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Numerical study of aircraft wake vortex evolution near ground in stable atmospheric boundary layer

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Abstract The evolutions of aircraft wake vortices near ground in stable atmospheric boundary layer are studied by Large Eddy Simulation (LES). The sensitivity of vortex evolution to the Monin-Obukhov (M-O) scale is studied for the first time. The results indicate that increasing stability leads to longer lifetimes of upwind vortices, while downwind vortices will decay faster due to a stronger crosswind shear under stable conditions. Based on these results, an empirical model of the vortex lifetime as a function of 10-m-high crosswind and the M-O scale is summarized. This model can provide an estimate of the upper boundary of the vortex lifetime according to the real-time crosswind and atmospheric stability. In addition, the lateral translation of vortices is also inspected. The results show that vortices can travel a furthest distance of 722 m in the currently-studied parameter range. This result is meaningful to safety analysis of airports that have parallel runways.

1. Introduction

During an approach to an airport, the wake vortex of a leading aircraft poses danger to a following one. Therefore, it is necessary to study the wake vortex behavior in the atmospheric background. Fast-time wake prediction models have been developed by scholars.[1–4] In the early phase of the approach, the aircraft wake vortex is generated far from the ground, which is the so-called Out-of-Ground-Effect (OGE) condition. The wake vortex will turn into a rapid decay in tens of seconds as a result of the development of linear instability[5,6] due to the multi-reaction of the vortex pair. Furthermore, the vortex pair will leave the flight path by lateral displacement due to the crosswind, or by descending under the induction of each other, both of which contribute to the safety of the following aircraft.

In the final approach, the wake vortex is generated near the ground. Compared to the OGE condition, the In Ground Effect (IGE) condition requires more concerns. In the ground effect, image vortices will increase the separation of the vortex pair,[7] which weakens the interaction between the vortex pair and decreases the vortex decay rate. Besides, the vortices will rebound in the ground effect[7] and come back to the glide slope. These factors increase the wake-encounter risk for the following aircraft.

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One of the early IGE wake prediction models was developed by Proctor et al.[8] They revealed that the vortices turn into a rapid decay soon after the rebound from the ground. In addition, the evolution of vortex circulation after the rebound is described with an exponential model based on Large Eddy Simulation (LES) results. Except for the circulation, the displacement of the vortices was modeled by Robins et al.[7] In their work, the separation of the vortex pair is modeled by bringing in image vortices below the ground, and the rebound is modeled by introducing secondary vortices. The influence of the atmospheric background was taken into consideration by Holzäpfel and Steen.[9] In their model, the decay rate of vortex circulation is related to the 10-m-height crosswind velocity. The newest model is the Deterministic wake Vortex Model (DVM) developed by De Visscher et al. in 2013[10], in which Holzäpfel's model[9] is used to predict the vortex circulation, and the vortex displacement is predicted by the method of discrete vortices, in which vortex particles are released from the ground to simulate ground induced secondary vortices.[11,12]

However, the influence of atmospheric stability has not been considered in the aforementioned near-ground models. In an unstable boundary layer (or convective boundary layer), vortices will deform and decay rapidly under updraft and downdraft velocities, which is to the benefit of the following aircraft's safety.[13] The influence of a stable boundary layer will be much more complex. On one hand, the stable stratification can suppress the atmospheric turbulence, which will lead to a longer wake vortex lifetime. On the other hand, the stratification will promote the vortex decay by buoyancy effects.[14–16] Therefore, it is necessary to study the wake vortex decay in the stable atmospheric boundary layer to improve wake prediction models.

In the current OGE wake vortex prediction models, the B runt–Väisälä (BV) frequency and the Eddy Dissipation Rate (EDR) are used as the parameters describing stability and atmospheric turbulence, respectively.[1–3] In the IGE condition, these two parameters are not enough because wind shear and ambient turbulence kinetic energy can also influence the wake vortex evolution. However, it is impractical to bring all these atmospheric parameters into a fast prediction model because it is difficult to establish an empirical model with so many independent variables. In this paper, the Monin-Obukhov (M-O) scale L[17] is chosen as the parameter to measure the atmospheric stability. On one hand, in the IGE condition, vortices are generated in the atmospheric surface layer (below 60 m), where the BV frequency and the EDR are not mutually independent and can be related to the M-O scale.[17] According to the M-O simulation theory, atmospheric information including wind and potential temperature profile and the ambient turbulence can be estimated from the 10-meter-height crosswind V_{10} and the M-O scale L. In this way, the number of independent atmospheric parameters is prominently reduced. On the other hand, a model using the M-O scale may be more practical because the M-O scale can be easily estimated from the wind speed and the net radiation index[18,19] which can be provided by the airport control tower without additional observing facilities. In this paper, LES is applied to the wake vortex decay process in the stable atmospheric boundary layer. The vortex evolution is studied under different V_{10} and L, and simulation results are discussed and modeled. The paper is organized as follows. The numerical method and the physical model are introduced in Section 2. The results are displayed and discussed in Section 3. Finally, main conclusions are summarized in Section 4.

2. Methodology

2.1. Numerical methods

The LES in this paper solves the Boussinesq-approximated Navier-Stokes equations.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \cdot \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(v + v_t)\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \tag{2}$$

$$\frac{\partial \theta}{\partial t} + u_j \frac{\partial \theta}{\partial x_j} = \frac{\partial}{\partial x_j}\left[Pr_t(v + v_t)\frac{\partial \theta}{\partial x_j}\right] \tag{3}$$

where u_i and u_j are the velocity component and x_i and x_j are the coordinate, with p the pressure, ρ the density, t the time. v and v_t are the molecular kinematic viscosity and sub-grid scale viscosity, respectively. In the equation of the potential temperature θ, the turbulent Prandtl number Pr_t is set to 0.72. The Lagrangian dynamic sub-grid model[20] is used.

These equations are solved numerically on a movable, non-staggered Cartesian grid which is automatically adapted to the real-time flow field to obtain a higher resolution in a large gradient region such as the vortex cores with a limited total grid number. The self-adaptive algorithm is based on Gnoffo and Nakahashi's spring analogy method.[21,22] The Finite Volume Method (FVM) is applied for the spatial discretization and a fourth-order Runge-Kutta integration is used in the time advancement. The details of the numerical method are described in Refs.[23,24] This method has been proven reliable in both wake vortex simulation[18] and micro-scale atmospheric boundary layer LES[25,26]

2.2. Setup of the initial field

The initial field is combined with the atmospheric background and a pair of wake vortices. In the background atmosphere, the profile of wind V and the potential temperature θ in the surface layer are initialized with the M-O simulation theory[27] as

$$\begin{cases} V = \frac{v_\tau}{\kappa}\left(\ln\frac{z}{z_0} + 5\frac{z}{L}\right) 0 \leqslant z < L \\ V = \frac{v_\tau}{\kappa}\left(\ln\frac{z}{z_0} + 4 + 5\ln\frac{z}{L} + \frac{z}{L}\right) L \leqslant z < 2L \\ L = \frac{\theta_0 v_\tau^2}{\kappa g \theta_\tau} \end{cases} \tag{4}$$

$$\begin{cases} \theta = \frac{\theta_\tau}{\kappa}\left(\ln\frac{z}{z_0} + 5\frac{z}{L}\right) 0 \leqslant z < L \\ \theta = \frac{\theta_\tau}{\kappa}\left(\ln\frac{z}{z_0} + 4 + 5\ln\frac{z}{L} + \frac{z}{L}\right) L \leqslant z < 2L \end{cases} \tag{5}$$

where v_τ and θ_τ are the friction velocity and friction temperature, respectively. L is the M-O scale and $\theta_0 = 290$ K is the reference temperature. $\kappa = 0.4$ is the Karman constant, and $g = 9.8$ m/s^2 is the gravity acceleration. z_0 is the roughness

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