Large-Eddy Simulation of Spatially Developing Aircraft Wake

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ABSTRACT
Development of aircraft's wake vortex from the roll-up until vortex decay is studied. An aircraft model and a surrounding flow field obtained from high-fidelity Reynolds Averaged Navier-Stokes simulation are swept through a ground fixed computational domain to initialize the wake. After the initialization, large-eddy simulation of the vortical wake is performed until vortex decay, i.e., 2-3 minutes after the passage of aircraft. Here, the methodology and some results from the simulations using the DLR-F6 wing-body model are presented.

1. Introduction

Wake vortices generated by a flying aircraft pose a potential risk for following aircraft due to the strong and coherent vortical flow structure[1]. In addition, it is pointed out that condensation trails (contrails) originated from the interaction of jet exhaust, wake vortices and the environmental atmosphere may trigger the formation of cirrus clouds (contrail cirrus), which is suspected to have influence on the climate change[2]. The evolution of aircraft's wake can be divided into several phases, for example, (1) roll-up phase, (2) vortex phase, and (3) diffusion phase. Because of the broad spatiotemporal scale of the problem, the use of numerical simulation is usually limited to each of those phases. The roll-up phase is simulated by high-fidelity Reynolds Averaged Navier-Stokes (RANS) simulations because detailed aircraft geometries of fuselage, flaps, etc. affect the roll-up process and the resulting wake vortices. Dynamics of wake vortices in the vortex phases is studied mainly by large-eddy simulation (LES) or direct Navier-Stokes (DNS) simulation[3]. The third diffusion phase is related to meteorological simulations where microphysical processes of contrails are of primary interest.

The present study aims to develop a methodology which enables to simulate wake vortex evolution from the generation until the decay, i.e., from the roll-up phase to the vortex phase mentioned above. The vortex decay occurs 2-3 minutes after the passage of aircraft in a typical cruise condition, i.e., 28-43 km behind a flying aircraft. The study bridging the gap between the roll-up and the vortex phases would provide understandings toward properties of realistic aircraft wake such as vortex core radius and circulation evolutions, as well as roll-up and entrainment of jet exhaust by considering tracer materials, which might be useful for detailed contrail modeling studies.

2. Method

An aircraft model and the surrounding flow field obtained from high-fidelity RANS simulation are swept through a ground fixed LES domain to initialize the aircraft's wake[4]. The RANS flow field is provided as a forcing term of Navier-Stokes equations in the LES. Similar approach might be referred to as the fortified solution algorithm (FSA)[5], or a nudging technique used in data assimilation[6]. The resulting velocity vector of the flow field is represented by the weighting sum of LES velocity field $\mathbf{V}_{\mathrm{LES}}$ and RANS velocity field $\mathbf{V}_{\mathrm{RANS}}$,

$$\mathbf{V} = f\ \mathbf{V}_{\mathrm{LES}} + (1-f)\mathbf{V}_{\mathrm{RANS}}. \qquad (1)$$

The weighting function f could be a smooth function of the wall-distance y, or of other physical quantities such as velocity magnitude. Here, we employ the following function of wall-distance to realize smooth transition between the solutions,

$$f(y) = \frac{1}{2}\left[\tanh\left[\alpha\left(\frac{y}{\beta} - \frac{\beta}{y}\right)\right] + 1.0\right], \qquad (2)$$

where the constants α and β represent the slope of the transition and the wall-distance where solutions of RANS and LES are equality weighted, respectively. These constants can be determined by try and error basis, as well as by optimization techniques.

In this study, the RANS flow field around the DLR-F6 wing-body model is employed to initialize the wake. The RANS solution is obtained by the DLR TAU-code with hybrid unstructured mesh, where the number of mesh points is approximately 8.5 million[7]. The flow conditions of Mach number M=0.75 and Reynolds number Re=5.0×10^6 are considered.

There are several reasons to employ the ground fixed LES domain. Decay of a fully rolled-up vortex pair strongly depends on environmental conditions such as ambient turbulence, temperature stratification and wind shear. Therefore, the control of these conditions is crucially important to assess the influence of ambient conditions on vortex decay. Unlike the consideration of realistic inflow conditions, the generation of controlled turbulence fields in the ground fixed LES domain is straightforward. The other reason is that the present approach can reduce a domain length in the flight direction compared to an aircraft fixed computational domain. Therefore, computational resources can be used to increase spatial resolution.

Because of the large difference of RANS and LES mesh sizes near body surfaces, the connection of detailed flow and turbulence quantities cannot be hoped.

Here, we rather attempt to connect flow quantities related to wake vortex evolution, e.g., the strength of wing-tip vortex, downwash along wings and span-wise load distributions obtained from a high fidelity RANS flow field.

In this study, the incompressible Navier-Stokes code MGLET is employed for LES[8,9]. An equation for potential temperature is solved to take into account buoyancy effects employing Boussinesq approximation. The equations are discretized by a finite-volume approach with the fourth-order finite-volume compact scheme. Lagrangian dynamic model is employed for a turbulence closure. The third-order Runge-Kutta method is used for time integration.

3. Results and Discussion

Figure 1 shows vorticity distributions on several downstream planes where the results from different mesh resolutions of 0.5 and 1.0 m are compared. The origin of the coordinate in the flight direction is set to trailing edge of wing-tip and the downstream distance x is normalized by the wing-span b. Boundary layer around the fuselage appears in the region with high vorticity magnitude in both mesh resolutions. The boundary layer of 0.5 m mesh case shows a sharp vorticity distribution compared to that of 1.0 m at x/b=0.0, however, the thickness of boundary layer does not reflect that in the RANS simulation even with the 0.5m mesh. It is simply due to the less resolution of the LES mesh compared to RANS mesh near body surfaces. At x/b=1.0, peaks of vorticity magnitude from wing-tip and fuselage are kept high in the 0.5 m mesh case. Then, the roll-up of wing-tip vortices proceeds at x/b=3.0. The overall vorticity distribution is similar in both cases during the roll-up phase, however, the underestimated vorticity peak might affect the time evolution of wake vortex at a later time.

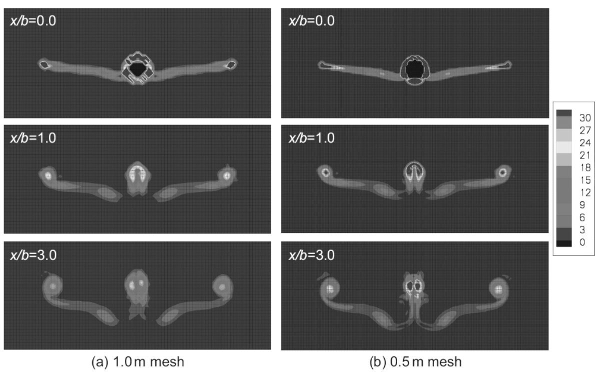

Fig. 1 Vorticity distribution on several downstream planes with mesh resolutions of 0.5 and 1.0 m.

Figure 2 shows the time evolution of vorticity distribution on a ground fixed vertical plane from T=2 until 39 s, which corresponds to the distance of 450 to 8,800 m (x/b=7 to 146) from the aircraft model. The vorticity from fuselage decays quickly as shown in Fig. 2(c), on the other hand, the vorticity distribution from wing-tips preserve their peak values. The vorticity from inboard wing rotates around the wing-tip vortex, which realizes the wake's roll-up establishing a well-known counter-rotating vortex pair. In Fig. 2(f), the flow field is reorganized to a fully rolled-up vortex pair. The roll-up process takes approximately one vortex time unit, i.e., the time a vortex pair descends one vortex separation.

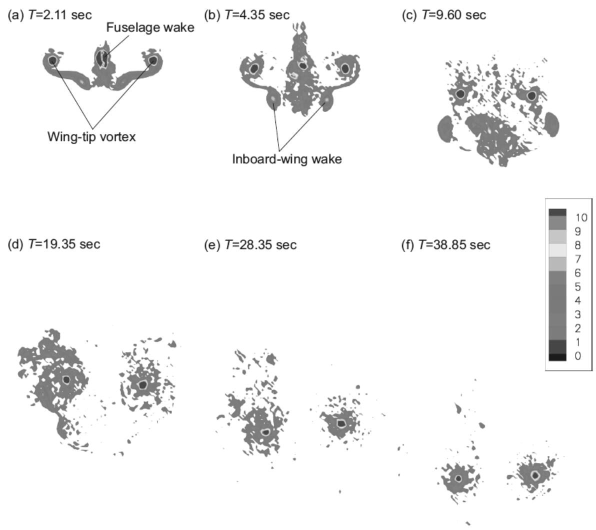

Fig. 2 Time evolution of vorticity distribution during the roll-up of DLR-F6 model's wake.

4. Concluding remarks

LES of wake vortex evolution from its generation to vortex decay is performed by combining flow fields from RANS and LES computations. The RANS flow field is employed in the LES computation as a forcing term sweeping through the ground-fixed LES domain.

Finer mesh resolution in the LES domain realizes higher peaks of vorticity distribution in the aircraft wake, however, the global vorticity structure of the wake is not sensitive to the mesh resolution. The roll-up process is simulated by the present approach, which realizes a counter-rotating vortex pair after one vortex time unit. It is confirmed that the consideration of spanwise load distribution is important to study realistic aircraft wake.

Acknowledgements

Computer time provided by Leibniz-Rechenzentrum (LRZ) is greatly acknowledged. The current work is conducted within the DLR project Wetter & Fliegen (Weather & Flying).

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