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DYNAMICS OF EXHAUST PLUME ENTRAINMENT IN AIRCRAFT VORTEX WAKES

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Abstract

The prediction of wake/exhaust mixing for subsonic and supersonic aircraft is an important aspect of the assessment of the atmospheric effects of aviation. The primary objective of the work described herein has been to address the need for a consistent, comprehensive treatment of plume entrainment in the near field regime downstream of aircraft operating in the upper troposphere and lower stratosphere. Previous work implemented several of the capabilities required to support such assessments, including a coupling with a passive chemistry model. This paper focuses on the development, modification, and testing of analysis methods for the specific application of predicting the mixing of the aircraft vortex wake with the engine exhaust. The implementation of new features designed to capture near wake rollup and variable density effects in the wake are described, as is the exercise of key numerical and physical modeling aspects of the modified code. The case studies described indicate the importance of buoyancy and variable density effects in realistic simulations, and have helped quantify important differences in plume entrainment and detrainment between major classes of commercial aircraft.

Nomenclature

a	speed of sound, m/sec
b	modeling constant = .125
C_L	aircraft lift coefficient, $2L / \rho_\infty U_\infty^2 S$
c	local wing chord
$\bar{c}$	mean wing chord
c_ℓ	lift coefficient, $2\ell / \rho_\infty U_\infty^2 c$
$\frac{D}{Dt}$	derivative operator, $(1+U)\frac{d}{dx} + V\frac{d}{dy} + W\frac{d}{dz}$
g_i	gravitational vector, m/sec^2
h	grid spacing, m
k	thermal conductivity normalized by ρc_p
L	lift
ℓ	lift per unit span
M	Mach number
Pr	Prandtl number ν / c_p
p	normalized pressure $\mathbf{p}-\mathbf{p}_\infty / \rho_\infty U_\infty^2$
$\mathbf{p}$	pressure, N/m^2
q	turbulent kinetic energy $(\overline{u_i u_i})^{1/2}$
R	universal gas constant cal / gm-K
r	radial distance inside vortex, m
Re	Reynolds number $\mathbf{U}_\infty s / \nu$
Ri*	modified Richardson number $gs / \mathbf{U}_\infty^2$
S	wing area, m^2
s	wing semispan, m
T	normalized temperature $\mathbf{T}-\mathbf{T}_\infty / \mathbf{T}_\infty$
$\mathbf{T}$	temperature, K
t	time, s
U	axial velocity excess $(\mathbf{U}-\mathbf{U}_\infty)/\mathbf{U}_\infty$
U_i	mean velocity in ith Cartesian direction, normalized by $\mathbf{U}_\infty$
$\mathbf{U}$	axial velocity, m/sec
$\mathbf{U}_\infty$	free stream velocity, m/sec
$\mathbf{u}$	magnitude of $\vec{\mathbf{u}}$, m/s
u_i	fluctuating component of velocity in ith direction, normalized by $\mathbf{U}_\infty$
$\vec{u}$	$\vec{\mathbf{u}}$ normalized by $\mathbf{U}_\infty$
$\vec{\mathbf{u}}$	total velocity vector, m/s
V	velocity in y direction, normalized by $\mathbf{U}_\infty$
W	velocity in z direction, normalized by $\mathbf{U}_\infty$
x_i	ith Cartesian direction, normalized by s
$\mathbf{x}_i$	ith Cartesian direction, m
x,y,z	Cartesian coordinates, origin at the wing root; x positive downstream, y positive to the right, z positive up
Γ	bound circulation of the wing or circulation strength of a vortex, m^2/s
γ	ratio of specific heats

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