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A new vortex sheet model for simulating aircraft wake vortex evolution

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Abstract A new vortex sheet model was proposed for simulating aircraft wake vortex evolution. Rather than beginning with a pair of counter-rotating cylindrical vortices as in the traditional models, a lift-drag method is used to initialize a vortex sheet so that the roll-up phase is taken into account. The results of this model report a better approximation to a real situation when compared to the measurement data. The roll-up induced structures are proved to influence the far-field decay. On one hand, they lead to an early decay in the diffusion phase. On the other hand, the growth of linear instability such as elliptical instability is suppressed, resulting in a slower decay in the rapid decay phase. This work provides a simple and practicable model for simulating wake vortex evolution, which combines the roll-up process and the far-field phase in simulation. It is also proved that the roll-up phase should not be ignored when simulating the far-field evolution of an aircraft wake vortex pair, which indicates the necessity of this new model.

1. Introduction

The wakes of heavy aircraft pose danger to the following light planes, which calls for studies on the evolution of wake vortices. The lifetime of a wake vortex pair can be divided into the near-field evolution (or roll-up process), during which the vortex sheet shedding from the wing rolls up to a pair of counter-rotating vortices, and the far-field evolution, during which the vortices decay in the atmosphere. These two phases have been studied respectively by investigators using experimental or numerical methods.

For aviation safety, fast-time wake prediction models have been developed to predict the wake vortex evolution.[1–3] Large eddy simulation (LES) plays an important role in testing and calibration of these models. In most present LES, wake vortices are initialized with a vortex model such as the Lamb-Oseen model, Burnham-Hallock model,[4] or Proctor model,[5] with the roll-up process ignored. These simulations can be called non-roll up (NRU) simulations since the roll-up phase is skipped and only the far-field phase is simulated. However, the roll-up process does not end with a clean pair of vortices, but with turbulent structures as well. These structures may act in the following process and influence the far-field decay of the primary vortices. As this potential influence is ignored by

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NRU simulations, white noise is added to the initial vortices in some simulations[6,7] to deal with this conflict. A more direct approach is to combine the roll-up and far-field phases in a numerical simulation. However, the simulation of these two phases usually needs different numerical methods. In the simulation of the roll-up phase, Reynold averaged Navier–Stokes (RANS)[8] is appropriate and the mesh should distinguish the shape of an aircraft. In the far-field phase, LES is the most appropriate method. Misaka et al.[9] achieved this aim by coupling a high-fidelity RANS to LES. In Ref. 9, the RANS result of flow field around a wing-body configuration and a high-lift configuration was inserted into the LES domain to initialize the wake, by which the influences of the roll-up process as well as the complex flow structures around aircraft components such as wing, fuselage, and flaps were taken into account. However, this method is far from practical application because of the large requirement of calculation amount. Therefore, a more practical numerical model is needed.

In this paper, a new lift-drag model is developed to simulate the whole lifetime of wake vortices from a vortex sheet to far-field decay. In this model, the action to the air by the aircraft is simplified to lift and drag in an elliptical distribution. This is a practicable engineering wake simulation model which takes the roll-up phase into account with the calculation amount similar to those of NRU models. The accuracy of this model is proved by a comparison to the measurement data. The results are also compared to those of NRU cases initialized with a cylindrical vortex pair to investigate the influence of the roll-up process to prove the inadequacy of NRU models. The conditions of moderate and strong atmospheric turbulences are both studied. This paper is organized as follows. The numerical methods as well as the initialization of the vortex sheet and ambient turbulence are introduced in Section 2. The result in the roll-up phase is discussed in Section 3, and the far-field evolution with analysis of the decay mechanism is described in detail in Section 4. Finally, in Section 5, the main conclusions are summarized.

2. Methodology

2.1. Numerical methods

The LES code self-Adaptive Tsinghua Turbulence lab Large Eddy Simulation (ATTLES)[10] solves the Boussinesq-approximated Navier-Stokes equations as follows:

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

$$\frac{\partial u_i}{\partial t} + u_j\frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\cdot\frac{\partial p}{\partial x_i} + (\nu + \nu_t)\frac{\partial^2 u_i}{\partial x_j \partial x_j} \tag{2}$$

where u_i is the velocity component in direction i (i = 1, 2, 3) and x_i is the coordinate. p is the pressure, t is the time, and ρ is the density. ν and ν_t are the molecular kinematic viscosity and sub-grid kinematic viscosity, respectively. ATTLES solves equations on a movable cartesian grid to deal with the requirement for high resolution in the vortex cores. The movement of the mesh is controlled by a self-adaptive algorithm which is developed from the spring analogy method by Gnoffo[11] and Nakahashi and Deiwert.[12] The details of the numerical method are described in Refs. 10,13,14.

2.2. Vortex sheet initialization

The vortex sheet shedding from an elliptic wing is generated by imposing a body force in a flakiness region. As shown in Fig. 1, with x, y, z being the fight direction (or axial direction of vortices), span-wise direction, and vertical direction, respectively, the flakiness region has a width equal to the wing span B, and a thickness of $h << B$, while the length of this region is throughout the simulation domain in the flight direction. A periodic boundary condition is applied in x-direction to simulate the temporal evolution of the wake vortex, equivalent to a vortex sheet with an infinite length in the flight direction. The distribution of the body force is set to

$$f_z = -\frac{\Gamma_0}{h\tau}\sqrt{1-4y^2/B^2} \tag{3}$$

where τ is the duration of the body force and Γ_0 is the maximum circulation. In this paper, the thickness of the vortex sheet h = 0.677 m is employed. The duration of the body force τ should be as short as possible to ensure accuracy, while too short a τ, or too large an f_z, would lead to numerical instability. We employ τ = 0.1 s after balance. Considering the axial vorticity transport equation,

$$\frac{D\omega_x}{Dt} = (\boldsymbol{\omega}\cdot\nabla)u + \nu\Delta\omega_x + \frac{\partial f_z}{\partial y} \tag{4}$$

where $\boldsymbol{\omega}$ is the vorticity vector. As τ is small, the third term on the right of Eq. (4) is much larger than the other two. Thus the intensity of the vortex sheet γ can be calculated as

$$\frac{D\omega_x}{Dt} = \frac{\partial f_z}{\partial y} = \frac{\Gamma_0}{h\tau}\cdot\frac{\partial}{\partial y}\sqrt{1-4y^2/B^2} \tag{5}$$

$$\gamma(y) = \int_0^\tau \left(h\frac{D\omega_x}{Dt}\right)dt = \frac{d}{dy}\left[\Gamma_0\sqrt{1-4y^2/B^2}\right] \tag{6}$$

which is exactly the intensity distribution of a vortex sheet from an elliptic wing. The physical meaning of f_z is the reactive force acting on the air by the wing. Therefore, f_z is numerically equal to the local lift, which is in an elliptical distribution. In this paper, an approaching A340 aircraft is considered with a wing span B = 60.3 m, lift coefficient C_L = 1.40, aspect ratio λ = 9.5, and approaching speed V_A = 75 m/s, corresponding to the wake parameters Γ_0 = 424 m^2/s, initial vortex separation $b_0 = \pi B/4$ = 47.4 m, initial vortex descending speed $w_0 = \Gamma_0/(2\pi b_0)$ = 1.42 m/s, and characteristic time scale $t_0 = w_0/b_0$ = 33.3 s using an elliptically loaded wing assumption.

Moreover, to take the influence of the flight drag into account, a body force in the flight direction f_x is also added

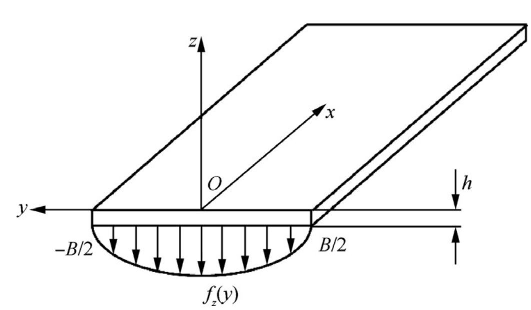

Fig. 1 Schematic of initialization of vortex sheet.