AIAA 80-0009R

Turbulent Trailing Vortices in Stratified Fluids

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The effects of stable atmospheric-density stratification, vortex core size, and turbulent scale on the descent of aircraft-trailing vortices are investigated using numerical solutions of a second-order closure turbulence model. A Boeing 747 vortex descent is simulated numerically and compared to reported measurements of descent distance, velocity, and circulation profiles. It is concluded that the pair was halted in its descent by a diffuse region of countersign vorticity primarily outboard and above the vortex cores. It is shown that the core size and turbulent macroscale have significant effects on vortex behavior through their influence on turbulence production, diffusion, and dissipation.

Nomenclature

Fr = Froude number, $\Gamma_0/2\pi s^2 N$
g = acceleration of gravity
N = Brunt-Väisälä frequency, $[-(g/\rho_0)d\rho_0/dz]^{1/2}$, $[(g/\theta_0)d\theta_0/dz]^{1/2}$
P = impulse
q = root mean square of twice the turbulent kinetic energy
r = radial coordinate measured from center of vortex-pair core
r_1 = radius of maximum swirl velocity
s = vortex-pair semiseparation distance
T = kinetic energy
t = time
u,v,w = velocities parallel to x, y, and z coordinates, respectively
V = vortex-pair descent velocity
w = core swirl velocity
x,y,z = coordinates parallel to vortex-pair cores, horizontal and vertical, respectively
Γ = vortex-pair circulation
ϵ = dissipation rate, $(1/8)(q^3/\Lambda)$
ζ = vorticity
θ = mean temperature
Λ = turbulent macroscale parameter
ν = kinematic viscosity
ρ = density
σ = core vorticity spread parameter
ψ = stream function

Subscripts

avg = average
c = countersign
max = maximum value
p = principal vortex
0 = initial value

Superscripts

$(\bar{\ })$ = ensemble averaged
$(\ )'$ = deviation of variable from its initial condition

Presented as Paper 80-0009 at the AIAA 18th Aerospace Sciences Meeting, Pasadena, Calif., Jan. 14-16, 1980; submitted Jan. 16, 1980; revision received Jan. 5, 1981.

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I. Introduction

TRAILING vortex wakes of wide-body transports are a significant threat to following aircraft due to the considerable rolling moments they generate. The safety hazard they impose and the economic impact created by increased aircraft separation requirements during takeoff and landing have spurred numerous analytical and experimental studies of vortex behavior. Simplifying assumptions which have been adopted to achieve purely analytical solutions have resulted in contradictory predictions of vortex descent in the real atmosphere.[1-10] Numerical methods must be used to more fully account for real fluid effects, such as turbulence. The present investigation has been carried out to clarify the effects of stratification on aircraft vortex descent. The calculations reported here were made with WAKE, a finite difference computer code which solves the two-dimensional, unsteady mean and ensemble-averaged Reynolds stress equations of fluid motion based on a second-order closure turbulence model. The axisymmetric version of the WAKE code was used, as reported by Hecht et al.,[11] to validate the model for vortex flows in stratification by numerically simulating the measured descent of vortex rings in discontinuous and linear-density stratified fluids. The agreement between the calculated and measured vortex-ring trajectories and geometric parameters provided the necessary validation of the model for stratified fluids and opened the way for the study of a full-scale flight-test vortex-pair descent.

The flight data analyzed here were selected from a set of measurements reported by Burnham et al.[12] which consist of Boeing 747 vortex-pair rotational velocity, descent velocity and altitude and inferred circulation profile histories. The numerical simulation was run using an initial vortex rotational velocity close to the actual initial data. The measured core spread was small compared to the size of the computational domain normally required to define the flow in and adjacent to the recirculation cell, and the maximum rotational velocity was exceptionally high. The size of the numerical grid required to resolve the core flow, combined with the large velocities in this region, lead to a very small allowable time step to preserve numerical stability. A new method was devised to calculate the evolution of tight, strong vortices based on computing the departure of the vortex from an analytically defined initial condition. For the vortex pair analyzed, this departure remained small during most of descent.

Results of the code were used as a guide in interpreting vortex-pair behavior in a stratified atmosphere, and the role of turbulence in influencing this behavior.