PARAMETRIC STUDY & SIMPLIFIED APPROACH TO WAKE VORTEX ENCOUNTER OFFLINE SIMULATION

D. Bieniek, R. Luckner
Technische Universität Berlin
Institute of Aeronautics and Astronautics
Flight Mechanics, Flight Control and Aeroelasticity
Marchstraße 12, 10587 Berlin, Germany

ABSTRACT

This paper describes the application of an existing Wake Vortex Encounter (WVE) Model in a parameter sensitivity study and in a simplified simulation. Within this model an encounter scenario is defined by a list of different parameters. The effects of a variation of these parameters on the reaction of various encountering aircraft types are being investigated and results are presented and discussed. Furthermore, a simplified approach to an offline WVE simulation is presented. Since the primary effect of a near parallel WVE is a bank angle disturbance, only roll motion is taken into consideration. The possibility of combining results from the parametric study with the simplified offline-simulation model to investigate worst-case encounter scenarios is discussed.

1 INTRODUCTION

1.1 Background

WVEs represent a great threat to all classes of aircraft. Especially during approach and landing the effects on flight path and attitude may endanger safe flight operation. In areas with dense air traffic the potential of a vortex encounter particularly exists. In order to avoid severe WVEs the International Civil Aviation Organization (ICAO) has set up minimum separation requirements for takeoff, cruise, approach and landing (FIG 1). However these requirements are only based on maximum takeoff weights (MTOW) of generating and following aircraft. They do not consider the actual weight of the generating aircraft and completely neglect the influence of meteorological conditions on vortex transport and decay. Detailed flight mechanical characteristics and control capabilities of the encountering aircraft are also not taken into account. Therefore the existing separation requirements are conservative in many cases. Particularly airport capacities are limited more than necessary by these requirements. This will impact future air traffic growth. In order to satisfy future air traffic requests, the separation requirements need to be revised and reduced where possible while maintaining current safety standards.

With the development of large aircrafts as the A380 and B747-800 the adjustment of the ICAO requirements becomes even more important. Currently aircraft are separated into three weight classes, with the class “heavy” starting at 136t MTOW. As the A380s MTOW of 590t is larger than previous aircraft, ICAO has set up specific requirements for aircraft following an A380 [1] limiting capacities even more. The A380 Wake Vortex Steering Group recommends 6nm for a Heavy, 8nm for a Medium and 10nm for a Small aircraft behind an A380 [2]. Thus further research on the effects of WVEs is needed.

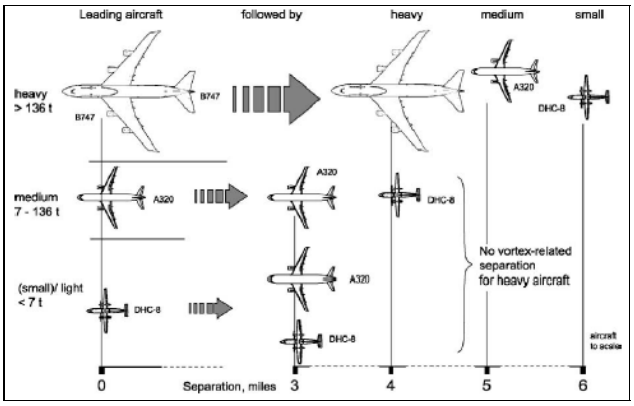

FIG 1. ICAO separation requirements for landing

1.2 Wake Vortex Encounter Simulation

Alongside flight tests using smoke or vaporized oil to visualize wake vortices, measure induced wind fields and assess WVE severity, simulation based analysis has become more involved in these investigations. Since flight tests are rather expensive and encounter parameters such as vortex strength and encounter angle can only be controlled with limited accuracy, simulated encounters using modern high-fidelity flight simulators have made research more time and cost effective.

One programme dealing with WVE simulation was the European technology project “Assessment of Wake Vortex Safety” (S-WAKE, 6th Framework Programme of the EC). Its objective was to simulate vortex encounters during ILS approaches using existing full flight simulators. The WVE model that was developed was used to perform piloted experiments. The results were transformed into hazard criteria to quantify encounter severity. Based on the work performed during the S-WAKE project, an offline simulation based methodology for “Vortex Encounter Severity Assessment” (VESA) was developed [3]. Elements of the VESA tool are the WVE model, a high-fidelity offline simulation of the encountering aircraft and a pilot model. The hazard criteria from the flight simulator tests were used to find worst-case encounter conditions [4].

1.3 Objective

In this study the effects of varied encounter parameters on induced aircraft reaction were investigated. Recent studies use time costly optimization software to find worst-case encounter scenarios. The results found in this study present the separate effects of each parameter on the vortex-induced accelerations and load factors. With this knowledge simulation effort in future studies could be reduced when assessing worst-case scenarios.

In the second part of this paper a simplified model for WVE offline simulation is presented. Existing offline based analysis tools use high-fidelity simulation models of a specific following aircraft. This makes investigations with different encountering aircraft types problematic. Using a more simplified approach reduces the effort to simulate various aircraft types when assessing wake vortex encounter severity. To see whether simulation fidelity can be reduced while retaining acceptable quality of results is part of the objectives of this paper.

The following chapters start with a brief description of the WVE model. Elements as the vortex velocity and decay models are explained and the function of the software program "TestWVE" that has been used during this investigation is described. Following results from the parametric study, the offline simulation model and the simplifications that were made are explained in detail. Results are compared to data from piloted experiments using the level D ZFB A330 full flight simulator.

2 THE WVE SIMULATION MODEL

The WVE simulation model calculates vortex induced forces and moments from the a/c state, encounter geometry and vortex parameters. It is designed as an add-on software tool to be integrated easily into existing flight simulations [5]. The basic aerodynamic and kinematical calculations are performed by the host simulation. The additional forces and moments from the WVE model are transformed into a linearized induced wind field which is passed on to the host simulation (FIG 2). This practice ensures that the physical and kinematical effects on the encountering aircraft are simulated correctly.

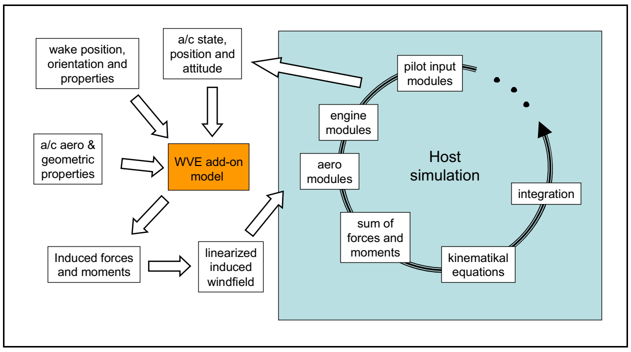

FIG 2. Integration of the add-on WVE model [5]

2.1 Simplifications within the model

In order to simulate encounter scenarios with desired parameters and to be able to repeat them, the following simplifications have been made while developing the encounter model:

- *Induced wind field:* The rotation axes of the vortices are modelled as straight lines and the induced wind field is two-dimensional. Only two perpendicular velocity components $v_{WV}(r)$ and $w_{WV}(r)$, respectively the tangential component $u_\theta(r)$ are calculated.
- *Vortex decay:* The vortex decay is not simulated continuously. Instead a vortex age can be chosen and the vortex parameters are kept constant throughout a simulation run.
- *Vortex transport:* To define a desired encounter, the vortex position is fixed in respect to the ILS glide path.

2.2 Encounter geometry

The encountering aircraft is doing an ILS landing approach while the ILS flight path is crossed by the vortex pair. The reference point for the definition of the encounter geometry is the "Encounter Fix" (EF). It is the perpendicular downward projection of the wake vortex coordinate system's origin O_{WV} to the ground and is used to position the vortex pair. Using different parameters (FIG 3) the EF's position and the position of the origin O_{WV} can clearly be set with respect to the ground coordinate system (index: gr). The complete encounter geometry is then defined using the encounter deviation angles $\Delta\Psi_{WV}$ and $\Delta\gamma_{WV}$. In addition, the vortex pair can be tilted (parameter Φ_{WV}).

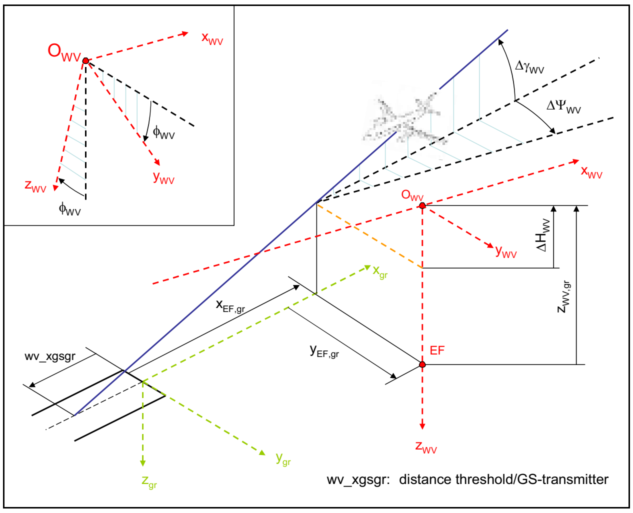

FIG 3. Definition of the encounter geometry

2.3 Induced velocity field and vortex decay

To compute the two-dimensional velocity field, four analytical approaches have been implemented into the WVE model [6]. The LAMB-OSEEN, BURNHAM & HALLOCK (BH), PROCTOR and WINCKELMANS (WM) models describe the tangential velocity $u_\theta(r)$ as function of the distance r to the vortex centre and the vortex circulation Γ (FIG 4). As part of the parametric study, the influence of the core radius r_c on the induced forces and moments was investigated. Since the BURNHAM & HALLOCK model is rather simple and includes the core radius as a parameter it was used as the reference model.

$$u_\theta(r) = \frac{\Gamma}{2\cdot\pi}\cdot\frac{r}{r_c^2 + r^2} \tag{1}$$

Five analytical decay models have been implemented: (1) DONALDSON & BILANIN, (2) GREENE, (3) ROBINS & DELISI, (4) HAN et. al and (5) SARPKAYA. However they were not used in this study. Instead the vortex strength for the encounter was defined directly.

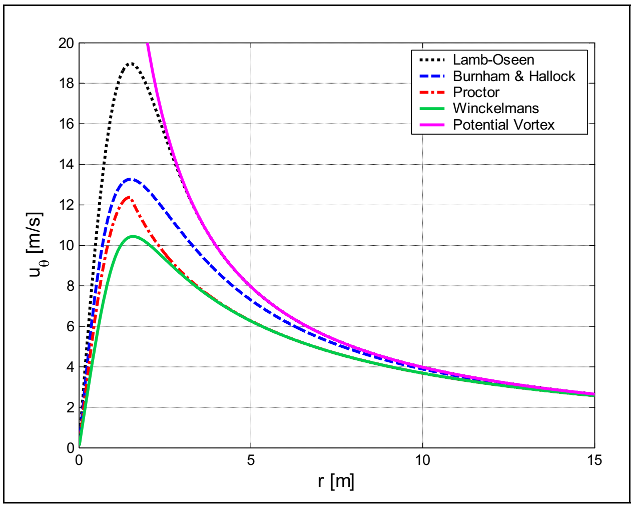

FIG 4. Comparison of vortex velocity models

2.4 Vortex induced forces and moments

To compute the vortex induced forces and moments two methods have been implemented, the “Lifting Surface Method” and the simpler “Strip Method”. The Strip Method [7] was used for this parametric study and will be described briefly.

2.4.1 Computation of incremental forces and moments with the Strip Method

The Strip Method is based on the principle of modelling the aircraft as a wing, tailplane and fin combination and dividing those into single strips, also referred to as Aerodynamic Elements (AE). For every AE the incremental forces and moments resulting from the local vortex induced air flow are computed and transferred into body axes. The incremental forces and moments are calculated using a simple two-dimensional approach. The local vortex induced air flow leads to an additional angle of attack (AOA), respectively angle of sideslip (AOS), at each strip. To determine those, the local undisturbed ($V_{proj,i}$) and induced ($v_{ind,i}$ / $w_{ind,i}$) air flow is calculated taking sweep and dihedral of the wing into account. The ratio of those two velocities leads to the induced AOA or AOS at each strip.

(2) $$\alpha_{ind} = -\frac{w_{ind,i}}{V_{proj,i}}$$

(3) $$\beta_{ind} = -\frac{v_{ind,i}}{V_{proj,i}}$$

With the additional flow angles and aerodynamic parameters of the airfoil additional forces can be determined.

2.4.2 Forces and moments for the entire aircraft

The WVE model calculates the following five induced forces and moments with respect to the body axes system of the aircraft:

- vertical and lateral forces (lift and sideforce)
- roll, pitch and yaw moments

Equation (4) illustrates how the incremental moments of each strip are added up to determine the total induced roll moment [7].

(4) $$\Delta L_b = \frac{1}{2}\rho\left[-C_{L\alpha}\sum_{W} V_{proj,i}^2 S_i \alpha_{ind,i} y_i W_{W,i} - \ldots - C_{L\alpha HT}\left(1-\left(\frac{d\varepsilon}{d\alpha}\right)_{HT}\right)\sum_{HT} V_{proj,i}^2 S_i \alpha_{ind,i} y_i W_{HT,i} + \ldots + C_{L\alpha VT}\left(1-\left(\frac{d\varepsilon}{d\beta}\right)_{VT}\right)\sum_{VT} V_{proj,i}^2 S_i \beta_{ind,i} z_i W_{VT,i}\right]$$

As (4)* shows wing, tailplane and fin contribute to the vortex induced roll moment.

2.4.3 Modelling of stall effects

To model local stall, reference AOA and induced AOA are combined at each strip. Minimum and maximum values for AOA have to be defined for root and tip of wing, tailplane and fin according to the aerodynamic properties of the airfoil. For each strip these limits are then computed by linear interpolation of the root/tip values. If the total AOA exceeds the defined minimum or maximum values, the induced flow angle is limited.

(5) $$\alpha_{t,i} = \max\left(\min\left(\alpha_r + \alpha_{ind,i}, \alpha_{max,i}\right), \alpha_{min,i}\right)$$

The same is done for the AOS:

(6) $$\beta_{t,i} = \max\left(\min\left(\beta_r + \beta_{ind,i}, \beta_{max,i}\right), \beta_{min,i}\right)$$

This results in limited induced force on that particular strip. The approach leads to a lift coefficient curve as shown in FIG 5. The complex lift loss experienced when exceeding maximum AOA is certainly not reflected by this but it limits modelling expense achieving acceptable simulation quality.

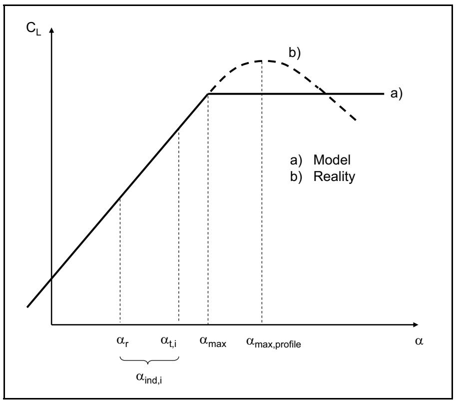

FIG 5. Modelling of local stall effects

3 THE SOFTWARE TOOL TESTWVE

The software package of the WVE model is also available embedded in a stand alone software tool named TestWVE. It runs completely independently from a host simulation and was originally designed for test purposes. But it can be used to calculate induced forces and moments for frozen encounter conditions and varied

* A definition of each variable used in (4) can be found in the chapter “Nomenclature”

aircraft position with respect to the vortex pair. The version that was used for this study included eight types for the encountering/following aircraft from the three ICAO weight classes.

3.1 Structure of a simulation run

A typical simulation run consists of three steps:

1) *Definition of the encounter scenario:* This includes the encounter geometry and vortex properties such as circulation Γ, core radius r_c or vortex span b_v and choice of velocity field [and decay] model[s]. Also parameters defining the geometry and aerodynamic properties of the encountering aircraft have to be prepared. The complete input data is given to the software via input files.
2) *Computation:* During a simulation run the aircraft CG position is varied within a predefined area around the vortex pair within the $y`_{gr}$-$z`_{gr}$-plane which is set to be perpendicular to the runway (see FIG 6).
3) *Analysis of results:* Results from this static simulation can be analized using any common software.

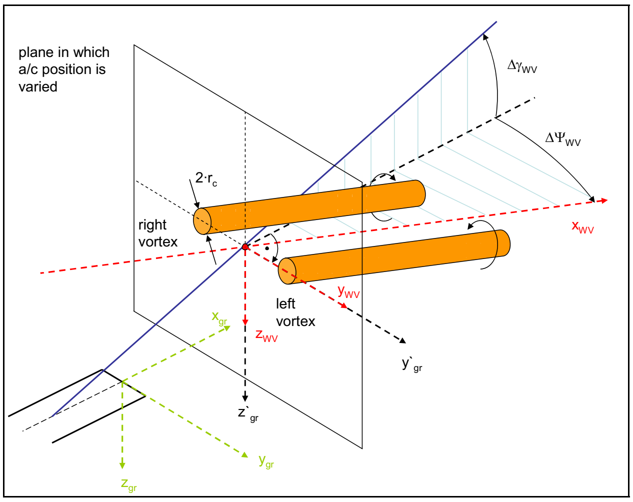

FIG 6. Variation of aircraft position in $y`_{gr}$-$z`_{gr}$-plane

3.2 TestWVE results

Vortex-induced forces and moments increase with the encountering aircraft's size. However, the aircraft reaction is larger for a small follower encountering the same vortex. Therefore the option to calculate induced angular accelerations and load factors taking the aircraft's moments of inertia and mass into account is also available. This makes an evaluation of the WVE effects easier. The results of a simulation run include:

- vertical and lateral forces,
- roll, pitch and yaw moments,
- load factors n_y and n_z,
- induced roll, pitch and yaw acceleration,
- components of induced velocity field.

To visualize these results, contour plots are used. As FIG 7 shows, the largest accelerations and load factors appear at CG positions close to the vortex centres.

Additionally the functionality of identifying the aircraft positions in the vortex field at which local stall appeared has been included. This makes it possible to investigate the influence of local stall on the induced accelerations closely.

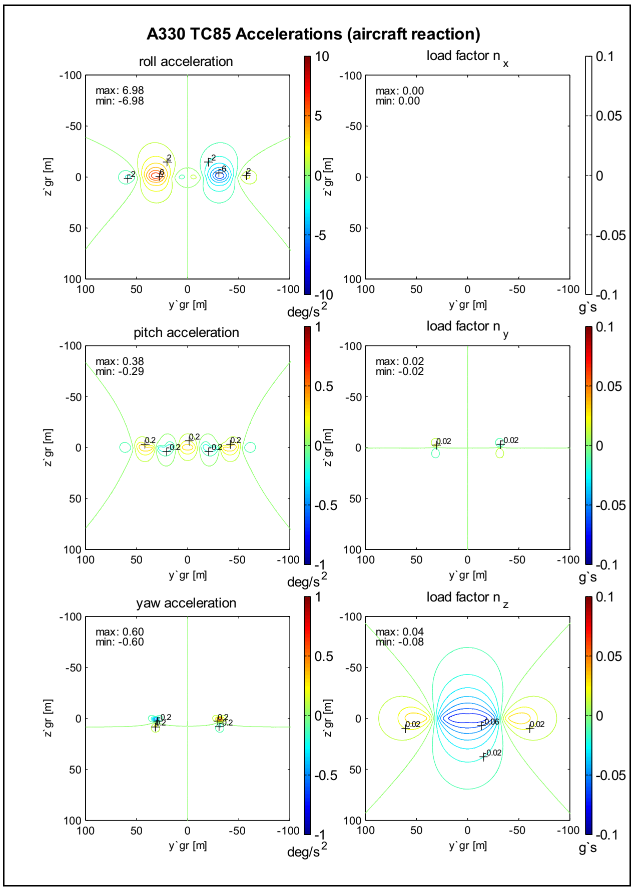

FIG 7. Simulation results in $y`_{gr}$-$z`_{gr}$-plane

4 PARAMETRIC STUDY

Within this parametric study the influence of different encounter conditions on the induced aircraft reaction was investigated. For this reason, parameters which define the encounter scenario were varied separately within a reasonable range and the effects on induced accelerations and load factors were analyzed. The list of varied parameters includes:

1) *Vortex parameters:*
   - Circulation Γ [m^2/s]
   - Core radius r_c [$\%b_g$]
   - Wing span ratio b_g/b_f
   - Vortex velocity model

2) *Encounter geometry:*
   - Deviation angle $\Delta\Psi_{WV}$ [°]
   - Deviation angle $\Delta\gamma_{WV}$ [°]

4.1 Simulated encountering aircrafts

Various aircraft types were simulated to investigate vortex effects on followers of different size. Only publically available data was used. Therefore the results of this study do not exactly represent these aircraft types, and real responses may differ from the results found here. TAB 1 shows the eight trailing (vortex encountering) aircraft types that were simulated.

ICAO weight class	Simulated aircraft types
"Light"	Dornier DO 228
	Cessna Citation
"Medium"	VFW614-ATD
	Bombardier CRJ-700
	Fokker 100
	Boeing 737
	Airbus A320-200
"Heavy"	Airbus A330-300

TAB 1. Simulated encountering aircraft types

4.2 Vortex reference parameters

Vortex parameters were defined for a large aircraft like the Airbus A380. For investigations with constant circulation Γ two sets of vortex parameters were used. To avoid the influence of stall effects on the results, studies were first performed with a rather low value of $\Gamma = 100.00\text{m}^2/\text{s}$. To get realistic results and to see the influence of local stall, the studies were repeated with a higher circulation of $\Gamma = 533.52\text{m}^2/\text{s}$.

- Circulation: $\Gamma = 100.00\text{m}^2/\text{s}$
  $\Gamma = 533.52\text{m}^2/\text{s}$
- Generator span: $b_g = 79.80\text{m}$
- Vortex span: $b_v = 62.67\text{m}$
- Core radius: $r_c = 2.5\% b_g = 2.00\text{m}$

4.3 Reference encounter geometry

TAB 2 shows the set of reference data that was used for studies with constant encounter geometry. With all deviation angles $\Delta\Psi_{WV}$, $\Delta\gamma_{WV}$, Φ_{WV} and the height offset ΔH_{WV} set to zero, the centre line of the vortex pair is equivalent to the ILS path.

Encounter geometry	$\Delta\Psi_{WV}$	$\Delta\gamma_{WV}$	Φ_{WV}
	0°	0°	0°
Position of vortex system	$x_{EF,gr}$	$y_{EF,gr}$	ΔH_{WV}
	4000m	0m	0m

TAB 2. Parameters of encounter geometry

4.4 Results

The effects of a parameter variation were analyzed for all induced angular accelerations and load factors. Since the primary effect of a WVE is in the roll axis mostly results for induced roll acceleration are presented here. From the field of induced accelerations calculated by the WVE model the highest negative and positive absolute values were used to determine the influence of varying parameter. These results are referred to as minimum and maximum values.

4.4.1 Influence of circulation strength

The circulation strength was varied within $0 \le \Gamma \le 700\text{m}^2/\text{s}$. As expected, induced roll acceleration increases with higher circulation Γ. The values of Γ at which local stall was observed on at least one strip for the first time, have been marked by filled line markers. At lower circulation strengths roll accelerations rise linearly. When local stall appears this linearity ends and roll acceleration increases less. For low circulation induced roll acceleration is larger for the Cessna Citation than for the Do 228. With the presence of stall this ratio changes however. This effect should be thought of when comparing single results in further studies. If local stall is effective on all strips that contribute to the total additional force or moment, the induced acceleration or load factors reach a maximum. This can be also seen for sideslip in FIG 9.

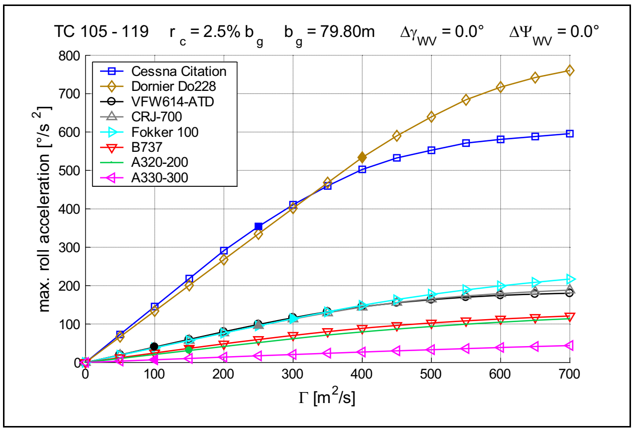

FIG 8. Effect of Γ variation on roll acceleration

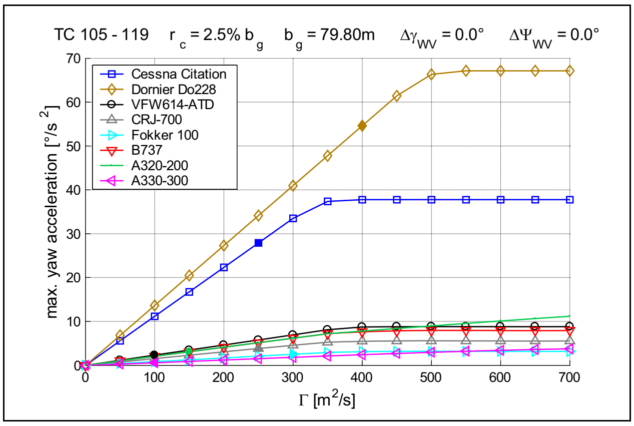

FIG 9. Effect of Γ variation on yaw acceleration

4.4.2 Influence of core radius choice

For the core radius values from $0.5 \le r_c \le 6.0\% b_g$ were investigated. The induced roll accelerations decrease with a growing core radius r_c. Since the core radius is part of the denominator within the BH velocity model, there is no linear relation between r_c and the induced accelerations and load factors. The effect of r_c variation is larger for smaller encountering aircrafts. The value of r_c primarily influences the induced velocities at the vortex core. For smaller aircrafts these high velocities affect a larger portion of strips than for larger aircrafts. Within the investigated range an increase of up to approx. 70%, respectively a decrease of approx. 50% compared to the reference parameter value can been observed for the roll acceleration (see FIG 10; Cessna Citation).

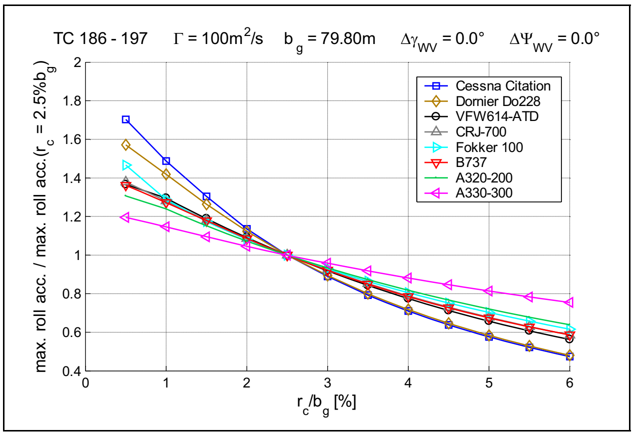

FIG 10. Effect of r_c variation on roll acc. (Γ = 100m^2/s)

For higher circulation (Γ = 533.52m^2/s) the influence of core radius size is limited by local stall. Especially the increase of roll acceleration for smaller core radius has diminished. In case of the Do 228 the roll acceleration ratio varies between 0.5 and 1.1 (FIG 11).

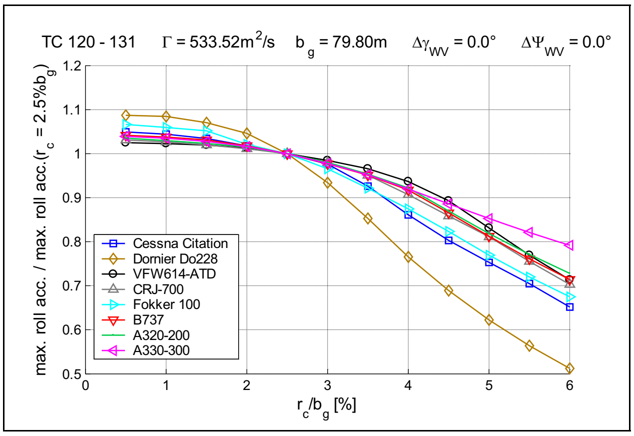

FIG 11. Effect of r_c variation on roll acc. (Γ = 533.52m^2/s)

4.4.3 Influence of span ratio

The generator wing span was varied within 1 ≤ b_g ≤ 80m. For the roll axis a value of the span ratio at which the largest induced acceleration appear can be estimated. If the trailing aircraft's position is at a vortex centre and the other vortex centre is near the wingtip, the highest roll moment is induced. This configuration is connected to a wing span ratio of

$$b_g/b_f = 0.5 \cdot \frac{4}{\pi} = 0.6366 \tag{7}$$

if the vortex span is nominal: $b_v = \pi/4 \cdot b_g$. The results from the WVE model confirm the estimated value of approx. 0.64 (see FIG 12). The largest induced roll accelerations can be observed for span ratios of 0.53 ≤ b_g/b_f ≤ 0.7. Because the step size of 5m that was used to vary the generator wing span is rather large, smaller deviations from the theoretical value occur.

In practice generator wing spans of less than 10m can be neglected. However, the largest induced roll accelerations for smaller followers still appear within the range of 10 ≤ b_g ≤ 80m. In contrast to this wing span ratios of approx. 0.8 and more are interesting for larger trailing aircraft.

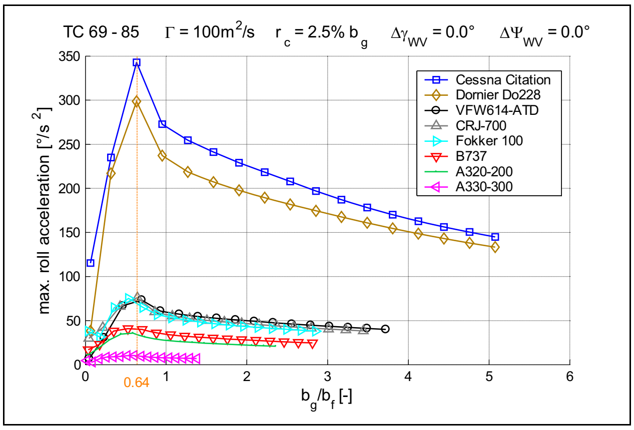

FIG 12. Effect of b_g/b_f variation on roll acceleration

4.4.4 Influence of the vortex velocity model

The WINCKELMANS model computes a maximum tangential velocity that is approx. 20% below the BURNHAM & HALLOCK model (see FIG 4). This ratio is partly reflected by the results of the induced accelerations and load factors. FIG 13 shows the induced load factors n_y. The BH results have been used as reference. The difference of the velocity models directly impacts the induced load factors.

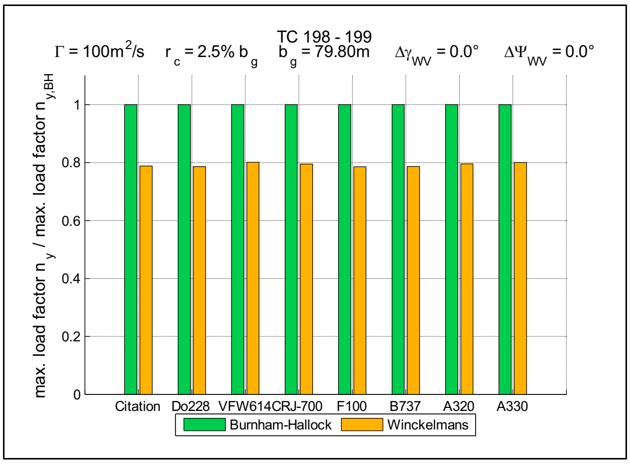

FIG 13. Effect of velocity model variation on n_y

The difference between the velocity profiles disappears for larger distances to the vortex core. Because of that the influence of the vortex model is lower especially for induced load factor n_z and roll acceleration. Only small parts of the wing are affected by the high induced velocities around the vortex core. For larger parts the different velocity models produce equal vortex induced forces. That is why the maximum roll acceleration ratio varies with aircraft size (see FIG 14).

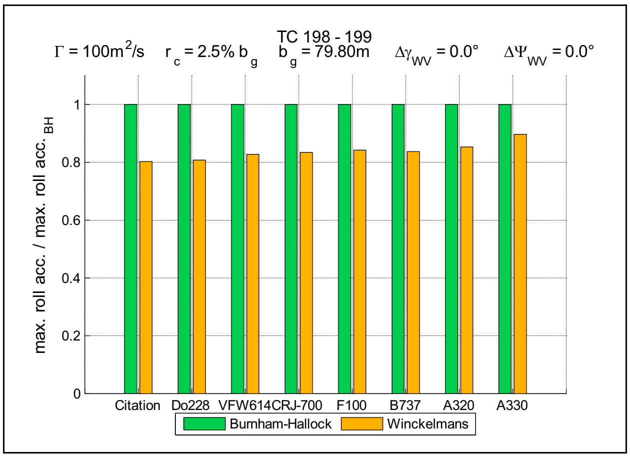

FIG 14. Effect of velocity model variation on roll acc.

4.4.5 Influence of encounter angle $\Delta\Psi_{WV}$

For $\Delta\Psi_{WV}$ values within $0 \le \Delta\Psi_{WV} \le 90°$ were analyzed. The induced roll acceleration increases with larger encounter angles. The largest values appear in the region of $60° < \Delta\Psi_{WV} < 70°$ due to the swept wing. For larger angles the accelerations decrease again. At $\Delta\Psi_{WV} = 90°$ almost no roll motion is induced. The influence of $\Delta\Psi_{WV}$ variation also increases with follower size. For the A330-300 an increase of approx. 80% can be observed while Do 228 and Cessna Citation show almost no change up to $\Delta\Psi_{WV}$=70°. Even though the largest induced accelerations appear at $60° < \Delta\Psi_{WV} < 70°$ the aircraft reaction should be small because at such high encounter angles the follower passes the vortices relatively fast. This needs to be considered when assessing the static results.

In contrast to roll acceleration load factor n_y and yaw acceleration decrease steadily (FIG 16).

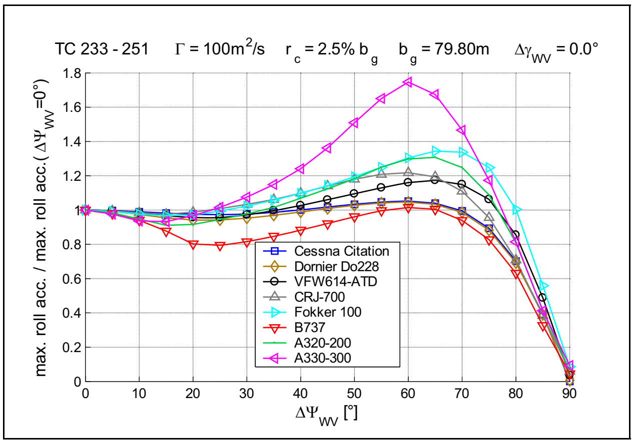

FIG 15. Effect of $\Delta\Psi_{WV}$ variation on roll acceleration

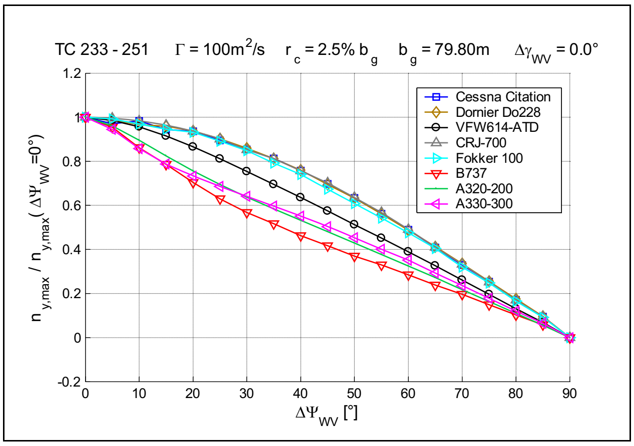

FIG 16. Effect of $\Delta\Psi_{WV}$ variation on n_y

4.4.6 Influence of encounter angle $\Delta\gamma_{WV}$

$\Delta\gamma_{WV}$ was varied within $-40 \le \Delta\gamma_{WV} \le 40°$. The effect of positive and negative encounter angles can be seen in FIG 17. A decrease of up to 50% can be observed within investigated region. A significant difference regarding aircraft size cannot be noticed.

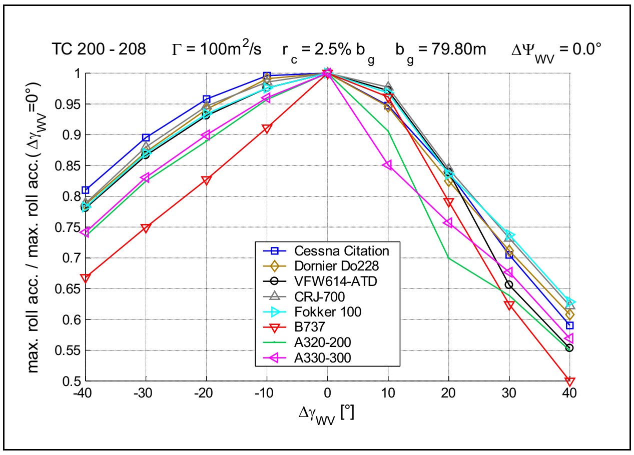

FIG 17. Effect of $\Delta\gamma_{WV}$ variation on roll acceleration

5 SIMPLIFIED WVE OFFLINE SIMULATION

The simulation model has been developed within Matlab/Simulink to simulate WVEs of an A330-300. Results from two piloted full flight simulator experiments with encounter angles of 15°/20° were used as reference data. Because of the simple build up, the model can be adjusted very easily to simulate WVEs of any other aircraft type, which is the objective of this approach.

5.1 Simplifications of the model

To reduce the complexity of the model to a minimum the following simplifications and assumptions have been made:

- Reduction of aircraft motion to one degree of freedom (only roll motion is simulated)
- The flight path is approximated by a straight line
- Aerodynamic and flight mechanical parameters are kept constant during the encounter.
- Only aileron deflections are considered. Spoiler and

rudder effects on roll motion are neglected.

- To simulate pilot inputs a simple pilot model is used.
- The flight control system (FCS) is modelled in a very simple way (see FIG 19).

5.2 Simulation structure

The simulation model consists of three modules. A typical simulation run includes the following steps:

1) *TestWVE computation:* The encounter scenario has to be defined including all parameters. A TestWVE run is started to compute the field of induced roll acceleration.
2) *Definition of flight path:* The flight path is already (indirectly) defined by the encounter scenario. The $\Delta\Psi_{WV}$ - $\Delta\gamma_{WV}$ combination is entered in the m-file.
3) *Simulation run:* The positions and roll accelerations along the flight path are calculated and passed on to the Simulink model to simulate aircraft roll motion.

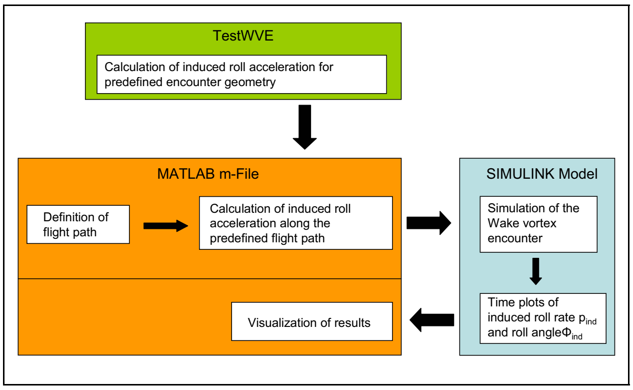

FIG 18. Structure of the simulation model

5.3 Structure of the Simulink model

To include pilot input on the aircraft motion a WVE pilot model [4], which connects the pilots Side Stick Roll (SSRO) command to the bank angle, was used with these parameters:

- T_e = 0.52s
- T_{lead} = 1.15s
- T_{lag} = 0.04s
- K_p = -0.0435

The FCS model consists of a time delay τ_{FCS}, a gain $K_{\xi,SSRO}$, a rate limiter and a saturation block. This structure certainly has its deficiencies and does not reflect the complex FCS and control laws of the A330-300. However it was found to be adequate for this approach.

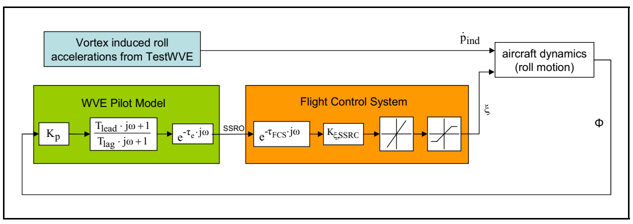

FIG 19. Structure of the Simulink model

5.4 Results

5.4.1 Quality of roll motion

To asses the quality of the simplified approach, the results were compared step by step to the data of the simulator experiments. At first flight path and aileron deflections were taken directly from the simulator data to investigate the reduction of aircraft motion. The results from two encounters with $\Delta\Psi_{WV}$ = 15°/20° were used. For $\Delta\Psi_{WV}$ = 15° the results of the model and simulator experiment match very well (FIG 20). For $\Delta\Psi_{WV}$ = 20° a larger differ-rence especially in the bank angle results can be observed (FIG 21). Neglecting spoiler and rudder effects on roll motion leads to larger aircraft reactions for the simplified approach.

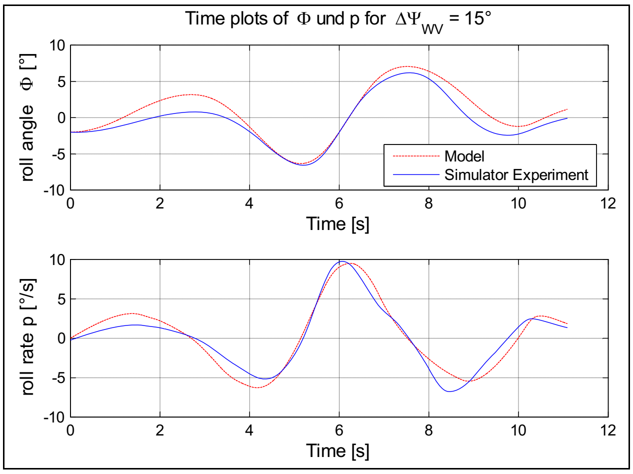

FIG 20. Comparison of results ($\Delta\Psi_{WV}$ = 15°)

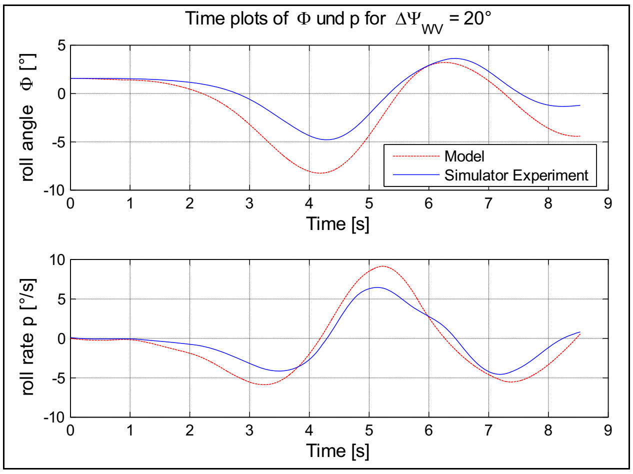

FIG 21. Comparison of results ($\Delta\Psi_{WV}$ = 20°)

5.4.2 Definition of gain $K_{\xi,SSRO}$

The identification of the FCS model gain $K_{\xi,SSRO}$ was done manually. For $K_{\xi,SSRO}$ = 40° a fair correspondence was achieved for the 20° encounter (FIG 23). The results from the 15° encounter show greater deviations to the simulator data especially in the second part of the encounter (FIG 22, time > 6s).

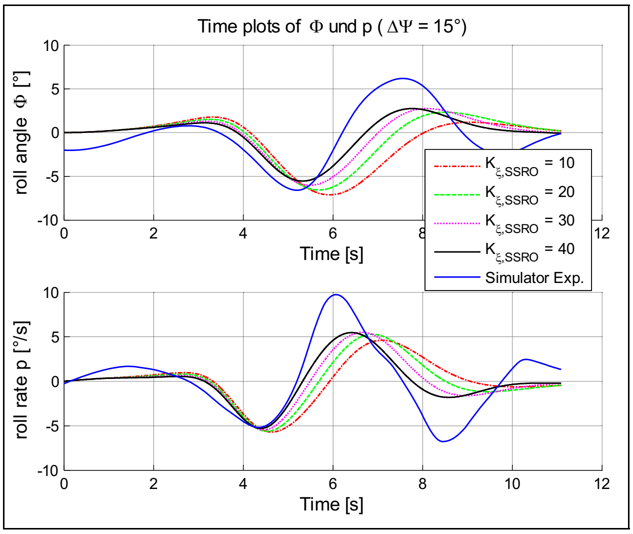

FIG 22. Variation of $F_{\xi,SSRO}$ ($\Delta\Psi_{WV}$ = 15°)

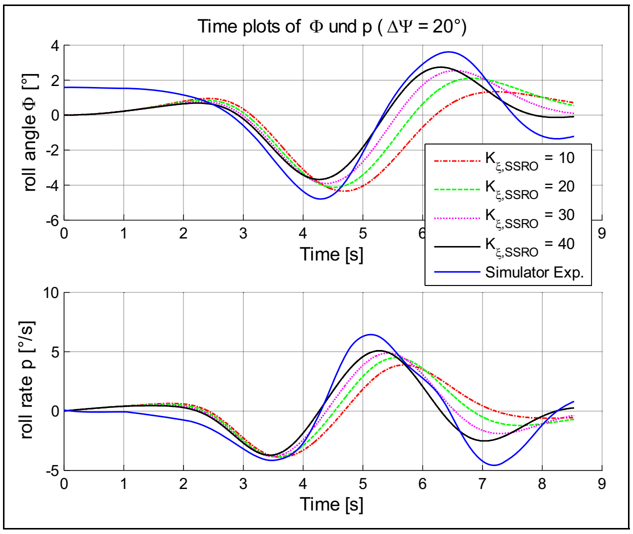

FIG 23. Variation of $F_{\xi,SSRO}$ ($\Delta\Psi_{WV}$ = 20°)

5.4.3 Results for a straight flight path

In order to be able to use the simplified model completely independently, the trailing aircrafts flight path through the vortices needs to be defined before a simulation run. In this last step this has been done by approximating the flight paths from the simulator experiments through straight lines.

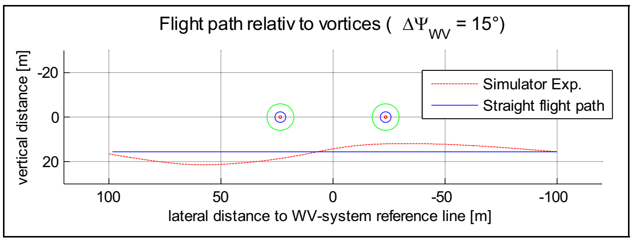

FIG 24. Approximation of flight path

This simplification only causes small changes in the results if the flight path disturbance due to vortex effects is minor. For encounter angles of 15°/20° this is certainly the case (see FIG 24). When simulating WVEs with smaller deviation angles the assumption of a straight flight path however is not correct. FIG 25 and FIG 26 show that the simplified models match the simulations quite well, especially in the 20° encounter case.

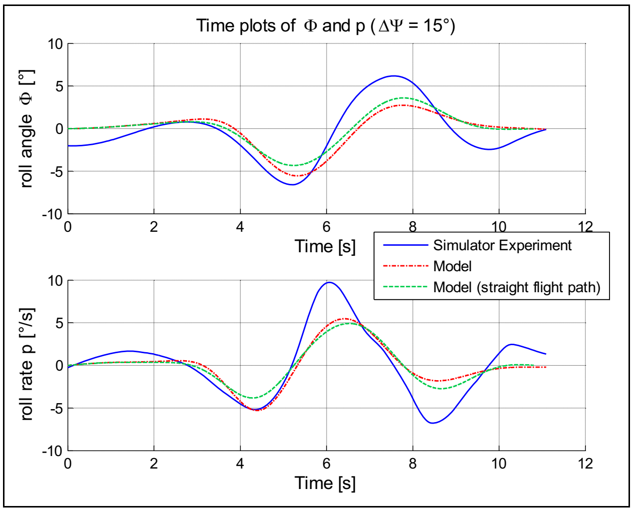

FIG 25. Results with flight path approximation (15°)

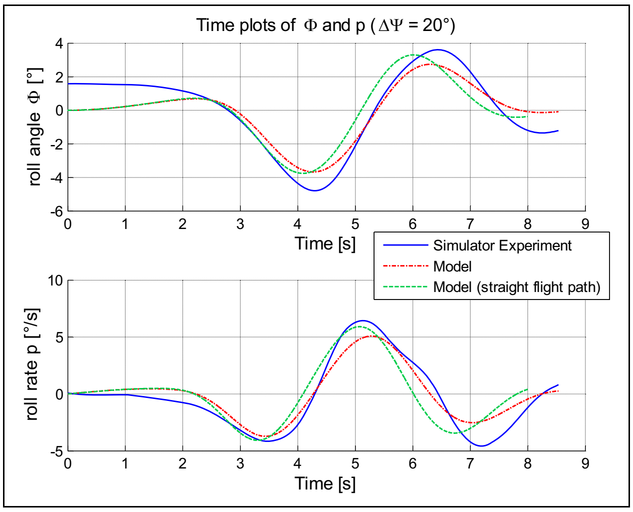

FIG 26. Results with flight path approximation (20°)

6 CONCLUSIONS

Based on an existing WVE model developed within the S-WAKE program, a parameter study to observe effects of varying encounter parameters on aircraft reaction was performed. Results for induced roll acceleration were primarily presented. Interestingly core radius and vortex velocity model have a significant influence on maximum induced aircraft acceleration. When performing probabilistic WVE simulations attention needs to be paid to these parameters. Identifying the exact values of core radius and vortex velocity distribution is an important goal of future experiments. The results found in this study can contribute to future WVE simulation. When redefining ICAO separation requirements, the data can be used to preset encounter parameters thus reducing optimization time to simulate worst-case scenarios.

Also a simplified approach to WVE offline simulation was presented. The results from the simplified model show a fair correspondence to data from more complex simulations. Reducing aircraft motion to a simple roll motion seems to be valid if horizontal encounter angles are 15° or larger. However the implemented simplifications limit result quality. A revision of the applied assumptions and simplifications has potential to further increase the quality of the model. In addition more encounter scenarios should be investigated to identify the range to which the simplified model can be applied. Using the model could reduce time and cost expense when performing systematic research one different encountering aircraft types. The model can easily be adjusted to any desired aircraft type which is rather difficult when using complex nonlinear 6 degree of freedom simulation models.

NOMENCLATURE

Symbols

b_f	Trailing aircraft wing span
b_g	Generator wing span
b_v	Vortex span
$c_{L\alpha}$	Lift curve slope of the airfoil
$d\varepsilon/d\beta$	Flow deflection coefficient
O_{WV}	Origin of vortex coordinate system
p	Roll rate
r	Radial distance to vortex centre
r_c	Core radius
S_i	Strip area
SSRO	Side stick roll
u_θ	Tangential component of induced wind field
$v_{ind,i}$	Lateral induced air flow in strip coordinates at strip i
$V_{proj,i}$	Undisturbed local air flow in strip coordinates at strip i
v_{WV}	Lateral component of induced wind field
$w_{ind,i}$	Vertical induced air flow in strip coordinates at strip i
W_W, W_{HT}, W_{VT}	Weighting functions for wing, horizontal and vertical tail
w_{WV}	Vertical component of induced wind field
$x_{EF,gr}$	Longitudinal offset from ILS
$y_{EF,gr}$	Lateral offset from ILS
y_i, z_i	Distance of strip i to aircraft CG
$\Delta\Psi_{WV}$	Horizontal encounter angle (deviation angle to ILS glide path)
$\Delta\gamma_{WV}$	Vertical encounter angle (deviation angle to ILS glide path)
Φ	Roll / Bank angle
ΔL	Vortex induced roll moment
ΔH_{WV}	Vertical offset of O_{WV}
Φ_{WV}	Bank angle of vortex system
Γ	Circulation
α_{ind}	induced AOA
α_{min}, α_{max}	minimum, maximum AOA
β_{ind}	induced AOS
β_{min}, α_{max}	minimum, maximum AOS
ξ	Aileron deflection

Subscripts

0	Initial
b	Body fixed
c	Core
f	Follower
g	Generator
gr	Ground
HT	Horizontal tail, Tailplane
i	Strip number
ind	Induced
r	Reference
t	Total
v	Vortex
VT	Vertical tail, Fin
W	Wing
WV	Wake vortex

Abbreviations

AE	Aerodynamic Element
AOA	Angle of attack
AOS	Angle of sideslip
BH	Burnham & Hallock
CG	Centre of Gravity
EF	Encounter Fix
ICAO	International Civil Aviation Organization
ILS	Instrument Landing System
MTOW	Maximum Take Off Weight
S-WAKE	Assessment of Wake Vortex Safety
VESA	Vortex Encounter Severity Assessment
WM	Winckelmans
WVE	Wake Vortex Encounter
ZFB	Centre of Flight Simulation Berlin

REFERENCES

[1] Shah, L. B.: *“Wake turbulence aspects of Airbus A380-800 aircraft”*; ICAO State Letter T3/4.4 – AP099/06 (ATM); 10.10.2006

[2] - : *Safety Case for Wake Vortex Encounter Risk due to Airbus A380*; A380 Wake Vortex Steering Group, Edition 2.0, Eurocontrol, JAA, FAA, Airbus; 2007

[3] Luckner, R.; Höhne, G.; Fuhrmann, M.: *Hazard criteria for wake vortex encounters during approach*; Zeitschrift Aerospace Science and Technology 8 (2004); S. 673-687

[4] Höhne, G.; Fuhrmann, M.; Luckner, R.: *Critical wake vortex encounter scenarios*; Zeitschrift Aerospace Science and Technology 8 (2004); S. 689-701

[5] Fuhrmann, M.; Luckner, R.; Reinke, A.; Verbeek, M.: *Description of flight simulators for wake vortex encounter simulations and flight simulator validation Part (c): TUB Airbus A330*; S-WAKE Technical Note TN 312-1 (c) v1.2; 22.08.2002

[6] Grondin, G.; Moet, H.; *Analytical Wake Vortex Model*; S-WAKE Report No: SW_TN_121_3; 16.07.2003

[7] Escande, B.; *Software code: FORTRAN code of strip method for implementation into simulators – Documentation (Version2)*; SWAKE-D-212_1-v2; 29.06.2001