

Contents

Preface	page ix
1 Introduction to LES	1
1.1 Book's scope	1
1.2 Basic principles of fluid dynamics	4
1.2.1 Continuity equation	5
1.2.2 Balance of forces	5
1.2.3 Thermodynamic equation	6
1.2.4 Vorticity	9
1.3 Isotropic turbulence	10
1.3.1 Formalism	10
1.3.2 Kolmogorov $k^{-5/3}$ energy spectrum	12
1.3.3 Kolmogorov dissipative scale and wavenumber	13
1.3.4 Integral scale and Taylor microscale	14
1.4 Direct numerical simulations of turbulence	15
1.5 A brief history of LES	15
1.6 LES and determinism	17
1.7 The place of LES in turbulence modeling	19
2 Vortex dynamics	21
2.1 Vorticity dynamics	21
2.1.1 Helmholtz–Kelvin's theorem	22
2.2 Coherent vortices	22
2.2.1 Definition	22
2.2.2 Pressure	23
2.2.3 The Q-criterion	23
2.2.4 The λ_2 -criterion	25
2.2.5 Simple two-dimensional vortex interactions	26
2.3 Vortex identification	26
2.3.1 Isotropic turbulence	27
2.3.2 Backward-facing step	33

2.4	Coherent structures	36
2.5	Animations	37
3	LES formalism in physical space	39
3.1	LES equations for a flow of constant density	39
3.2	LES Boussinesq equations in a rotating frame	41
3.3	Eddy viscosity and diffusivity assumption	42
3.3.1	Smagorinsky's model	44
3.3.2	Dynamic Smagorinsky model	46
4	Spectral LES for isotropic turbulence	50
4.1	Spectral eddy viscosity and diffusivity	50
4.2	EDQNM theory	51
4.3	EDQNM plateau-peak model	55
4.3.1	Spectral-dynamic model	58
4.3.2	Spectral random backscatter	59
4.4	Return to the bump	61
4.5	Other types of spectral eddy viscosities	61
4.5.1	Heisenberg's eddy viscosity	61
4.5.2	RNG analysis	62
4.6	Anterior spectral LES of isotropic turbulence	63
4.6.1	Double filtering in Fourier space	64
4.7	EDQNM infrared backscatter and self-similarity	65
4.7.1	Finite-box size effects	74
4.8	Recent LES studies of decaying isotropic turbulence	76
4.8.1	Ultraviolet pressure	80
5	Spectral LES for inhomogeneous turbulence	81
5.1	Temporal mixing layer	81
5.1.1	Plateau-peak model	81
5.1.2	Spectral-dynamic model	84
5.2	Incompressible plane channel	85
5.2.1	Wall units	85
5.2.2	Streaks and hairpins	86
5.2.3	Spectral DNS and LES	86
5.2.4	Channel pdfs	91
6	Current challenges for LES	97
6.1	Structure-function model	97
6.1.1	Formalism	97
6.1.2	Nonuniform grids	99
6.1.3	Structure-function versus Smagorinsky models	99
6.1.4	Isotropic turbulence and free-shear flows	100
6.1.5	SF model, transition, and wall flows	100
6.2	Selective structure-function model	101

6.2.1	Formalism	101
6.2.2	The problem of constant adjustment	102
6.3	Filtered structure-function model	102
6.4	Temporal mixing layer	103
6.5	Spatial mixing layer	104
6.6	Round jet	107
6.6.1	The natural jet	110
6.6.2	The forced jet	112
6.7	Backstep	117
6.7.1	Strouhal numbers	119
6.8	New models	119
6.8.1	Dynamic structure-function model	121
6.8.2	Generalized hyperviscosities	122
6.8.3	Hyperviscosity	123
6.8.4	Scale-similarity and mixed models	124
6.8.5	Other approaches	124
6.9	Animations	125
7	LES of compressible turbulence	127
7.1	Simplified compressible LES formalism	128
7.1.1	Compressible Navier–Stokes equations	128
7.1.2	Compressible filtered equations	129
7.1.3	Compressible LES equations	132
7.2	Compressible mixing layer	134
7.2.1	Convective Mach number	134
7.2.2	Temporal mixing layer	135
7.2.3	Spatial mixing layer	140
7.2.4	Compressible round jets	143
7.3	Weakly compressible wall flows	149
7.3.1	LES of spatially developing boundary layers	149
7.3.2	Boundary layer on spanwise cavities	155
7.3.3	Obstacle with a wall effect	161
7.3.4	Pipe flow	163
7.4	Drag reduction by riblets	163
7.5	Transonic flow past a rectangular cavity	167
7.6	European space shuttle <i>Hermès</i>	168
7.7	Heat exchanges in ducts	174
7.7.1	Straight ducts of square section	175
7.7.2	Ducts with riblets	177
7.7.3	Spatially growing turbulence through a straight duct	178
7.7.4	Curved ducts of square section	181
7.8	Animations	183
8	Geophysical fluid dynamics	185
8.1	Introduction to geophysical fluid dynamics	186

8.1.1	Rossby number	186
8.1.2	Earth atmosphere	186
8.1.3	Oceanic circulation	188
8.1.4	Internal geophysics	190
8.2	Effects of spanwise rotation on shear flows of constant density	190
8.2.1	Rotating channel	191
8.2.2	Rotating free-shear layers	193
8.3	Storm formation	197
8.3.1	Eady model	197
8.3.2	Baroclinic jet	198
8.4	Animations	203
	Bibliography	205