

A Novel Framework to Assess the Wake Vortex Hazards Risk Supported by Aircraft in En-Route Operations

Marc Melgosa and Xavier Prats

Department of Physics - Aerospace Division
Technical University of Catalonia
Castelldefels (Barcelona), Spain

Sergio Ruiz, Joan Tarragó and
Javier Busto
GTD Sistemas de Información
Barcelona, Spain

Meiko Steen
Institut fuer Flugfuehrung
Technische Universitaet Braunschweig
Braunschweig, Germany

Abstract—This paper presents the simulation environment developed within the framework of R-WAKE project, funded by SESAR 2020 Exploratory Research. This project aims to investigate the risks and hazards of potential wake vortex encounters in the en-route airspace, under current and futuristic operational scenarios, in order to support new separation standards aimed at increasing airspace capacity. The R-WAKE simulation environment integrates different components developed by different partners of the R-WAKE consortium, including simulators for weather, traffic, wake vortex phenomena, wake vortex interactions and different tools and methodologies for safety and risk assessment. A preliminary example is presented in this paper, in which 200 historical trajectories were simulated to show that the novel framework works properly. A WVE encounter has been detected in such first scenario, however with no significant safety effect on the follower aircraft. A second controlled scenario has been then run to force the detection of a severe wake encounter under realistic en-route conditions. Such scenario has given evidences that confirm the safety relevance of the underlying research concept.

Keywords—wake vortex encounter; safety analysis; air traffic services; separation standards; en-route operations; SESAR 2020.

I. INTRODUCTION

Wake vortex issues in terminal maneuvering areas (TMA), especially in the final approach and initial take-off segments, are well known and have received a particular attention in the last decades [1], [2], [3]. In the en-route phase, however, wake vortex encounters are unlikely and so far, are still considered rare events (although few significant accidents have occurred in the recent years, such as the encounter reported in [4]). Current knowledge on wake vortex encounters (WVE) hazards, and the corresponding separation standards, is strongly based on studies and data collection at low altitudes, mostly at the vicinity of airports. Few projects have tried to

The work presented in this paper was partially funded by the SESAR Joint Undertaking under grant agreement No 699247, as part of the European Union's Horizon 2020 research and innovation programme: R-WAKE project (Wake Vortex Simulation and Analysis to Enhance En-route Separation Management in Europe - <http://www.rwake-sesar2020.eu/>). The opinions expressed herein reflect the authors' view only. Under no circumstances shall the SESAR Joint Undertaking be responsible for any use that may be made of the information contained herein.

investigate WVE at typical cruise altitudes and most of the research is based in simulation, since data collection at high altitudes (above FL200) is a difficult task. Recent research has shown that current separation standards might not be enough for protecting aircraft against WVE hazards, while in other cases they might be over-conservative [5], [6], [7], [8], [9]. Hazardous WVE en-route might become a serious issue in the near future if we take into account, for instance, a) forecast for higher volumes of traffic in certain areas; b) a more heterogeneous and diverse traffic fleet (different aircraft sizes and performance, introduction of unmanned aerial vehicles, etc.); c) new concepts of operation, in line with SESAR 2020 paradigm [10]; d) more accurate navigation systems (reducing the dispersion of flight tracks); and d) new (or refined) standards leading to reduced separation minima between two aircraft. For these reasons, there is an increasing interest in the air traffic management (ATM) community to assess potential issues related to wake vortex phenomena when refining or proposing new en-route separation standards, aiming to increase airspace capacity. R-WAKE is a SESAR 2020 Exploratory Research project performing an initial risk assessment, with regards to the wake vortex phenomena, of a hypothetical introduction of lower tactical separation standards en-route. For this purpose, a simulation environment is developed within the project activities to perform a safety and robustness analysis and a standards development methodology, thoroughly consistent with reference methodology taken from EUROCONTROL and SESAR [11]. This paper presents the simulation environment developed in the R-WAKE project, which embeds several components with the aim to: a) synthesise trajectories at European scale, according to different concepts of operations and implementing different air traffic control (ATC) tactical separation criteria; b) simulate accurate wake vortex phenomena; c) simulate realistic weather conditions, affecting both the traffic patterns and the behaviour of the vortices; d) detect possible WVE in the simulated scenario; and finally, e) assess the severity of the WVE detected.

II. THE R-WAKE PROJECT

The R-WAKE Concept [12] is linked to the following research question: 'What Separation Minima Reductions can be applied in specific and clearly defined operational conditions keeping the current safety level related to En-Route WVE hazards?'. In order to support the generation of validation evidences and to illustrate the 'R-WAKE concept', the 'R-WAKE system' has been developed, which is composed of a tailored safety and robustness research methodology and a simulation platform to reproduce a given traffic scenario and the generated wake vortices, and to approximate in a quantitative way the level of risk of the potential WVE hazards (dynamic risk modelling approach). The aim of this project architecture is the achievement of five main outcomes, referred in the Fig. 1 as O_x, from O₁ to O₅.

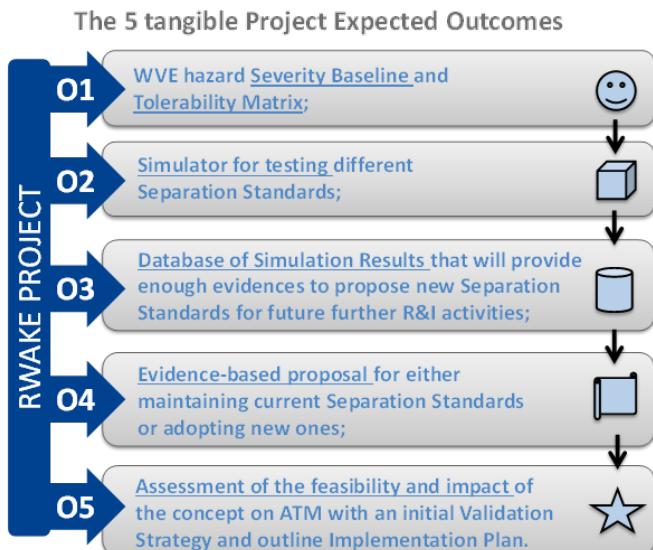


Figure 1. Project expected outcomes.

The research goals of the project, i.e., proposal of potential enhancements in the current separation standards to protect against WVE hazards (refer to [13] for details), are approached by the study of a safety and robustness analysis on the three basic components of WVE hazard risks: the severity, the potential frequency, and the level of risk after applying the ATM risk mitigation measures. The methodological approach of the research can be synthetized in the following five activities:

- 1) To assess and quantify the level of severity of different WVE situations and establish the level of acceptance for each WVE hazard risk.
- 2) To quantify the probability of finding potentially hazardous WVE in today's traffic conditions.
- 3) To analyse how much the level of risk is mitigated due to the ATC separation provision (applied to mitigate risk of collision between aircraft rather than for WVE avoidance).

4) To assess the potential impact on safety after introducing future SESAR concepts of operations (in line with TBO/PBO) and approximate guesses for future traffic demand.

5) To propose a new (possibly dynamic) separation standard, along with mitigation methods to be applied during either the flight execution (tactical separation management) or the 4D trajectory planning (including strategic separation management in a TBO/PBO context).

In order to perform the methodology and the project outcomes, the R-WAKE framework is divided in two steps:

- The Step 1, or 'micro-analysis', aims at providing a wake vortex safety baseline in form of a severity matrix and a tolerability matrix. Such outputs of the micro analysis will be used as an input for the simulator system and for the macro model analysis. For this reason, the micro model analysis has to be executed during the implementation phase and before starting the macro model analysis.
- The Step 2, or 'macro-analysis', in which current and future traffic situations will be simulated in order to determine if the separation standards are enough to ensure a safety operation of the airspace.

The above research methodology of the R-WAKE project and the relationship between the Step 1 and Step 2 (i.e., micro and macro analysis) can be found in Fig. 2.

III. R-WAKE MICRO ANALYSIS FRAMEWORK

The goal of the micro-scale simulations (or R-WAKE Step 1) is to generate the wake vortex safety baseline. It means that the severity and tolerability matrix used as inputs in the macro model analysis will be the outputs of this step. Given an aircraft pair, a geometry of the crossing, a separation distance (in the horizontal and/or vertical domain) between follower and generator aircraft, and given set of contextual scenario variables (such as altitude and speed of both aircraft, etc.), the micro-scale simulation will compute the severity of the encounter on the follower aircraft. For this purpose, this simulation is divided in three major phases:

- 1) Computation of the vortex circulation, generated by the generator aircraft and encountered by the follower aircraft.
- 2) Computation of the aircraft upset experimented by the follower flight due to the vortex encounter.
- 3) Assessment of the severity of the upset, based on expert knowledge.

IV. R-WAKE MACRO ANALYSIS FRAMEWORK

Once the potential WVE hazards and the severity of their potential consequences is well-understood, the purpose of the Step 2 research approach of the project is to assess the level of risk for each of the identified hazard categories that may be present in the European ATM context. Different frequency/risk analyses will be performed with the Step 2 R-WAKE simulation framework under the consideration of different ECAC-wide traffic demand patterns and different

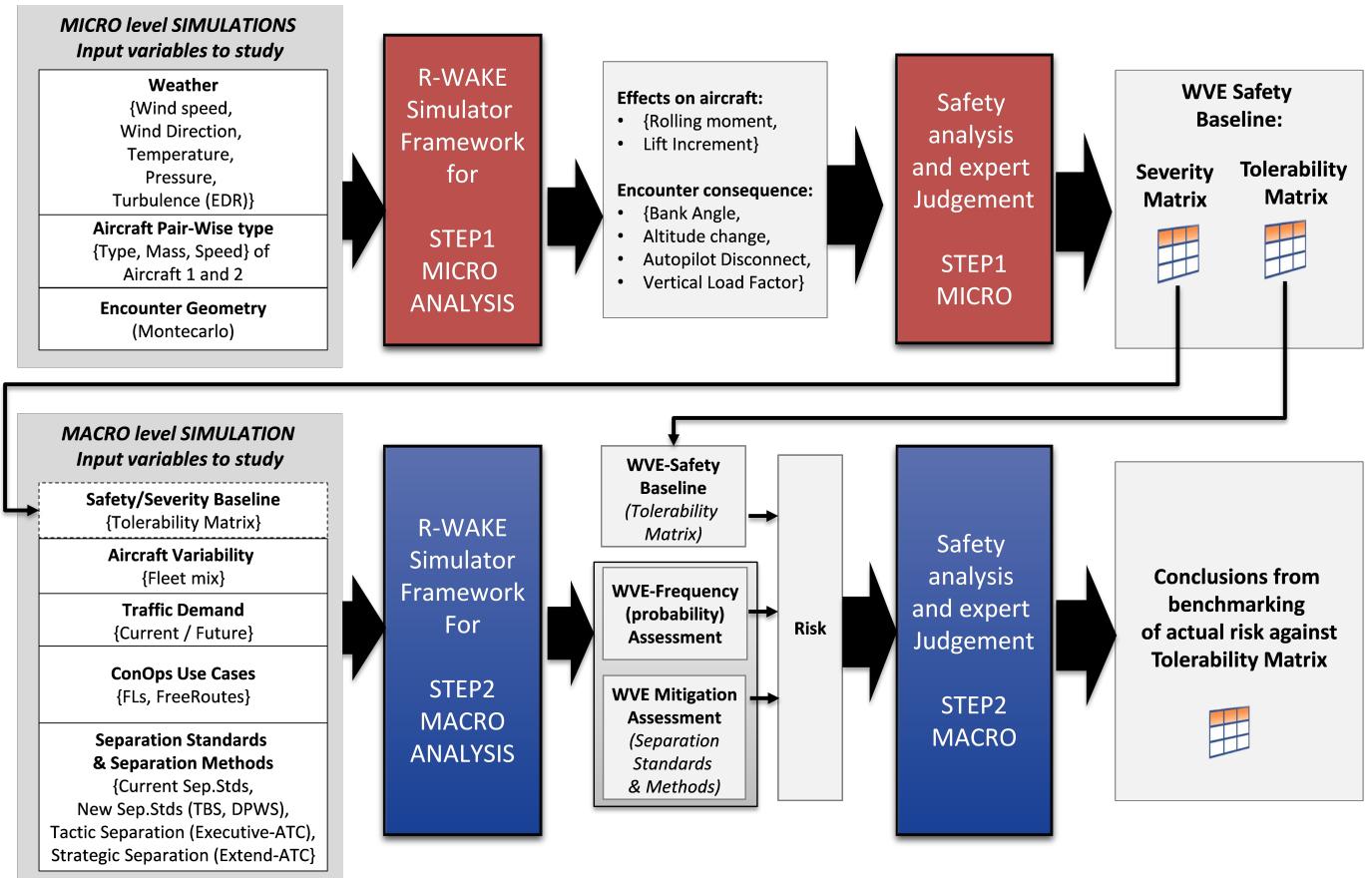


Figure 2. High-level description of the R-WAKE research methodology.

ATM mitigation measures applied. The main workflow of the R-Wake system [14] for macro analysis is described below by functionality (different functionalities might be provided by a same software tool used in R-WAKE project) and showed in Fig. 3.

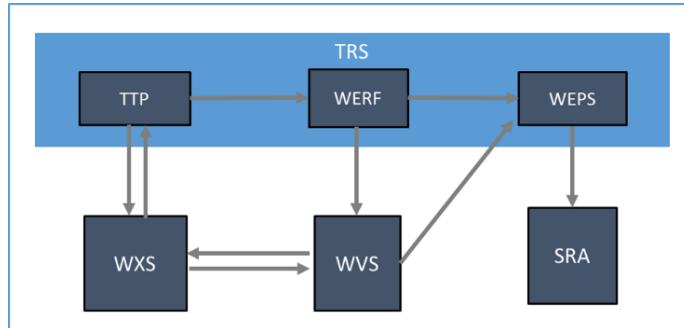


Figure 3. R-WAKE framework [14].

- 1) **Weather Simulator (WXS):** The WXS provides historic weather data to the Traffic Simulator (TRS) and to the Wake Vortex Simulator (WVS), in order to have realistic weather conditions during the trajectory and wake vortex simulations in European ECAC airspace, and to perform statistical simulation based studies to

obtain results that are statistically significant during the hazards risk evaluation process. The proposed Weather Simulator concept is based on the background system SIMET, a realistic simulator of atmospheric conditions developed for the evaluation of new generation Flight Management Systems that take into account weather conditions for trajectory optimization.

- 2) **Traffic Simulator – Traffic and Trajectory Planner (TRS.TTP):** Generates and simulates traffic scenarios based on real or future traffic demand and considering weather data fed by the weather simulator. The output trajectories feed the traffic planner with realistic trajectories. The traffic planner will apply the corresponding ATM constraints according to the concept of operations modelled (current ATM or SESAR 2020+) and the ATM layers activated (airspace, ATFM, Extended ATC Planner, ATC or none). As mentioned before, the Traffic and Trajectory Planner (TTP) module consists of two components working together somehow act as a kind of ATM simulator: 1) the trajectory planner submodule, which can be understood as the component that simulates the airspace users (AUs) and generate the traffic demand in form of 4D trajectories subject to the existing ATM constraints, and 2) the ATM model

(or traffic planner), which will be useful to represent the basic ATM mitigation/separation layers in charge of ensuring the required safety performance in the ECAC sky.

- 3) **Traffic Simulator – Wake Encounter Region Finder (TRS.WERF):** This sub-module identifies regions of airspace (volumes) in which potential wake vortex encounters could occur. Since the simulation of precise wake vortices for all the ECAC-wide flight trajectories requires a high computational burden, the simulation of WV will be limited to those regions that have some likeliness of hazardous WV encounter therein. Therefore, this module acts as a filter to reduce computational burden and the output will feed to the Wake Vortex Simulator and Traffic Planner modules with the regions of risk and with the segments of flight trajectories crossing such hazardous regions.
- 4) **Wake Vortex Simulator (WVS):** This module simulates realistic wake vortexes given the flight parameters of each trajectory (aircraft mass, speed, path, etc.) and the weather for the airspace region of interest. As an output for feeding the WEPS system, this module will generate a simplified macro-model of the vortexes in which the stochastic behaviour of the vortex (position, size and strength) can be represented as a 4D tube. Such 4D tube will be modelled to still capture all the relevant information for an effective wake vortex prediction process.
- 5) **Traffic Simulator – WV Encounter Prediction System (TRS.WEPS):** This sub-module receives the discrete model of the 4D tubes from the WV simulator and the trajectory segments from the WERF system and then crosses all the information to perform a probabilistic analysis and predict potential encounters. If an encounter is detected, the system will obtain the expected strength of the vortex and assess the severity of the vortex in relation to the parameters of the affected flight (aircraft, speed, geometry of the encounter, etc.) and other contextual conditions (e.g., surrounding traffic, excess thrust, etc.), as identified in the Step 1 of the R-WAKE research approach. The event and corresponding hazard severity will be recorded for the safety analysis post-process.
- 6) **Safety & Robustness Analysis (SRA for Step 2):** This module represents a process rather than a simulator. A risk analysis will be performed with the inputs coming from the other modules, and new knowledge will be generated from the different scenario simulations. The insights obtained will be used to report and refine the tool and next scenarios. As part of the knowledge generated will be an evidence-based proposal of new separation standards and methods.

V. INTEGRATION TEST

In order to check the framework, an initial test scenario with 200 flights was carried out. The first module TTP was configured with the initial conditions showed in Table I. The

TABLE I
TTP INITIAL CONDITIONS

Number of flights	200
Aircraft type	A320
Crossing area	France
Date	28/07/2016
Weather	Only vertical
ConOps	Structured route
Horizontal Separation Standard	5 NM
Vertical Separation Standard	1000 ft

TABLE II
MAXIMUM UPSETS OBTAINED

Altitude change	0.0036741 m
Bank angle	2.9445e-05 rad
Rate of Climb/Descent	0.0022483 m/s
Airspeed change	0.00049465 m/s

airspace and traffic historical data needed by the TTP was obtained from the Demand Data Repository (DDR2) provided by Eurocontrol. The Traffic and Trajectory Planner generated 200 trajectories. The Wake Encounter Region Finder was used to detect aircraft pairs that were close enough (less than 10 NM) to have a potential wake vortex encounter. The same module identified which aircraft were the follower and the generator, respectively. In this scenario, 13 potential encounters were identified.

After this process, the Wake Vortex Simulator used the information from the generator aircraft to simulate the wake vortex of all these flights. WEPS was used to find which of these potential encounters could be considered actual encounters. It was found that only one follower flight was in the actual influence area of the generator's wake vortex, therefore being a wake vortex encounter susceptible of causing a potential hazard. Then, this encounter was simulated in order to calculate the upsets suffered by the follower due to the encounter. To determine the severity of the previous encounter, the maximum absolute values of altitude change, bank angle, rate of climb/descent and airspeed change are considered. The values of this encounter are summarized in the Table II.

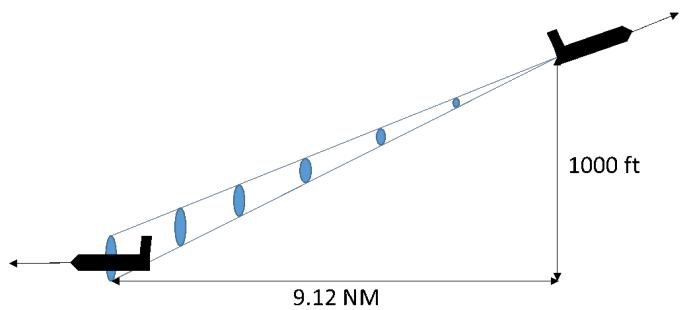


Figure 4. Relative position the new trajectory.

Using the severity matrix based on expert knowledge, these upset values can be categorized as severity level 1, which means that 'No significant safety effect' was found in such particular encounter. In order to show the potential hazard

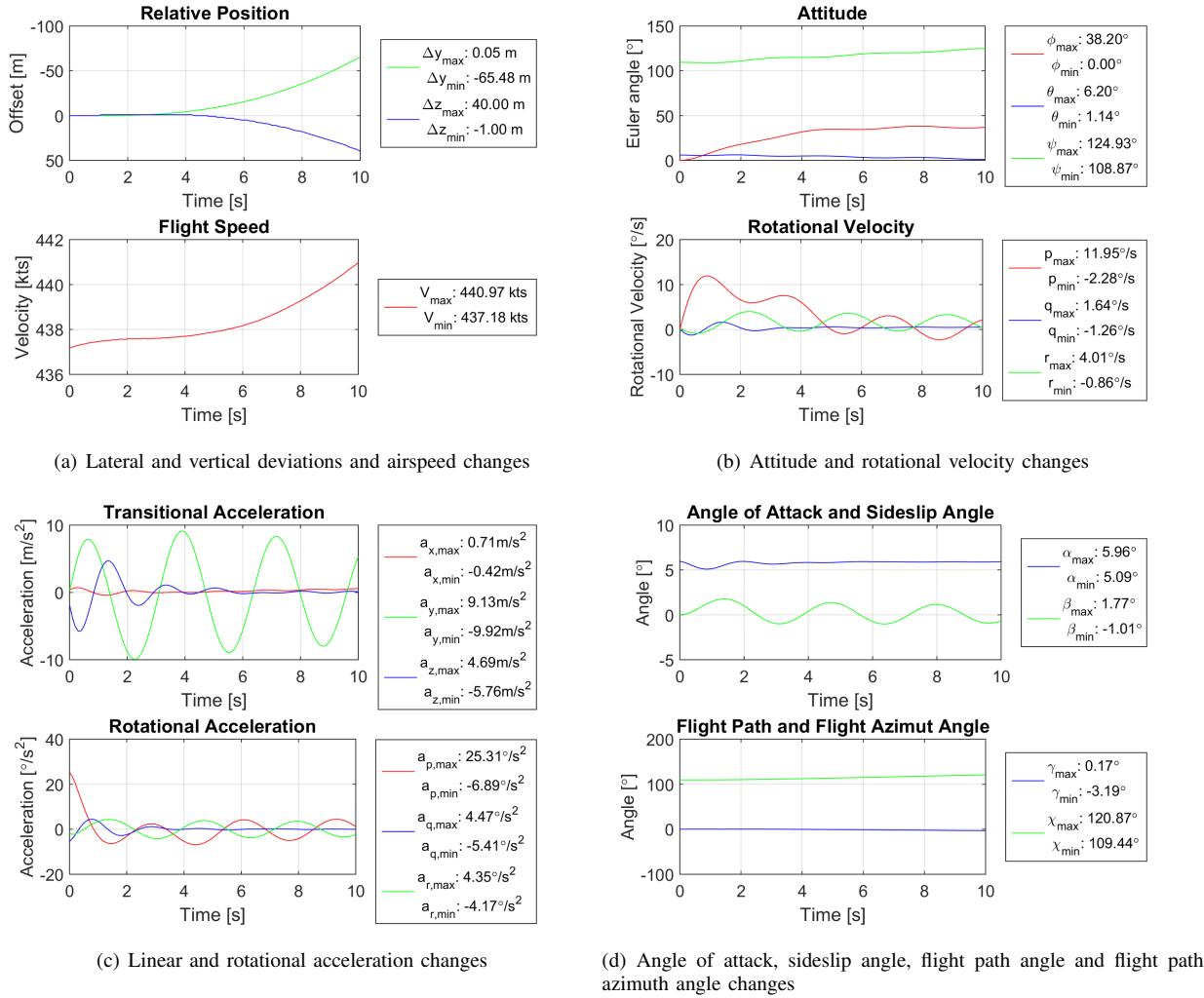


Figure 5. Results of the controlled scenario

of the wake vortex encounters in the en-route phase, a new controlled scenario was configured with a climbing aircraft (generator) and a leveled one (follower), both separated 9.12 NM and 1000 ft. as shown in Fig. 4.

The WV Encounter Prediction System was used in order to calculate how the wake vortex affects to the follower aircraft. Fig. 5(a) shows the lateral (Δy) and vertical (Δz) changes of the follower aircraft with respect to the nominal trajectory as well as the velocity changes. After 10 s, the aircraft descended 40 m and was deviated 65.48 m. No significant changes in the airspeed were observed.

The attitude change, corresponding to pitch angle (θ), bank angle (ϕ) and yaw angle (ψ), and the rotational velocity change, represented by p (x-axis), q (y-axis) and r (z-axis), is showed in Fig. 5(b). Important changes in the bank angle were found. A maximum turn of 38.20° was achieved. In addition, limited changes in the pitch and relevant changes in the yaw angle were identified. Furthermore, the follower aircraft underwent major changes in the x-component of the rotational velocity. The transitional acceleration behavior can

be described as an oscillation in the lateral acceleration. On the other hand, the rotational acceleration response shows an important value in the roll acceleration. Both transitional and rotational accelerations changes can be found in Fig. 5(c). With respect to the angle of attack, sideslip angle, flight path angle and flight path azimuth angle changes, Fig. 5(d) shows how this variable changes due to the wake vortex. The angle of attack (α) is slightly affected during the first 3 seconds after the encounter. However, a dynamic oscillation appeared in the Sideslip angle (β). The flight path angle (γ) changed to negative because the aircraft started to descend and the flight azimuth angle (χ) changed significantly because the heading changed as well. The maximum upset values of this encounter are summarized in the Table III. As shown, a change in the bank angle was the main effect (characteristic effect in case of coaxial encounters). Such encounter was categorized as having a potential “Major safety consequence”, therefore being an actual severe hazard.

The results of this scenario in which a WVE has been forced, while the two aircraft were respecting the current stan-

TABLE III
MAXIMUM UPSETS OBTAINED IN THE COAXIAL ENCOUNTER

Altitude change	40 m
Bank angle	0.66675 rad
Rate of Climb/Descent	12.617 m/s
Airspeed change	1.9492 m/s

dard separation, show that severe hazards due to wake vortex encounters cannot be discarded in the en-route operations, and therefore the topic deserves further attention.

VI. CONCLUSION

The R-WAKE project (a SESAR 2020 Exploratory Research project) proposes an advanced simulation framework to assess the risks and hazards of potential wake vortex encounters in the en-route airspace. This can support the definition of new separation standards and the generation of evidences for the corresponding safety case. An initial integration test for this framework has been presented in this paper. A first set of 200 historical flights was simulated applying the current separation standard defined by a horizontal separation of 5NM and vertical separation of 1000 ft. Such first test has been useful as a validation exercise of the R-WAKE framework, showing that the macro-scale framework is ready to be used and all its modules are working well together. No significant wake encounters have been found from the point of view of safety, possibly due to the fact that the traffic sample is still not fully representative of the entire traffic demand patterns in the ECAC area. A second scenario in which a wake encounter was forced with the aircraft separated horizontally and vertically 9.12 NM and 1000 ft, respectively, has shown that severe encounters with major consequences for either the crew, the aircraft, or both, can actually happen in the en-route environment. Future work will include simulations traffic data sets that are more representative of the actual ECAC demand, and the hazard risk will be explored and benchmarked with the application of different separation standards, to analyze their effect in the safety performance of the entire European ATM. A new separation standard will be defined and proposed to reduce over-conservative separations and to protect better the flights in some cases, if it is found necessary.

REFERENCES

- [1] Luckner, R., & Reinke, A. (2010). *Pilot Models for Simulation of Wake Vortex Encounters in Cruise*. Proceedings of the AIAA Guidance, Navigation and Control Conference. Toronto, Canada.
- [2] RECAT. (2010a). *Technical Report to Support the Safety Case for the Recategorization of ICAO Wake Turbulence Standards: Methodology for Recategorization of ICAO Wake Turbulence Standard*.
- [3] RECAT. (2010b). *Technical Report to Support the Safety Case for the Recategorization of ICAO Wake Turbulence Standards: Safety Assessment Report*.
- [4] Bundesstelle für Flugunfalluntersuchung (BFU). *Interim report BFU17-0024-2X*. May 2017.
- [5] De Visscher, I., Winckelmans, G., & Treve, V. (2015). *A Simple Wake Vortex Encounter Severity Metric*. Eleventh USA/Europe Air Traffic Management Research and Development Seminar. Lisbon, Portugal.
- [6] Hoogstraten, M., Visser, H., Hart, D., Trevé, V., & Rooseleer, F. (2014). *Improved Understanding of En Route Wake-Vortex Encounters*. Journal of Aircraft , 52 (3), 981–989.

- [7] Holzapfel, F., Reinke, et al. (2015). *Aircraft Wake Vortex State-of-the-Art & Research Needs*. WakeNet3-Europe public document under EC Grant Agreement No.: ACS7-GA-2008-213462. JUN 2012
- [8] Schumann, U., & Sharman, R. (2014). *Aircraft wake-vortex encounter analysis for upper levels*. (A. I. Astronautics, Ed.) Journal of Aircraft , 52 (4), 1277–1285.
- [9] De Visscher, I., Winckelmans, G., & Treve, V. (2015). *A Simple Wake Vortex Encounter Severity Metric*. Eleventh USA/Europe Air Traffic Management Research and Development Seminar. Lisbon, Portugal.
- [10] SESAR. *European ATM Master Plan*. Edition 2015
- [11] SESAR Joint Undertaking, 2010. *SESAR Safety Reference Material*, Edition 00.03.00.
- [12] R-Wake Consortium (2017). *D4.2 System Release 2* (Deliverable)
- [13] R-Wake Consortium (2016). *D2.1 System Specification Document* (Deliverable)
- [14] R-Wake Consortium (2017). *D3.1 System Design Document* (Deliverable)