Neutral Atmospheric Effects on the Dissipation of Aircraft Vortex Wakes

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Enhanced dispersion of two-dimensional trailed vortex pairs within simplified neutral atmospheric backgrounds is studied numerically for three conditions: when the pair is imbedded in a constant turbulent bath (constant dissipation); when the pair is subjected to a mean crosswind shear; and when the pais is near the ground. Turbulent transport is modeled using second-order closure turbulent transport theory. The computed results allow several general conclusions to be drawn with regard to the reduction in circulation of the vortex pair and the rolling moment induced on a following aircraft: 1) the rate of decay of a vortex pair increases with increasing background dissipation rate; 2) crosswind shear disperses the vortex whose vorticity is opposite to the background; and 3) the proximity of a ground plane reduces the hazard of the pair by scrubbing. The phenomenon of vortex bounce is explained in terms of secondary vorticity produced at the ground plane. Qualitative comparisons are made with available experimental data, and inferences of these results upon the persistence of aircraft trailing vortices are discussed.

Nomenclature

C	=passive tracer ($C^* = C/C_0$)
C_ℓ	=proportional to the induced rolling moment, Eq. (3)
q	=root mean square of the turbulent kinetic energy, ($q^* = q2\pi s/\Gamma_0$)
r	=radial coordinate measured from vortex center
s	=initial semiseparation between vortices
t	=time, $t^* = t\Gamma_0/2\pi s^2$
U_i	=mean Cartesian velocity components
$\langle u_i u_j \rangle$	=ensemble-averaged Reynolds stress correlation
x_j	=Cartesian coordinates
z_0	=hydrodynamic roughness length
β	=normalized constant cross shear, $(2\pi s^2/\Gamma_0)\partial V/\partial z$
Γ_0	=initial circulation
ϵ	=turbulent dissipation rate, $\epsilon^* = (2\pi)^3 s^4 \epsilon/\Gamma_0^3$
ζ	=streamwise component of vorticity, $\zeta^* = \zeta 2\pi s^2/\Gamma_0$
Λ	=turbulent macroscale parameter
ν	=kinematic viscosity
σ	=vortex spread parameter
ψ	=streamfunction

I. Introduction

THE decay of aircraft vortex wakes has been the focus of extensive investigation by both NASA and DOT, in an effort to determine hazard potential and wake lifetime. Because of the inherent difficulty in making measurements in the wakes of aircraft, investigations have included the development of computer codes to simulate vortex behavior and predict vortex interaction. The work described herein are results from one such code "VORTEX WAKE."

Donaldson and Bilanin[1] present a review of the physics underlying vortex generation and decay, and the approaches used to analyze these effects. A comprehensive review of the entire subject has recently been given by Hallock and Eberle.[2] In Bilanin et al.[3] (hereafter referred to as "I"), we used the point-vortex approach of Rossow[4] to initiate a discussion of vortex merging, wherein vortices of like sign interact. The thrust in I was the application of turbulent transport theory to the merging process, to provide for a complete description of the convective and dissipative processes within the vortices themselves. The two-dimensional, unsteady numerical code "VORTEX WAKE" programs the Reynolds stress equations modeled by Donaldson.[5] The formulation of the modeled equation and the numerical procedures involved in solving them are included in I, as is an extensive discussion of the merging of multiple trailing vortices and the minimum hazard potential for a wing.

One important result from I is that a pair of opposite-signed vortices exhibit a surprisingly slow rate of decay when descending in a calm, neutral atmosphere away from the ground. These ideal conditions, fortunately, are not met often in practice. More commonly, vortex pairs encounter background turbulence, mean wind gradients, or the ground while descending in an atmosphere which is not in general neutrally stable. The effects of background turbulence, wind shear, and ground interaction form the subject of this paper. Here, we demonstrate through the use of our turbulent transport code that any of these quite naturally occurring effects may substantially reduce the lifetime of a vortex pair. Descent of a vortex pair in a stably stratified atmosphere will be the subject of a subsequent paper.

In Section II, we briefly review the turbulent transport model and examine a practical limit of the model used to provide idealized atmospheric environments. Improvements in the numerical code are also discussed here.

In Section III, we examine the effects of background turbulence on a vortex pair, showing that decay increases with increasing dissipation rate. In Section IV, we investigate the effects of mean shear and offer an explanation of the "solitary" vortex phenomenon. Finally, in Section V, we investigate vortex interaction with a ground plane and explain the phenomenon of vortex bounce which has been observed on runways and in subscale tests.

II. Turbulence Model and "VORTEX WAKE" Code

A need to predict turbulent transport in rapidly rotating, as well as stratified flows, led Donaldson to develop a second-order closure model of turbulent transport. A second-order model implies that partial differential equations are solved for the Reynolds stress tensor $\langle u_i u_j \rangle$ as well as for the mean ensemble-averaged U_i velocity components. Higher-order

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