounters of varying strengths and characteristics [11]. The aircraft simulation used was the same as that in VESA-D. The aircraft reactions as well as the pilot inputs on the control elements (side stick, thrust lever, pedals etc.) have been recorded for each flown encounter. Part of this data was used for the training of the neural net pilot model. After being trained the model was implemented in the A320 offline simulation in VESA-D and exposed to the same external disturbances than the pilots before. FIG 5 shows an example of the bank angle evolution during an encounter flown by 8 different pilots in comparison to the same encounter flown by the pilot model.

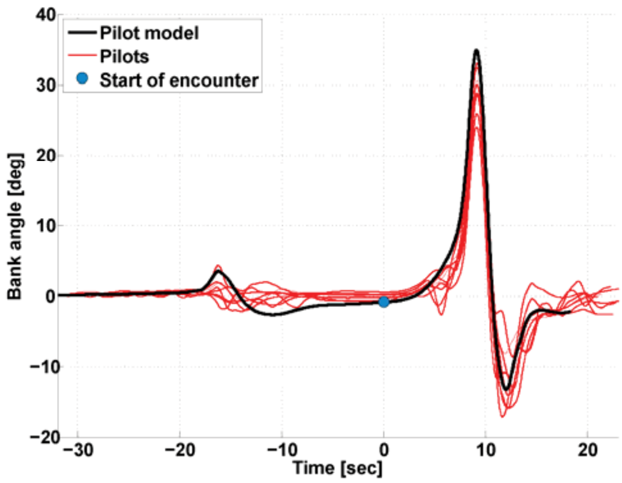

FIG 5. Bank angle evolution during encounter flown by pilot model and real pilots in simulator.

It can be seen that the time histories after beginning of the encounter match very well, and the amplitude in the case controlled by the pilot model lies within the spread of the amplitudes when flown by the real pilots. This validation has been performed for several flight dynamic parameters additional to the bank angle and several different encounter conditions, and it shows good results. Details on the development and validation of the pilot model can be found in [10].

2.4. Severity assessment

Finally, to assess the actual hazard an encounter poses to the aircraft, criteria must be available that allow a classification of encounters into hazardous and non-hazardous encounters. In previous VESA versions these were based e.g. on the bank angle, the vortex-induced rolling moment or, in the approach case, on the deviations from the glide slope (see also [5]). During the CREDOS project an advanced severity model was developed by TU Berlin in cooperation with Airbus that takes into account multiple parameters to determine the severity of an encounter to the encountering aircraft [12]. They are based on a multi-parameter approach initially suggested by Wilborn [13] to assess transport aircraft loss-of-control and first applied to wake encounters by Reinke [14]. In this approach parameters are paired into envelopes of two parameters each, characterizing a certain type of hazard, e.g. load factors or aircraft attitude. Four envelopes have been defined in CREDOS to be applied to the departure situation:

1. AAE: Aircraft Attitude Envelope, taking into account bank and pitch angle attitude,
2. CAE: Cabin Acceleration Envelope, taking into account the maximum lateral and vertical accelerations in the cabin,
3. ACE: Attitude Control Envelope, taking into account the control inputs (side stick roll and pitch) necessary to recover the aircraft,
4. AFE: Air Flow Envelope, taking into account the angle of attack and sideslip.

Each parameter taken into account is normalized to a maximum allowed value, determined using limits derived from handbook data or using engineering judgment. A second limit below these maximum allowed values defines an operational boundary, within which each parameter is expected to stay in normal operational conditions. FIG 6 (top) shows the four envelopes as an example with the time history of the normalized values for each parameter during one encounter. For each of these envelopes a quantitative value is calculated depending on how far the boundaries are exceeded. If both parameters stay within the inner, operational boundary during the encounter, the envelope value is 0, signifying a non-significant event. As soon as one parameter exceeds the inner boundary, the value is interpolated between 0 and 1, reaching 1 when the outer, maximum allowed value is reached or exceeded. Finally the values of all four envelopes are added in each time step to form the severity criterion value *SC*, which is limited itself to a value of 1. The addition of all four envelopes shall reflect the fact that an excursion in several areas at once is more severe than only in one of them. The maximum value of *SC* during an encounter is used to rate the overall severity of the encounter (see FIG 6, bottom). Encounters yielding a value of SC=1 are regarded as severe encounters. This severity assessment together with the frequency of encounters will be used to characterize the wake encounter risk of a simulation scenario. This will be described in more detail in ch. 3.

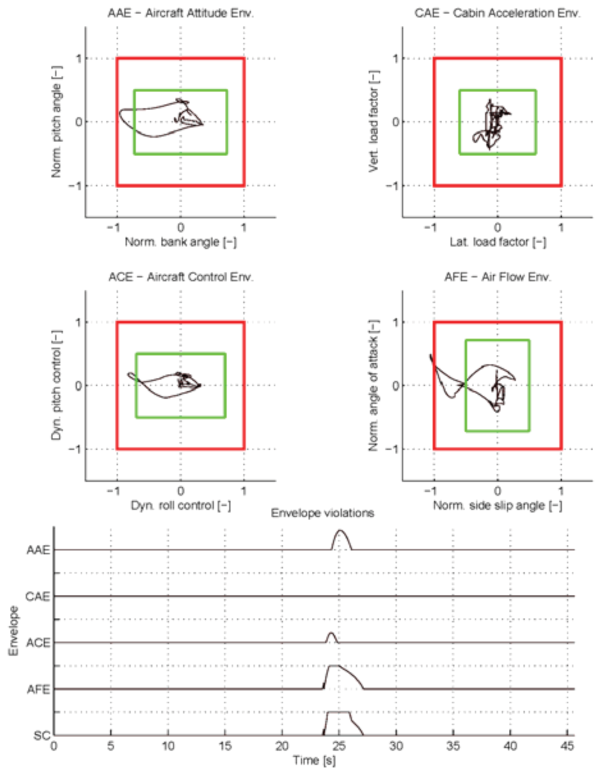

FIG 6. Example hazard envelopes for severity assessment (top) and addition of four different envelopes into severity criterion *SC* (bottom).

The severity model was validated using the same piloted simulator data that was also used to develop the pilot model. The model shows a good prediction quality when compared to subjective pilot ratings of the severity of simulated encounters. More details about the structure and validation of the model can be found in [12].

2.5. Simulation setup

VESA-D can be used as a stand-alone tool to perform sensitivity analyses on different parameters, worst-case searches or Monte Carlo-type simulations. A second possibility that was followed in the CREDOS project was to connect WakeScene-D simulations to VESA-D simulations, to allow combining the information about encounter frequency from WakeScene-D with the assessment of those encounter's severity in VESA-D. In addition, the capabilities of WakeScene-D allow setting up a complete airport scenario, taking into account weather conditions, traffic mixes and departure routings and assessing their influence on wake encounter risk.

The identification of encounters in WakeScene-D is done in the following way. The WakeScene-D simulation platform contains a hazard area model called *SHAPe* (Simplified Hazard Area Prediction) [15] that predicts areas around the vortices within which an estimated encounter strength is exceeded. The encounter strength is characterized by means of the Roll Control Ratio *RCR*, which relates the rolling moment induced by the vortices to the maximum roll control power of the encountering aircraft. These hazard areas have been calibrated using flight test and simulator data. SHAPe takes into account the varying strength of the decaying vortices and the diminishing influence of the vortices depending on the distance to their centers. Violation of the hazard area corresponding to a specified limit RCR leads to identification of a potential encounter which is then investigated in VESA-D. A conservative value of RCR_{limit}= 0.2 has been chosen for the simulations in order not to miss any potentially significant encounters. This means also that a relatively large number of actually benign encounters are detected, which finally lead to a severity rating of SC=0 in VESA-D. The encounter detection with SHAPe, in comparison to a simple minimum distance criterion, has the advantage that it takes into account the effect on the encountering aircraft depending on its distance to the vortices. On the other hand it does only consider the roll axis and assumes a flight parallel to the vortex lines, which might be close to the worst-case condition, but in reality is only rarely the case, especially during departure. A more accurate severity assessment considering the full dynamic motion of the aircraft can only be given after the simulation in VESA-D.

For each encounter to be investigated in VESA-D, WakeScene-D saves the wake vortex prediction model output for 5 gates before and behind the encounter, the follower aircraft's position and orientation, the weather data file used and the inputs to the trajectory model for the follower aircraft to allow setting the correct performance parameters in VESA-D. No temporal evolution of the wake vortex takes place in VESA-D during the encounter. Considering the usually short duration of an encounter of about 5-15 seconds, this is assumed to be an acceptable simplification which allows a considerable reduction in storage and memory space. With this data it is possible to reconstruct the WakeScene-D scenario as closely as possible with respect to aircraft performance, wake vortex condition and encounter geometry in VESA-D.

However, while WakeScene-D employs a 3 degree-of-freedom point-mass model to generate the flight tracks of the departing aircraft [7], which is well suited to produce probabilistic distributions of departure flight paths under variation of several performance parameters, VESA-D contains a fully dynamic 6 degree-of-freedom aircraft simulation of high accuracy. Small differences in the flight paths must therefore be expected. For this reason the vortices in VESA-D cannot be placed in a geodetically fixed position as it is determined in WakeScene-D. Already small deviations from the intended flight path would then make the aircraft miss the vortices. Instead the vortices are placed at a certain distance in front of the aircraft as soon as the aircraft reaches the encounter altitude determined in WakeScene-D. The altitude has been chosen as condition because the severity model also takes into account the altitude above ground. When WakeScene-D identifies an encounter, it determines a point where the aircraft is still R_{min}= 75 m away from the closest vortex. This is a distance where there is just no noticeable influence of the wake on the aircraft yet, even for the strongest vortices that can be expected. As the vortex influence on the aircraft is not considered in WakeScene, this is also the last point where the flight paths in both tools can be considered comparable (see FIG 7). Once the aircraft reaches the encounter altitude, the wake vortices are placed at the same position relative to the aircraft as they were in WakeScene-D when reaching this point.

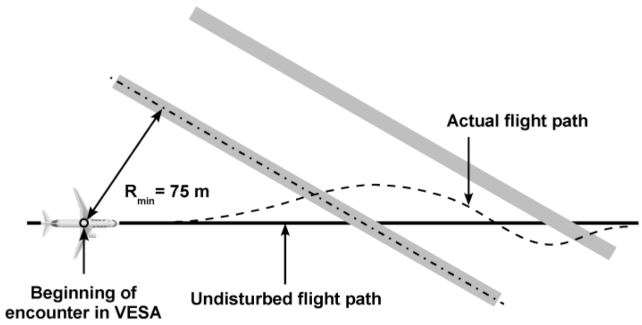

FIG 7. Activation of vortices in VESA-D simulation.

The VESA simulation then determines the actual path of the aircraft through the wake under the influence of the additional forces, and the dynamic reaction of the aircraft due to these forces.

3. APPLICATION RESULTS

Results will be presented using the above described simulation platforms for wake encounter risk assessments in the CREDOS project. The simulation platforms WakeScene-D and VESA-D described in the chapter before have been applied in CREDOS to compare the risk of significant wake encounters for different combinations of crosswind and aircraft separation time, with all other parameters like the traffic mix chosen as closely as possible to real operational conditions. The simulation scenarios are based on the setting of Frankfurt/Main International Airport in Germany. Most of the data that was made available or that was generated within the CREDOS project, and used for development and validation of the models described earlier, is from this airport. Therefore it was chosen as a baseline for the computations, although some of the findings can be generalized also for other airports. For the separations between leading and following aircraft the non-radar longitudinal wake turbulence separations were chosen according to ICAO rules described in [16]. Furthermore the ICAO weight categories for wake turbulence separations are assumed. Departures from intermediate parts of the runway were not considered, so the according reference separation time is 2 minutes (or 120 s). On the other hand the goal of the CREDOS concept is to allow suspension of these wake turbulence specific separations, which leads to application of Minimum Radar Separation (2.5 to 3 NM) or a corresponding time separation of about 1 minute. Therefore 1 minute (or 60 s) was chosen as the separation for CREDOS operation. These times were always kept fixed, not considering a natural variation in the actual separation times occurring in real operation, and are applied at brake release, i.e. the start of the take-off run at the threshold.

Further parameters are listed in Table 1. Although several Medium type follower aircraft are available in WakeScene-D, only the A320 is available so far in VESA-D. The lower load limit of 50% as indicated in the table corresponds to an aircraft with 50% of its payload and 50% of its fuel capacity loaded. In addition to these parameters the flight paths of the generator aircraft have been varied by introducing a cross track error with a standard deviation of up to σ= 100 m around the nominal departure route, and a longitudinal delay in initiating a course change at waypoints of 50 m ± (250-400) m depending on aircraft type. This means the flight tracks of generator and follower aircraft can also be laterally offset, and not only vertically caused by the respective climb performance.

TAB 1. Fix and varied parameters during simulations.

Fix Parameters	**Value**
Following a/c type	A320
Max. altitude	4000 ft
Configuration	Take-off
Varied Parameters	**Range**
Leading a/c types	A300-600 / A310 / A330-300 / A340-300 / B747-400 / B777-200
Aircraft mass	Between 50% load and MTOW
Thrust	TOGA or Flex. Thrust
Start point on runway	Between threshold and 1st taxiway entry (half-normal distribution)
Departure route	Straight or 5 FRA 25R SIDs
Wind conditions	Crosswind at 10 m ±0-10 kt Headwind at 10 m 0-20 kt Tailwind at 10 m 0- 5 kt

In each simulation a crosswind within a specified range of 2 kt width was employed (e.g. 6-8 kt). In contrast to the operationally simpler solution assuring that a crosswind is always greater than a certain threshold, this way allows a better interpretation of the dependency of wake encounter risk on crosswind magnitude and direction. Crosswind referred to here is always the wind component perpendicular to the departure runway at an altitude of 10 m above ground.

The evaluation of the simulation results with respect to encounter risk shown in the following is based on the multi-parameter severity model which was developed within CREDOS and was described before in ch. 2.4. This allows for example assessing the probability of encounters exceeding a certain level of severity. By additionally weighting each encounter with its actual severity value *SC* the severity of each single encounter can be taken into account. This means that scenarios including a lot of low-severity encounters will yield a lower value then those with a lot of high-severity encounters. The resulting value is called the *Risk*. It is computed according to:

$$Risk = \frac{1}{N}\sum_{1}^{N} SC \qquad (2)$$

with *N* the total number of simulated departures in WakeScene-D. All departures not identified as potential encounters in WakeScene-D are attributed a severity of *SC=0* and therefore do not contribute to the risk. Note that this kind of interpretation does not take into account the frequency of the specific crosswind condition over a longer period. Typically high crosswind conditions occur much less frequent than low crosswind conditions, thus contributing less to an overall encounter probability. Therefore the above defined Risk quantity does not allow to infer the absolute risk of wake encounters in real-life operation. It shall only be used here to quantify the difference in wake encounter risk between different scenarios. The interpretation of the values shown in the following could therefore be worded e.g. as: *If the crosswind is between 6 and 8 kt and the separation time is 60 sec., the wake encounter risk is "x"*.

Finally it has to be kept in mind that the simulations only covered A320 aircraft following several Heavy wake generators, and the resulting risk levels are thus only valid for these aircraft pairings, which represent only a fraction of the total traffic mix. Wake encounter risk for other aircraft pairings, particularly for smaller Medium category aircraft starting behind Heavies, can be different, but do not necessarily need to be significantly higher. A large fraction of the traffic on the other hand does not require any specific wake turbulence separations at all and is not affected by a reduction of separation minima. Therefore the overall wake encounter risk for the whole fleet over an extended period of time can be assumed to be some orders of magnitude lower than the values shown here. Finally, a comparison with the number of real wake encounter reports is very difficult as an unknown number of unreported wake encounter events must be assumed. The simulation approach presented here should thus only be used for relative comparisons of different scenarios.

The following sections show some key results from these CREDOS simulations. A comprehensive description of all the conducted simulations and the evaluation of the results, including sensitivity studies, can be found in [18].

3.1. Wake encounter risk depending on crosswind

The principal representation of the results that will be used here is a plot of wake encounter risk as defined above versus crosswind. Simulations in WakeScene-D have been performed with 500.000 departures (representing one generator-follower aircraft pair) for each crosswind bin of $|\Delta u_{cw}|=2$ *kt*, of which a fraction was investigated further in VESA-D. Investigations showing that this number of departures is sufficient to obtain converged results can be found in [17, 18]. The departures have been split by the principal direction of the crosswind that prevailed on the ground during the departure, and the altitude at which the encounter occurred, as explained in the following.

The first results that are shown are from a simulation scenario in which every generator-follower aircraft pair departed only on the two northerly SIDs of runway 25R (see FIG 10). They are essentially identical up to the considered maximum altitude and turn only slightly to the right shortly after take-off. Therefore all simulated aircraft depart in fact along the same route. This is closest to the operational conditions in Frankfurt as the southerly routes of runway 25R are usually only used in case the wind conditions prevent use of runway 18.

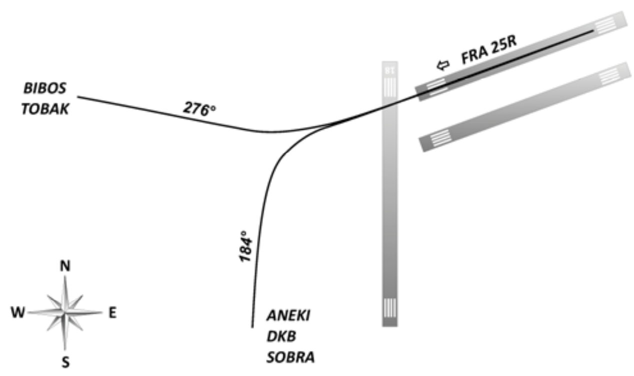

FIG 10. SID layout of the considered simulation scenario at Frankfurt Airport.

FIG 11 shows the results of the simulation. For 0-2 kt crosswind at 60 s separation no simulations have been performed. During the simulations it was noted that the altitude of the wake encounter had a major influence on how the encounter risk changes with crosswind magnitude. Therefore the results are split here into those encounters happening at an altitude below 300 ft (in the lower half of the plot) and those above 300 ft (in the top half of the plot). The boundary has been arbitrarily chosen and corresponds roughly to the height up to which the vortices can be considered to be in ground effect, as well as to the beginning of the Ekman layer (see below). Furthermore the plot distinguishes between cases where the crosswind component on the ground came from the left of the runway (negative sign, southerly crosswind) and from the right of it (positive sign, northerly crosswind). As can be seen the distributions in the two altitude domains are significantly different. Close to the ground the decrease of wake encounter risk with increasing crosswind magnitude is very efficient, and in fact above a crosswind component of 6 kt the risk is nearly 0 even at 60 s separation. This is the effect that was expected when introducing a crosswind component.

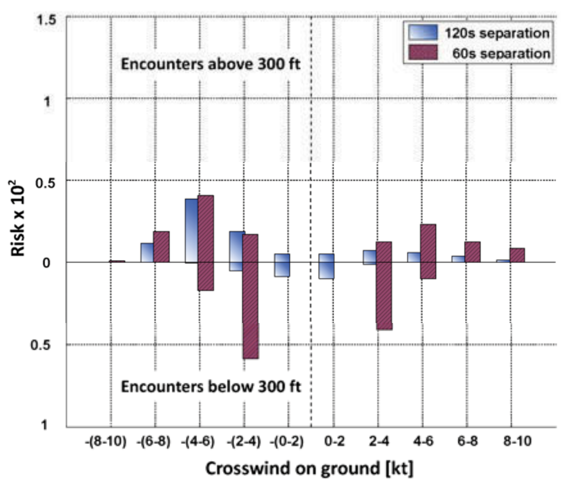

FIG 11. Wake encounter risk vs. crosswind with only northerly SIDs in use.

However, at higher altitudes the dependency of the wake encounter risk on crosswind is clearly different. This is the case for reduced separations as well as for the reference case with a separation of 2 minutes representing today's operations. The behavior is caused by several interacting effects. First of all the wind at 10 m above ground, which is used here to differentiate the results, does usually change considerably with increasing altitude above ground. Within a layer of the atmosphere between approx. 300 and 2000 ft the wind direction usually veers with altitude while wind speed increases at the same time, caused by a balance between friction, horizontal pressure gradient and Coriolis force [19]. On the northern hemisphere this leads to the wind direction turning in clockwise direction when looking towards the ground. The veering of the wind direction in reality rarely exceeds 30 degrees, although other effects can partially or fully counteract or intensify this veering. The weather profiles used in the simulations do contain this behavior of the wind direction as they are taken from a numerical weather database containing realistic vertical wind profiles. The effect of the wind veering with altitude is also known as the Ekman-spiral. It has an important effect on the wake encounter risk. The Ekman effect can be noted in the results by the high-altitude encounter risk being higher for crosswinds coming from the left of the runway (negative sign) then for those coming from the right. Even below 300 ft this tendency is already noticeable. Winds coming slightly from the left on the runway tend to turn into a headwind with increasing altitude. Headwind however increases encounter risk on departure as it transports the vortices towards the following aircraft. Interacting with the wind speed is the time the vortices have to be transported laterally and/or longitudinally by the wind, as well as their decay during this time. After 120 s the wakes are typically weaker already and thus do not affect an encountering aircraft in the same way. This is reflected in the plots by the risk at 120 s separation being generally lower then at 60 s separation. Finally of course the variable offset between generator and follower flight path in vertical and lateral direction influences the probability to encounter the wake.

Noteworthy in FIG 11 is in particular the region around –(4-6) kt crosswind for encounters at higher altitude. The encounter risk at 120 s separation even reaches the level of that at 60 s. Here the veering wind obviously plays a major role. The longer separation of 120 s can be sufficient for the vortices to come close enough to the following aircraft, while after 60 s the higher remaining circulation of the vortices also becomes important, even if they are still farther away.

FIG 12 shows the results with every generator-follower aircraft pair departing in random combinations along the five FRA 25R SIDs in the simulation. This is as mentioned before not the most common operational condition in Frankfurt. The wind conditions leading to aircraft departing also to the south on runway 25R instead of runway 18 would on the other hand mean significant crosswind for runway 25R, so it is not totally unrealistic to simulate this scenario as well. Again no simulation results are available for 0-2 kt crosswind at 60 s separation. The most noticeable difference to the plot before is that for high negative crosswinds (coming from the south in this scenario) the encounter risk significantly increases at higher altitudes, which is the case for 60 s and for 120 s separation. This is due to the fact that the southerly routes actually turn into the wind for these wind conditions, adding a considerable headwind component relative the flight path which increases encounter probability (cp. FIG 10).

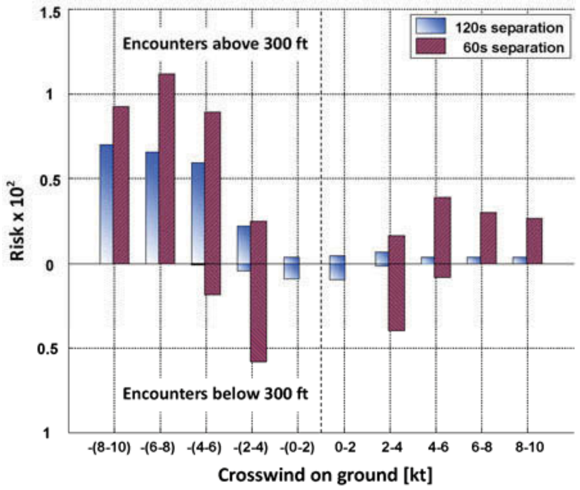

FIG 12. Wake encounter risk vs. crosswind with all SIDs in use.

This is true when both generator and follower depart on a southerly route, but also when the follower takes a northerly SID wakes can be transported from one route to another as long as the flight paths are not yet separated enough. This shows that it is important to take into account the departure route layout at an airport before implementing such a concept. Additional measures might be necessary such as restrictions on the combination of generator and follower SIDs depending on the crosswind when separations shall be reduced.

FIG 13 shows the same scenario as FIG 12 but without distinguishing between the crosswind directions, and additionally with results for a separation of 90 s. It shows that essentially the risk at 90 s separations lies between the levels at 60 and 120 s as expected. An exception is the case of 2-4 kt crosswind magnitude above 300 ft, which can again be attributed to an interaction between the time for the vortices to be transported by the wind, increasing the probability to encounter them, and the time for them to decay, reducing the final severity of the encounter.

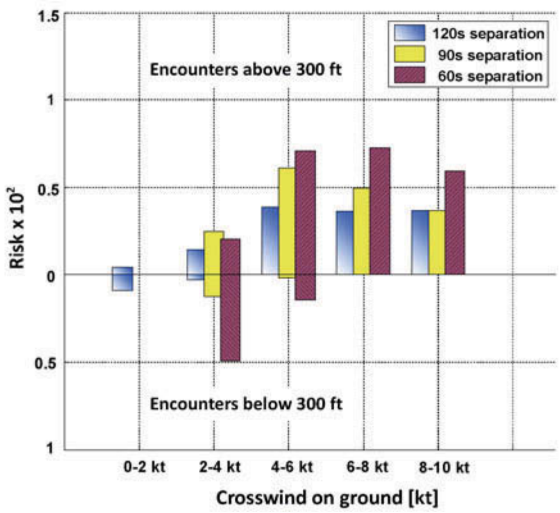

FIG 13. Wake encounter risk vs. crosswind with all SIDs in use, including 90 s separation.

Finally FIG 14 shall demonstrate how effective the crosswind is in transporting the vortices out of the way. The upper part of the figure shows the encounter severity SC versus encounter altitude H_{enc} for the scenario of FIG 11 for $|\Delta u_{cw}|$= 4-6 kt crosswind, including all encounters with a severity rating of *SC>0*. It becomes visible how many encounters remain close to the ground especially at 60 s separation, but also that generally the majority of encounters tends to have low severity ratings between *SC= 0 – 0.5*. In the lower part of the plot the remaining encounters at a crosswind level of $|\Delta u_{cw}|$= 8-10 kt are contained, showing the dramatic reduction of the number of encounters close to ground, but also up to 2000 ft altitude. Between approx. 2000 ft and 3000 ft however the number of encounters seems to slightly increase compared to the lower crosswind. The reason for this is probably to be found in the vortex transport towards the following aircraft at these high wind speeds.

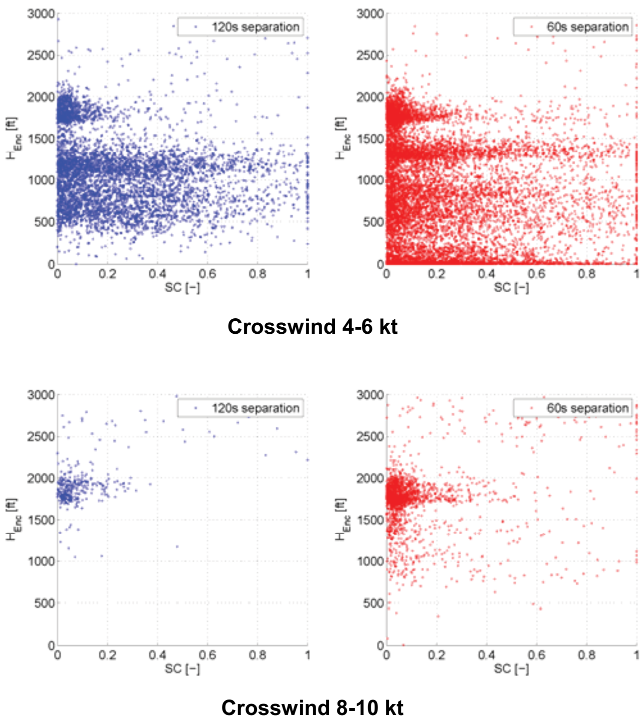

FIG 14. Encounter severity vs. encounter altitude, only northerly SIDs in use.

4. CONCLUSIONS

In this paper a simulation platform was presented that is able to assess wake encounter risk by determining the frequency of encounters as well as their actual severity. This platform is in general applicable to all flight phases. Here it has been applied to the problem of reduced departure separations under crosswind conditions in a specific airport layout. The main results of the simulations performed have been presented and some of the main effects discovered have been explained. Further simulation exercises and analyses have been performed and can be found in [17, 18, 20]. They have been used to support the CREDOS Safety Case for a potential Concept of Operations and to give indications of a possible crosswind threshold for such a concept.

The results indicate that to prevent encounters close to the ground (up to 300 ft altitude), a crosswind of 6 kt or more is generally sufficient. This is not depending on the departure routing, as usually up to this altitude all departing aircraft are still flying in runway direction. It is also independent of changes in wind direction and magnitude with altitude, as these do almost not come into effect yet below this altitude. This finding should furthermore be valid for other airport scenarios as well, although attention should be paid to local environmental effects which can have an influence on wind behavior, such as tree lines or hills close to the runway. The findings concerning wake encounter risk at higher altitude (between 300 and approx. 3000 ft) have shown that the departure route layout of the considered airport has to be taken into account in any case. In fact it might be necessary to introduce further restrictions than only a crosswind threshold, such as combinations of SIDs for consecutive aircraft, to sufficiently reduce wake encounter risk.

The combined WakeScene-VESA platform is to the author's knowledge the only simulation tool at the moment allowing to perform wake encounter simulations of this level of detail. It is however still considered a research tool. Some of the employed sub-models have not yet reached a level of validation that would allow the simulation platform to be used for production of an operational safety case. But further development work will be done e.g. during the SESAR European ATM research program which also contains several wake-vortex related projects. Especially the definition of severity metrics that allow judging if an encounter is hazardous or not, taking into account all factors influencing the actual encounter severity, will be further explored. The results and findings from the investigation in CREDOS however will nevertheless be helpful inputs e.g. to the definition of new weather-dependent separation schemes as envisaged in SESAR.

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