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Compressible large eddy simulations of wall-bounded turbulent flows using a semi-implicit numerical scheme for low Mach number aeroacoustics

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Abstract

Large eddy simulations (LES) of low-speed, wall-bounded turbulent flows were conducted by numerically integrating the compressible Navier–Stokes equations in a generalized curvilinear coordinate system. An efficient numerical scheme based on a third-order additive semi-implicit Runge–Kutta method for time advancement and a sixth-order accurate, compact finite-difference scheme for spatial discretization were used. The convective terms in the wall-normal direction were treated implicitly to remove the time-step limitation associated with the use of fine meshes in the near-wall region for high Reynolds number viscous flows. The dynamic Smagorinsky subgrid-scale eddy viscosity model was used to close the filtered equations. Generalized characteristic-based non-reflecting boundary conditions were used together with grid stretching and enhanced damping in the exit zone. The accuracy and efficiency of the numerical scheme was assessed by simple acoustic model problems and by comparing LES predictions for fully developed turbulent channel flow and turbulent separated flow in an asymmetric diffuser to previous direct numerical simulation (DNS) and experimental data, respectively. LES predictions for both flows were in reasonable agreement with the DNS and experimental mean velocity and turbulence statistics. The findings suggest that the numerical approach employed here offers comparable accuracy to similar recent studies at approximately one-third of the computational cost and may provide both an accurate and efficient way to conduct computational aeroacoustics studies for low Mach number, confined turbulent flows.

Keywords: LES; Turbulence; Wall-bounded flows; Semi-implicit scheme

1. Introduction

One challenge of efficient, direct computation of sound radiation from low Mach number turbulent flows is to relax the CFL restriction related to acoustic waves, while minimizing the amount of numerical dissipation

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Nomenclature

C	eddy viscosity model constant
c	speed of sound
C_f	skin friction coefficient
C_p	constant pressure specific heat
C_v	constant volume specific heat
$\mathbf{E}$, $\mathbf{F}$, $\mathbf{G}$	inviscid flux vectors
$\mathbf{E}_v$, $\mathbf{F}_v$, $\mathbf{G}_v$	viscous flux vectors
e_t	specific total energy
$\mathbf{f}$	spatial discretization of non-stiff terms
f	arbitrary variable
$\bar{f}$	large-scale component of variable f
f''	small-scale component of variable f
$\tilde{f}$	Favre-average of variable f
$\hat{f}$	test-filtered variable f
$\bar{f}(z)$	variable f averaged over homogeneous spatial plane and time
$G(\mathbf{x}-\mathbf{y},\Delta)$	filter function
$\mathbf{g}$	spatial discretization of stiff terms
H	inlet height
$\mathbf{I}$	identity matrix
J	Jacobian of coordinate transformation
$\mathbf{J}$	Jacobian matrix of stiff term in semi-implicit scheme
$\mathbf{k}$	increment of discretized flow field variable vector
L_i	amplitude of characteristic wave
L^*	newly updated amplitude of characteristics
M	Mach number
p	pressure
Pr	Prandtl number
Pr_t	turbulent Prandtl number
Q	second invariant of velocity gradient tensor
$\mathbf{Q}$	vector of dependent variables
$\mathcal{Q}_i$	subgrid-scale heat flux
q_i	heat transfer flux vector
Re	Reynolds number
$\mathbf{S}$	source term for channel flow computation
$\mathbf{S}_v$	source term from the viscous flux vectors
S_{ij}	symmetric part of velocity gradient tensor
T	temperature
T_{ij}	Lighthill source tensor
t	time
U_b	bulk velocity
U_c	centerline velocity
$\mathbf{u}$	discretized flow field variable vector
u, v, w	Cartesian velocity components
u_i	alternate notation for (u,v,w)
u_τ	friction velocity
$\mathbf{v}$	velocity vector
(x,y,z)	Cartesian coordinates
x_i	alternate notation for (x,y,z)
δ	half-height of inlet