

Contents

1. Introduction	1
1.1 Computational Fluid Dynamics	1
1.2 Levels of Approximation: General	2
1.3 Statement of the Scale Separation Problem	3
1.4 Usual Levels of Approximation	5
1.5 Large-Eddy Simulation: from Practice to Theory. Structure of the Book	9
2. Formal Introduction to Scale Separation: Band-Pass Filtering	15
2.1 Definition and Properties of the Filter in the Homogeneous Case	15
2.1.1 Definition	15
2.1.2 Fundamental Properties	17
2.1.3 Characterization of Different Approximations	18
2.1.4 Differential Filters	20
2.1.5 Three Classical Filters for Large-Eddy Simulation	21
2.1.6 Differential Interpretation of the Filters	26
2.2 Spatial Filtering: Extension to the Inhomogeneous Case	31
2.2.1 General	31
2.2.2 Non-uniform Filtering Over an Arbitrary Domain	32
2.2.3 Local Spectrum of Commutation Error	42
2.3 Time Filtering: a Few Properties	43
3. Application to Navier–Stokes Equations	45
3.1 Navier–Stokes Equations	46
3.1.1 Formulation in Physical Space	46
3.1.2 Formulation in General Coordinates	46
3.1.3 Formulation in Spectral Space	47
3.2 Filtered Navier–Stokes Equations in Cartesian Coordinates (Homogeneous Case)	48
3.2.1 Formulation in Physical Space	48
3.2.2 Formulation in Spectral Space	48

3.3	Decomposition of the Non-linear Term.	
	Associated Equations for the Conventional Approach	49
3.3.1	Leonard's Decomposition	49
3.3.2	Germano Consistent Decomposition	59
3.3.3	Germano Identity	61
3.3.4	Invariance Properties	64
3.3.5	Realizability Conditions	72
3.4	Extension to the Inhomogeneous Case	
	for the Conventional Approach	74
3.4.1	Second-Order Commuting Filter	74
3.4.2	High-Order Commuting Filters	77
3.5	Filtered Navier–Stokes Equations in General Coordinates	77
3.5.1	Basic Form of the Filtered Equations	77
3.5.2	Simplified Form of the Equations – Non-linear Terms Decomposition	78
3.6	Closure Problem	78
3.6.1	Statement of the Problem	78
3.6.2	Postulates	79
3.6.3	Functional and Structural Modeling	80
4.	Other Mathematical Models for the Large-Eddy Simulation Problem	83
4.1	Ensemble-Averaged Models	83
4.1.1	Yoshizawa's Partial Statistical Average Model	83
4.1.2	McComb's Conditional Mode Elimination Procedure	84
4.2	Regularized Navier–Stokes Models	85
4.2.1	Leray's Model	86
4.2.2	Holm's Navier–Stokes- α Model	86
4.2.3	Ladyzenskaja's Model	89
5.	Functional Modeling (Isotropic Case)	91
5.1	Phenomenology of Inter-Scale Interactions	91
5.1.1	Local Isotropy Assumption: Consequences	92
5.1.2	Interactions Between Resolved and Subgrid Scales	93
5.1.3	A View in Physical Space	102
5.1.4	Summary	104
5.2	Basic Functional Modeling Hypothesis	104
5.3	Modeling of the Forward Energy Cascade Process	105
5.3.1	Spectral Models	105
5.3.2	Physical Space Models	109
5.3.3	Improvement of Models in the Physical Space	133
5.3.4	Implicit Diffusion: the ILES Concept	161
5.4	Modeling the Backward Energy Cascade Process	171
5.4.1	Preliminary Remarks	171

5.4.2	Deterministic Statistical Models	172
5.4.3	Stochastic Models	178
6.	Functional Modeling:	
	Extension to Anisotropic Cases	187
6.1	Statement of the Problem	187
6.2	Application of Anisotropic Filter to Isotropic Flow	187
6.2.1	Scalar Models	188
6.2.2	Batten's Mixed Space-Time Scalar Estimator	191
6.2.3	Tensorial Models	191
6.3	Application of an Isotropic Filter to a Shear Flow	193
6.3.1	Phenomenology of Inter-Scale Interactions	193
6.3.2	Anisotropic Models: Scalar Subgrid Viscosities	198
6.3.3	Anisotropic Models: Tensorial Subgrid Viscosities	202
6.4	Remarks on Flows Submitted to Strong Rotation Effects	208
7.	Structural Modeling	209
7.1	Introduction and Motivations	209
7.2	Formal Series Expansions	210
7.2.1	Models Based on Approximate Deconvolution	210
7.2.2	Non-linear Models	223
7.2.3	Homogenization-Technique-Based Models	228
7.3	Scale Similarity Hypotheses and Models Using Them	231
7.3.1	Scale Similarity Hypotheses	231
7.3.2	Scale Similarity Models	232
7.3.3	A Bridge Between Scale Similarity and Approximate Deconvolution Models. Generalized Similarity Models	236
7.4	Mixed Modeling	237
7.4.1	Motivations	237
7.4.2	Examples of Mixed Models	239
7.5	Differential Subgrid Stress Models	243
7.5.1	Deardorff Model	243
7.5.2	Fureby Differential Subgrid Stress Model	244
7.5.3	Velocity-Filtered-Density-Function-Based Subgrid Stress Models	245
7.5.4	Link with the Subgrid Viscosity Models	248
7.6	Stretched-Vortex Subgrid Stress Models	249
7.6.1	General	249
7.6.2	S3/S2 Alignment Model	250
7.6.3	S3/ ω Alignment Model	250
7.6.4	Kinematic Model	250
7.7	Explicit Evaluation of Subgrid Scales	251
7.7.1	Fractal Interpolation Procedure	253
7.7.2	Chaotic Map Model	254

7.7.3	Kerstein's ODT-Based Method	257
7.7.4	Kinematic-Simulation-Based Reconstruction	259
7.7.5	Velocity Filtered Density Function Approach	260
7.7.6	Subgrid Scale Estimation Procedure	261
7.7.7	Multi-level Simulations	263
7.8	Direct Identification of Subgrid Terms	272
7.8.1	Linear-Stochastic-Estimation-Based Model	274
7.8.2	Neural-Network-Based Model	275
7.9	Implicit Structural Models	275
7.9.1	Local Average Method	276
7.9.2	Scale Residual Model	278
8.	Numerical Solution: Interpretation and Problems	281
8.1	Dynamic Interpretation of the Large-Eddy Simulation	281
8.1.1	Static and Dynamic Interpretations: Effective Filter	281
8.1.2	Theoretical Analysis of the Turbulence Generated by Large-Eddy Simulation	283
8.2	Ties Between the Filter and Computational Grid. Pre-filtering	288
8.3	Numerical Errors and Subgrid Terms	290
8.3.1	Ghosal's General Analysis	290
8.3.2	Pre-filtering Effect	294
8.3.3	Conclusions	297
8.3.4	Remarks on the Use of Artificial Dissipations	299
8.3.5	Remarks Concerning the Time Integration Method	303
9.	Analysis and Validation of Large-Eddy Simulation Data	305
9.1	Statement of the Problem	305
9.1.1	Type of Information Contained in a Large-Eddy Simulation	305
9.1.2	Validation Methods	306
9.1.3	Statistical Equivalency Classes of Realizations	307
9.1.4	Ideal LES and Optimal LES	310
9.1.5	Mathematical Analysis of Sensitivities and Uncertainties in Large-Eddy Simulation	311
9.2	Correction Techniques	313
9.2.1	Filtering the Reference Data	313
9.2.2	Evaluation of Subgrid-Scale Contribution	314
9.2.3	Evaluation of Subgrid-Scale Kinetic Energy	315
9.3	Practical Experience	318
10.	Boundary Conditions	323
10.1	General Problem	323
10.1.1	Mathematical Aspects	323
10.1.2	Physical Aspects	324

10.2	Solid Walls	326
10.2.1	Statement of the Problem	326
10.2.2	A Few Wall Models	332
10.2.3	Wall Models: Achievements and Problems	351
10.3	Case of the Inflow Conditions	354
10.3.1	Required Conditions	354
10.3.2	Inflow Condition Generation Techniques	354
11.	Coupling Large-Eddy Simulation	
	with Multiresolution/Multidomain Techniques	369
11.1	Statement of the Problem	369
11.2	Methods with Full Overlap	371
11.2.1	One-Way Coupling Algorithm	372
11.2.2	Two-Way Coupling Algorithm	372
11.2.3	FAS-like Multilevel Method	373
11.2.4	Kravchenko et al. Method	374
11.3	Methods Without Full Overlap	376
11.4	Coupling Large-Eddy Simulation with Adaptive	
	Mesh Refinement	377
11.4.1	Statement of the Problem	377
11.4.2	Error Estimation	378
12.	Hybrid RANS/LES Approaches	383
12.1	Motivations and Presentation	383
12.2	Zonal Decomposition	384
12.2.1	Statement of the Problem	384
12.2.2	Sharp Transition	385
12.2.3	Smooth Transition	387
12.2.4	Zonal RANS/LES Approach as Wall Model	388
12.3	Nonlinear Disturbance Equations	390
12.4	Universal Modeling	391
12.4.1	Germano's Hybrid Model	392
12.4.2	Speziale's Rescaling Method and Related Approaches	393
12.4.3	Baurle's Blending Strategy	394
12.4.4	Arunajatesan's Modified Two-Equation Model	396
12.4.5	Bush-Mani Limiters	397
12.4.6	Magagnato's Two-Equation Model	398
12.5	Toward a Theoretical Status for Hybrid	
	RANS/LES Approaches	399
13.	Implementation	401
13.1	Filter Identification. Computing the Cutoff Length	401
13.2	Explicit Discrete Filters	404
13.2.1	Uniform One-Dimensional Grid Case	404
13.2.2	Extension to the Multi-Dimensional Case	407

13.2.3	Extension to the General Case. Convolution Filters . . .	407
13.2.4	High-Order Elliptic Filters	408
13.3	Implementation of the Structure Function Models	408
14.	Examples of Applications	411
14.1	Homogeneous Turbulence	411
14.1.1	Isotropic Homogeneous Turbulence	411
14.1.2	Anisotropic Homogeneous Turbulence	412
14.2	Flows Possessing a Direction of Inhomogeneity	414
14.2.1	Time-Evolving Plane Channel	414
14.2.2	Other Flows	418
14.3	Flows Having at Most One Direction of Homogeneity	419
14.3.1	Round Jet	419
14.3.2	Backward Facing Step	426
14.3.3	Square-Section Cylinder	430
14.3.4	Other Examples	431
14.4	Industrial Applications	432
14.4.1	Large-Eddy Simulation for Nuclear Power Plants	432
14.4.2	Flow in a Mixed-Flow Pump	435
14.4.3	Flow Around a Landing Gear Configuration	437
14.4.4	Flow Around a Full-Scale Car	437
14.5	Lessons	439
14.5.1	General Lessons	439
14.5.2	Subgrid Model Efficiency	442
14.5.3	Wall Model Efficiency	444
14.5.4	Mesh Generation for <i>Building Blocks</i> Flows	445
15.	Coupling with Passive/Active Scalar	449
15.1	Scope of this Chapter	449
15.2	The Passive Scalar Case	450
15.2.1	Physical Model	450
15.2.2	Dynamics of the Passive Scalar	453
15.2.3	Extensions of Functional Models	461
15.2.4	Extensions of Structural Models	466
15.2.5	Generalized Subgrid Modeling for Arbitrary Non-linear Functions of an Advected Scalar	468
15.2.6	Models for Subgrid Scalar Variance and Scalar Subgrid Mixing Rate	469
15.2.7	A Few Applications	472
15.3	The Active Scalar Case: Stratification and Buoyancy Effects	472
15.3.1	Physical Model	472
15.3.2	Some Insights into the Active Scalar Dynamics	474
15.3.3	Extensions of Functional Models	481
15.3.4	Extensions of Structural Models	487
15.3.5	Subgrid Kinetic Energy Estimates	490

15.3.6 More Complex Physical Models	492
15.3.7 A Few Applications	492
A. Statistical and Spectral Analysis of Turbulence	495
A.1 Turbulence Properties	495
A.2 Foundations of the Statistical Analysis of Turbulence	495
A.2.1 Motivations	495
A.2.2 Statistical Average: Definition and Properties	496
A.2.3 Ergodicity Principle	496
A.2.4 Decomposition of a Turbulent Field	498
A.2.5 Isotropic Homogeneous Turbulence	499
A.3 Introduction to Spectral Analysis of the Isotropic Turbulent Fields	499
A.3.1 Definitions	499
A.3.2 Modal Interactions	501
A.3.3 Spectral Equations	502
A.4 Characteristic Scales of Turbulence	504
A.5 Spectral Dynamics of Isotropic Homogeneous Turbulence	504
A.5.1 Energy Cascade and Local Isotropy	504
A.5.2 Equilibrium Spectrum	505
B. EDQNM Modeling	507
B.1 Isotropic EDQNM Model	507
B.2 Cambon's Anisotropic EDQNM Model	509
B.3 EDQNM Model for Isotropic Passive Scalar	511
Bibliography	513
Index	553