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Hybrid simulation of wake-vortex evolution during landing on flat terrain and with plate line

Anton Stephan [a,*], Frank Holzäpfel [a], Takashi Misaka [b]

[a] *Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, 82234 Oberpfaffenhofen, Germany*
[b] *Tohoku University, Institute of Fluid Science, Sendai 980-8577, Japan*

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ABSTRACT

Wake-vortex evolution during approach and landing of a long range aircraft is investigated. The simulations cover final approach, touchdown on the tarmac, and the evolution of the wake after touchdown. The wake is initialized using a high fidelity Reynolds-averaged Navier–Stokes solution of the flow field around an aircraft model. The aircraft in high-lift configuration with deployed flaps and slats is swept through a ground fixed domain. The further development of the vortical wake is investigated by large-eddy simulation until final decay. The results show the formation of a pronounced shear layer at the ground and an increase in circulation in ground proximity, caused by the wing in ground effect. Disturbances at disconnected vortex ends, so-called end effects, appear after touchdown and propagate along the wake vortices against the flight direction. They lead to a circulation decay of the rolled-up wake vortices, combined with a growth of the core radius to 300% of its initial value. After touchdown wake vortices are subjected to strong three-dimensional deformations and linkings with the ground. The complete vortex evolution, including roll-up and decay, is accelerated in ground proximity. Additionally the effect of a plate line installed in front of the runway is studied with this method. The plates cause disturbances of the vortices propagating to either side and interacting with the end effects. The plate line further accelerates the vortex decay, reducing the circulation rapidly by another 25% of its initial value.

1. Introduction

As an unavoidable consequence of lift, aircraft generate a pair of counter-rotating and long-lived wake vortices that pose a potential risk to following aircraft, due to strong coherent flow structures (Gerz et al., 2002). The probability of encountering wake vortices increases significantly during final approach in ground proximity, since rebounding vortices may not leave the flight corridor vertically and the possibility of the pilot to counteract the imposed rolling moment is restricted (Critchley and Foot, 1991; Holzäpfel and Steen, 2007). In the recent “Challenges of growth 2013” report (Eurocontrol, 2013) the conceivable capacity problems of airports are elucidated. Several economic scenarios for the future European airport demands are analyzed, realizing that there will be around 1.9 million unaccommodated flights in the most-likely case, constituting approximately 12% of the demand in 2035. A reduction of the established static aircraft separation distances appears feasible employing advanced wake-vortex advisory systems (WVAS) incorporating the state-of-the-art wake-vortex physics to accurately predict vortex strength and position (Gurke and Lafferton, 1997; Hinton et al., 2000; Holzäpfel et al., 2009). However, established WVAS performance is unsatisfactory in runway proximity, as e.g. significantly less critical encounters are observed than expected (Holzäpfel et al., 2011). This means that the physical mechanisms of wake-vortex evolution and decay during and after landing are not sufficiently understood.

A landing aircraft generates a highly complex flow field in terms of structure and relevant scales. The flow around an aircraft's main wing, fuselage, slat, flap, jet engine and tail plain, as well as the interaction with the approaching ground and the sudden lift reduction during touchdown substantially affect the generated wake vortices. The evolution of the aircraft's wake in its meteorological environment is an example of complex turbulent flows, composed of strong coherent flow structures that exhibit a range of length scales spanning several orders of magnitude all interacting with one another.

In accordance with flight practice[1] we characterize the evolution of the aircraft's wake during landing by four main phases, *Final*

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* Corresponding author. Tel.: +49 8153282566.
E-mail address: anton.stephan@dlr.de (A. Stephan).

[1] http://www.skybrary.aero/index.php/Landing_Flare?utm_source=SKYbrary&utm_campaign=47ff8e1e92-SKYbrary_Highlight_04_07_2013&utm_medium=email&utm_term=0_e405169b04-47ff8e1e92-264071565 date: April 23, 2014.

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approach, Flare, Touchdown and *Roll-out*. Independently from this, the aircraft wake evolution is frequently considered to consist of three distinct phases, the *roll-up phase*, the *vortex phase* and the *decay phase* (Breitsamter, 2011). Usually Reynolds-averaged Navier–Stokes (RANS) simulations are used for the flow around the aircraft and the subsequent roll-up process of the wake in the roll-up phase (Stumpf, 2005). The dynamics of wake vortices after roll-up until decay have been mainly studied by large-eddy simulations (LES) considering various atmospheric conditions like turbulence, thermal stability and wind shear (Holzäpfel et al., 2001; Misaka et al., 2012). Those studies initialize a vortex pair with a constant velocity profile along flight direction. The interaction with the ground is also simulated by initializing fully rolled-up vortices (Proctor et al., 2000; Georges et al., 2005). This approach neglects the effects of different vortex generation heights above ground and of touchdown and may not capture full three-dimensional vortex deformations appearing during ground interaction. This simplified approach for modeling the landing phase was also used by Stephan et al. (2012). The current study reveals that the simplified modeling fails to reproduce many characteristic flow features. Complementary to simulations, field measurements of real aircraft landings have also been accomplished (Holzäpfel and Steen, 2007).

With this work we aim to understand several phenomena that could not be addressed with numerical simulations so far. How does the touchdown influence wake vortex decay? Which are the effects of the flight path angle on the vortex trajectories? Can we deduce the fully three-dimensional vortex characteristics? Do vortex evolution phases change in ground proximity?

Recent developments in RANS-LES coupling enable an innovative methodology to fly a realistic aircraft through a simulation domain generating a realistic wake (Misaka et al., 2013). For this purpose, a high-fidelity steady RANS flow field is swept through the LES domain. So a spatial development of the aircraft wake is introduced in the LES. We use this approach to simulate the final approach and landing and study the physics of the wake-vortex evolution and decay. A high-lift configuration of a long range aircraft is employed to account for the landing and flare phase. Note that this approach can be viewed as a one way coupling. The changing environment, i.e. the approach of the ground is not reflected by the RANS field. The wing in ground effect is simulated just by the LES. Therefore, particular emphasis is put on the wing in ground effect to assess the accuracy of the presented method.

The first investigations on ground effect have been performed by Wieselsberger (1922) and Prandtl (1923) employing a modification of Prandtl's lifting line theory. That is, the steady case is investigated, assuming a fixed altitude above ground, wing speed, as well as angle of attack. An overview over various analytical approaches for the quantification of the wing in ground effect (WIG) can be found in Pistolesi (1937). Solutions for two- and three-dimensional wings in ground effect may be found in Widnall and Barrows (1970). Daeninck et al. (2006) investigate wake vortex roll-up in ground effect for different wing aspect ratios and span loadings at different altitudes above ground. A double elliptical chord distribution as a model for high-lift configuration is also studied. The steady wing in ground effect is modeled using Prandtl's lifting line theory. All these considerations have been purely stationary, neither the flight path angle nor flare or the changing angle of attack have been considered. Real aircraft landings are characterized by a complex coupled system of parameters like angle of attack, flight speed, flight altitude, lift coefficient, etc. Such complex coupled systems can be derived from flight measurement data (Jategaonkar, 2006). An overview of the ground effect from the system identification view can be found in (Fischenberg, 1999). In the systemic approach analytical models for lift and drag coefficients in ground effect are considered. Model parameters are identified using flight test data and are validated in simulations.

Complex vortex deformations in ground proximity like vortex linking with the ground have been observed (Proctor et al., 2000). However, the effect of these structures encountered by following aircraft is not clear. We study so called end effects, appearing after touchdown, when vortex circulation is drastically reduced, as a reason that aircraft landings are safer than expected. End effects are vortex disturbances that appear in various situations when vortex characteristics change abruptly. These disturbances propagate along the vortices and reduce the circulation (Bao and Vollmers, 2005; Moet et al., 2005). Additionally, the interaction of end effects and disturbances caused by plate lines (Stephan et al., 2013a) – a method for artificial vortex decay enhancement – is investigated with the present approach. A comparison of simulations with experiments in a water towing tank dealing with artificial decay enhancement can be found in Stephan et al. (2013b). In the meanwhile first results of flight measurement campaigns at Oberpfaffenhofen airport as well as Munich airport (Germany) confirming plate line effects as well as landing effects have been presented in Holzäpfel et al. (2014), complementing the findings in this numerical study.

The "methods" section is divided into four parts. First, the LES code is presented. Second, we explain the wake initialization technique. Third, we list the parameters of the employed long range aircraft model. Finally, the domain and boundary treatment are presented. The "results" section consists of six subsections, a presentation of general flow features, an investigation of the wing in ground effect, the analysis of end effects, of vortex topology and vortex decay, and lastly, the illustration of vortex evolution phases in ground proximity.

2. Methods

2.1. Governing equations

The LES is performed using the incompressible Navier–Stokes code.

MGLET, developed at Technische Universität München, for solving the Navier–Stokes equations and the continuity equation (Manhart, 2004)

$$\frac{\partial u_i}{\partial t} + \frac{\partial (u_i u_j)}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p'}{\partial x_i} + \frac{\partial}{\partial x_j}\left((\nu + \nu_t)2S_{ij}\right), \tag{1}$$

$$\frac{\partial u_j}{\partial x_j} = 0. \tag{2}$$

Here u_i represents the velocity components in three spatial directions $(i = 1, 2, \text{ or } 3), S_{ij} = (\partial u_i/\partial x_j + \partial u_j/\partial x_i)/2$ denotes the strain rate tensor, and $p\prime = p - p_0$ equals the pressure deviation from the reference state p_0. The kinematic viscosity is given as the sum of molecular viscosity ν and eddy viscosity ν_t determined by means of a Lagrangian dynamic sub-grid scale model (Meneveau et al., 1996). Eqs. (1) and (2) are solved by a finite-volume approach, using a fourth-order finite-volume compact scheme (Hokpunna and Manhart, 2010). A split-interface algorithm is used for the parallelization of the tri-diagonal system (Hokpunna, 2009) computing coefficients of the compact scheme. A third-order Runge–Kutta method is used for time integration. The simulations are performed in parallel, using a domain decomposition approach.

The recently developed concept of artificial wake vortex decay enhancement by plate lines is also pursued in this work. A respective patent has been filed under number DE 10 2011 010 147. Fig. 1 displays the arrangement of the plates in a line perpendicular to the runway. The plate line is characterized by the plate separation Δy, the height h and the plate length. The plate line is modeled by