Initialization and Simulations of Three-Dimensional Aircraft Wake Vortices

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Final Report

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Summary of Research

The research period under the sponsorship of NAG1-1911 is two years: from Feb. 1, 1997 to Jan. 31, 1999 (extended no-cost to April 30, 1999). During the two-year research period, deliverables have included brief monthly progress statements, annual reports and subroutines of computational programs. Several technical papers have been published and are attached to this final report. This **Summary of Research** contains a brief description of those research results and refers the details to each attached paper.

1. Axial Flow Effects on Three-Dimensional Vortex Wake Decay

(Ref. Zheng, 1997)

The axial velocity component is important for three-dimensional wake vortex simulations. Initial axial velocity profiles influence the vortex decay behavior. Analytical relationships for small axial velocity deviation have been developed in single vortex cases. Those results show that the sign of the axial velocity deviation can change the relation between the total circulation and the vortex core size, but not the relations between vorticity, maximum tangential velocity, and the core size change.

Computational simulations were tested for both jet and wake type axial flow, with minimal influence from the ground and the mirror vortex in the wake vortex pair. Not surprisingly, the computational results are in agreement with the trend predicted in the analytical studies for the relationship between vorticity and core size, although at some locations opposite trend is detected with negligible influence on the overall vortex decay. The relationship for the total circulation needs to be validated using different simulation setup. For future research, the influence of strong axial currents, instead of small deviations, should be studied.

2. Interactions Between Wake Vortices and Shear Layers

(Ref. Zheng and Baek, 1998, 1999a)

Aircraft trailing vortices can be influenced significantly by atmospheric conditions such as cross wind, turbulence and stratification. According to the NASA 1994 and 1995 field measurement program in Memphis, Tennessee, the descending aircraft wake vortices could stall or be deflected at the top of low-level temperature inversions that usually produce pronounced shear zones.

Recently, Proctor et al. numerically tested effects of narrow shear zones on behavior of the vortex pair, motivated by the observation of the Memphis field data. The shear-layer sensitivity tests indicated that the downwind vortex was more sensitive and deflected to a higher altitude than its upwind counterpart. The downstream vortex contained vorticity of opposite sign to that of the shear. There was no detectable preference for the downwind vortex (or upwind vortex) to weaken (or strengthen) at a greater rate.

The above observations indicate that the mechanism responsible for the asymmetric deflection in the trailing vortices can be possibly deduced from inviscid interactions between the vortex pair and shear layers. Based on that hypothesis, a vortex method model is developed to study that mechanism. Furthermore, this vortex method is much faster than the Navier-Stokes numerical simulations, thus can be used for real-time predictions.

It has been shown, from the inviscid vortex method simulations, that the shear-layer deformation causes the vortex descent history difference in the two vortices of the trailing vortex pair. Due to the interactions between the vortices from the shear layer and the vortex pair, the induced velocities on the vortex pair have been changed. Such changes produce different trajectories when the vortex pair is interacting with a concentrated shear layer below or above it. The results show that if a shear layer is put below the vortex pair containing shear vortices with the same sign as the left vortex, the right vortex descends less than the left vortex. While the same shear layer is set above the vortex pair, the right vortex descends more. The descent altitude difference increases with the shear layer strength. The two vortices of the trailing vortex pair do not show altitude difference when they go through a constant, non-deformed shear layer. These trends are the same as predicted by Proctor et al. in their finite difference numerical simulations using the Navier-Stokes equations. Modifications of this model to include other atmospheric conditions are feasible for real-time wake vortex predictions.

3. N-S Simulations of Crow-Type Instabilities in Vortex Wake

(Ref. Zheng and Baek, 1999b)

Atmospheric turbulence can have influence on decay of aircraft wake by inducing vortex instabilities and vortex burst, along with direct contribution to the diffusion process. Influences of the Crow instability on the vortex system have obtained a lot of attention in wake vortex research community. In his well-known paper, Crow investigated the mutual- and self-inductions under small perturbations in a pair of trailing vortices, using inviscid vortex analysis. The stability diagrams developed in that study have been used as criteria for the Crow instability. However, it is not clear whether the criteria would be valid under realistic aircraft wake vortex conditions, where the flow field is turbulent and with axial flow at the vortex center.

On the other hand, atmospheric turbulence can have various wave modes as well as different amplitudes related with each mode, which can be shown by performing a spectral analysis on a typical atmospheric turbulence field. For finite initial amplitude Crow instability problems with turbulence diffusion effects, linear stability theories might not be applicable and three-dimensional Navier-Stokes simulations are required to verify their applicability.

In the current study, three-dimensional N-S simulations are carried out using the TASS program. Instead of initiating the Crow instability by numerically generated turbulence, which is also assumed to be steady throughout all the simulation time as in the previous numerical studies, initial sinusoidal displacement has been introduced as the perturbation and no further forcing functions exist after the initiation, as originally in Crow's analysis. Such initial disturbances allow both symmetric (S) and antisymmetric (A) modes to be analyzed, although the A-mode instability rarely occurs in aircraft wake vortices according to Crow's instability diagrams. Axial flow effects have been considered in the simulations to investigate any shift in the instability criteria.

By using large-eddy simulations for a pair of initially perturbed vortices in a quiescent (without atmospheric turbulence) background, we have found that the minimum Crow instability wavelength is about one vortex spacing shorter than predicted by Crow's linear stability theory. Features in agreement with Crow's analysis are that the planar standing wave angle is close to 45^o and the amplification rate is independent to the amplitudes of the initial disturbances. Crow instability influences the vortex decay in terms of vortex linking, which causes cancellation of axial vorticity component. In that sense, vortices decay faster with higher disturbance amplitudes. Superimposed jet- or wake-type axial flow has unsignificant effects on Crow instability. However, cautions need to be taken when interpreting the simulated axial flow results due to the periodic boundary conditions used in the axial direction.

List of Attachment

Zheng, Z. C., 1997, "Initialization and Simulation of Three-Dimensional Aircraft Wake Vortices", AIAA Paper No. 97-2264, *15th AIAA Applied Aerodynamics Conference*, Atlanta, GA, June, 1997.

Zheng, Z. C., and Baek, K., 1998, "Shear-Layer Effects on Trailing Vortices", AIAA Paper No. 98-0316, *36th Aerospace Sciences Meeting and Exhibit*, Reno, NV, January, 1998.

Zheng, Z. C., and Baek, K., 1999a, "Inviscid Interactions Between Wake Vortices and Shear Layers," *Journal of Aircraft*, Vol. 36, No. 2, pp. 477-480.

Zheng, Z. C., and Baek, K., 1999b, "N-S Simulations of Crow-Type Instabilities in Vortex Wake", AIAA Paper No. 99-0981, *37th AeroSpace Sciences Meeting and Exhibit*, Reno, NV, January, 1999.

Zheng, Z. C., Lim, S. H., and Proctor, F. H., 2000, "Validation and Operation of a Vortex Wake/Shear Interaction Model," Abstract, submitted to *38th AeroSpace Sciences Meeting and Exhibit*, Reno, NV, January, 2000.