
Contents

1	Introduction	1
2	LES Governing Equations	5
2.1	Preliminary Discussion	5
2.2	Governing Equations	6
2.2.1	Fundamental Assumptions	6
2.2.2	Conservative Formulation	7
2.2.3	Alternative Formulations	9
2.3	Filtering Operator	9
2.3.1	Definition	10
2.3.2	Discrete Representation of Filters	14
2.3.3	Filtering of Discontinuities	16
2.3.4	Filter Associated to the Numerical Method	18
2.3.5	Commutation Error	20
2.3.6	Favre Filtering	20
2.3.7	Summary of the Different Type of Filters	22
2.4	Formulation of the Filtered Governing Equations	22
2.4.1	Enthalpy Formulation	23
2.4.2	Temperature Formulation	24
2.4.3	Pressure Formulation	24
2.4.4	Entropy Formulation	25
2.4.5	Filtered Total Energy Equations	26
2.4.6	Momentum Equations	29
2.4.7	Simplifying Assumptions	30
2.5	Additional Relations for LES of Compressible Flows	33
2.5.1	Preservation of Original Symmetries	33
2.5.2	Discontinuity Jump Relations for LES	35
2.5.3	Second Law of Thermodynamics	37
2.6	Model Construction	38
2.6.1	Basic Hypothesis	38
2.6.2	Modeling Strategies	39

3	Compressible Turbulence Dynamics	41
3.1	Scope and Content of This Chapter	41
3.2	Kovasznay Decomposition of Turbulent Fluctuations	42
3.2.1	Kovasznay's Linear Decomposition	42
3.2.2	Weakly Nonlinear Kovasznay Decomposition	45
3.3	Statistical Description of Compressible Turbulence	46
3.4	Shock-Turbulence Interaction	48
3.4.1	Introduction to the Linear Interaction Approximation Theory	48
3.4.2	Vortical Turbulence-Shock Interaction	49
3.4.3	Mixed-Mode Turbulence-Shock Interaction	57
3.4.4	Consequences for Subgrid Modeling	62
3.5	Different Regimes of Isotropic Compressible Turbulence	64
3.5.1	Quasi-Isentropic-Turbulence Regime	65
3.5.2	Nonlinear Subsonic Regime	71
3.5.3	Supersonic Regime	74
3.5.4	Consequences for Subgrid Modeling	75
4	Functional Modeling	77
4.1	Basis of Functional Modeling	77
4.1.1	Phenomenology of Scale Interactions	77
4.1.2	Basic Functional Modeling Hypothesis	79
4.2	SGS Viscosity	79
4.2.1	The Boussinesq Hypothesis	79
4.2.2	Smagorinsky Model	81
4.2.3	Structure Function Model	82
4.2.4	Mixed Scale Model	82
4.3	Isotropic Tensor Modeling	83
4.4	SGS Heat Flux	84
4.5	Modeling of the Subgrid Turbulent Dissipation Rate	85
4.6	Improvement of SGS models	85
4.6.1	Structural Sensors and Selective Models	85
4.6.2	Accentuation Technique and Filtered Models	87
4.6.3	High-Pass Filtered Eddy Viscosity	88
4.6.4	Wall-Adapting Local Eddy-Viscosity Model	88
4.6.5	Dynamic Procedure	89
4.6.6	Implicit Diffusion and the Implicit LES Concept	93
5	Explicit Structural Modeling	95
5.1	Motivation of Structural Modeling	95
5.2	Models Based on Deconvolution	97
5.2.1	Scale-Similarity Model	100
5.2.2	Approximate Deconvolution Model	103
5.2.3	Tensor-Diffusivity Model	105
5.3	Regularization Techniques	105

5.3.1	Eddy-Viscosity Regularization	106
5.3.2	Relaxation Regularization	109
5.3.3	Regularization by Explicit Filtering	111
5.4	Multi-Scale Modeling of Subgrid-Scales	113
5.4.1	Multi-Level Approaches	113
5.4.2	Stretched-Vortex Model	116
5.4.3	Variational Multi-Scale Model	117
6	Relation Between SGS Model and Numerical	
	Discretization	119
6.1	Systematic Procedures for Nonlinear Error Analysis	119
6.1.1	Error Sources	119
6.1.2	Modified Differential Equation Analysis	121
6.1.3	Modified Differential Equation Analysis in Spectral Space	126
6.2	Implicit LES Approaches Based on Linear and Nonlinear Discretization Schemes	129
6.2.1	The Volume Balance Procedure of Schumann	129
6.2.2	The Kawamura-Kuwahara Scheme	130
6.2.3	The Piecewise-Parabolic Method	131
6.2.4	The Flux-Corrected-Transport Method	132
6.2.5	The MPDATA Method	136
6.2.6	The Optimum Finite-Volume Scheme	138
6.3	Implicit LES by Adaptive Local Deconvolution	140
6.3.1	Fundamental Concept of ALDM	140
6.3.2	ALDM for the Incompressible Navier-Stokes Equations ..	143
6.3.3	ALDM for the Compressible Navier-Stokes Equations ..	148
7	Boundary Conditions for Large-Eddy Simulation of	
	Compressible Flows	155
7.1	Introduction	155
7.2	Wall Modeling for Compressible LES	156
7.2.1	Statement of the Problem	156
7.2.2	Wall Boundary Conditions in the Kovasznay Decomposition Framework: an Insight	156
7.2.3	Turbulent Boundary Layer: Vorticity and Temperature Fields	159
7.2.4	Turbulent Boundary Layer: Acoustic Field	163
7.2.5	Consequences for the Development of Compressible Wall Models	169
7.2.6	Extension of Existing Wall Models for Incompressible Flows	170
7.3	Unsteady Turbulent Inflow Conditions for Compressible LES ..	172
7.3.1	Fundamentals	172
7.3.2	Precursor Simulation: Advantages and Drawbacks	174

7.3.3	Extraction-Rescaling Techniques	175
7.3.4	Synthetic-Turbulence-Based Models.....	179
8	Subsonic Applications with Compressibility Effects	185
8.1	Homogeneous Turbulence.....	185
8.1.1	Context	185
8.1.2	A Few Realizations	186
8.1.3	Influence of the Numerical Method	187
8.1.4	SGS Modeling	190
8.2	Channel Flow	191
8.2.1	Context	191
8.2.2	A Few Realizations	191
8.2.3	Influence of the Numerical Method	192
8.2.4	Influence of the SGS Model	194
8.3	Mixing Layer	195
8.3.1	Context	195
8.3.2	A Few Realizations	195
8.3.3	Influence of the Numerical Method	196
8.3.4	Influence of the SGS Model	197
8.4	Boundary-Layer Flow	198
8.4.1	Context	198
8.4.2	A Few Realizations	198
8.5	Jets.....	200
8.5.1	Context	200
8.5.2	A Few Realizations	201
8.5.3	Influence of the Numerical Method	202
8.5.4	Influence of the SGS Model	204
8.5.5	Physical Analysis.....	205
8.6	Flows over Cavities	206
8.6.1	Context	206
8.6.2	A Few Realizations	206
8.6.3	Influence of the Numerical Method	207
8.6.4	Influence of the SGS Model	208
8.6.5	Physical Analysis.....	208
9	Supersonic Applications	211
9.1	Homogeneous Turbulence.....	211
9.2	Channel Flow	212
9.2.1	Context	212
9.2.2	A Few Realizations	212
9.2.3	Influence of the Numerical Method	213
9.2.4	Influence of the Grid Resolution.....	214
9.2.5	Influence of the SGS Model	215
9.3	Boundary Layers	215
9.3.1	Context	215

9.3.2	A Few Realizations	216
9.3.3	Influence of the Numerical Method	216
9.3.4	Influence of the Grid Resolution	217
9.3.5	SGS Modeling	219
9.4	Jets	220
9.4.1	Context	220
9.4.2	A Few Realizations	220
9.4.3	Influence of the Numerical Method	221
9.4.4	Influence of the SGS Model	221
9.4.5	Physical Analysis	221
10	Supersonic Applications with Shock-Turbulence	
	Interaction	223
10.1	Shock-Interaction with Homogeneous Turbulence	224
10.1.1	Phenomenology of Shock-Interaction with Homogeneous Turbulence	224
10.1.2	LES of Shock-Interaction with Homogeneous Turbulence	228
10.2	Shock-Turbulence Interaction in Jets	230
10.2.1	Phenomenology of Shock-Turbulence Interaction in Jets	230
10.2.2	LES of Shock-Turbulence Interaction in Jets	231
10.3	Shock-Turbulent-Boundary-Layer Interaction	233
10.3.1	Phenomenology of Shock-Turbulent-Boundary-Layer Interaction	233
10.3.2	LES of Compression-Ramp Configurations	237
	References	255
	Index	273