

Contents

1	Numerical Simulation of Fluid Flows.	1
1.1	Introduction	1
1.2	Overview of Fluid Flow Simulations	2
1.3	Governing Equations of Fluid Flows	4
1.3.1	Conservation Laws	4
1.3.2	Closure of the Governing Equations	6
1.3.3	Divergence and Gradient Forms	7
1.3.4	Indicial Notation	9
1.3.5	Governing Equations of Incompressible Flow	10
1.3.6	Properties of Partial Differential Equations	13
1.4	Grids for Simulating Fluid Flows	14
1.5	Discretization Methods	17
1.6	Verification and Validation	18
1.7	Remarks	19
1.8	Exercises.	20
	References.	21
2	Finite-Difference Discretization of the Advection-Diffusion Equation.	23
2.1	Introduction	23
2.2	Advection-Diffusion Equation.	24
2.3	Finite-Difference Approximation.	25
2.3.1	Taylor Series Expansion	26
2.3.2	Polynomial Approximation	32
2.3.3	Central Difference at Midpoints.	35
2.3.4	Compatibility of Finite Differencing	36
2.3.5	Spatial Resolution	38
2.3.6	Behavior of Discretization Error	42
2.4	Time Stepping Methods	47
2.4.1	Single-Step Methods	47
2.4.2	Multi-Step Methods.	50

2.5	Stability Analysis	51
2.5.1	Stability of Time Stepping Methods	52
2.5.2	von Neumann Analysis	54
2.5.3	Stability of the Discrete Advection Equation	55
2.5.4	Stability of the Discrete Diffusion Equation	57
2.5.5	Stability of the Discrete Advection-Diffusion Equation	59
2.5.6	Time Step Constraints for Advection and Diffusion	62
2.5.7	Amplitude and Phase Errors	64
2.6	Higher-Order Finite Difference	65
2.7	Consistency of Finite-Difference Methods	67
2.8	Remarks	68
2.9	Exercises.	69
	References.	72
3	Numerical Simulation of Incompressible Flows.	73
3.1	Introduction	73
3.2	Time Stepping for Incompressible Flow Solvers.	73
3.3	Incompressible Flow Solvers	76
3.3.1	Fractional-Step (Projection) Method	77
3.3.2	Simplified MAC (SMAC) Method	78
3.3.3	Highly Simplified MAC (HSMAC) Method and Semi-Implicit Method for Pressure Linked Equation (SIMPLE).	79
3.3.4	Accuracy and Stability of Time Stepping	80
3.3.5	Summary of Time Stepping for Incompressible Flow Solvers	82
3.4	Spatial Discretization of Pressure Gradient Term	87
3.4.1	Pressure Poisson Equation.	87
3.4.2	Iterative Method for the Pressure Poisson Equation. . . .	92
3.4.3	Iterative Method for HSMAC Method.	99
3.5	Spatial Discretization of Advection Term.	100
3.5.1	Compatibility and Conservation	101
3.5.2	Discretization on Nonuniform Grids	107
3.5.3	Upwinding Schemes	110
3.6	Spatial Discretization of Viscous Term.	114
3.7	Summary of the Staggered Grid Solver	118
3.8	Boundary and Initial Conditions.	120
3.8.1	Boundary Setup.	120
3.8.2	Solid Wall Boundary Condition	123
3.8.3	Inflow and Outflow Boundary Conditions.	128
3.8.4	Far-Field Boundary Condition.	133
3.8.5	Initial Condition	135

3.9	High-Order Accurate Spatial Discretization	136
3.9.1	High-Order Accurate Finite Difference	136
3.9.2	Compatibility of High-Order Finite Differencing of Advective Term	137
3.9.3	Boundary Conditions for High-Order Accurate Schemes	139
3.10	Remarks	141
3.11	Exercises.	141
	References.	144
4	Incompressible Flow Solvers for Generalized Coordinate System . . .	147
4.1	Introduction	147
4.2	Selection of Basic Variables.	148
4.3	Strong Conservation Form of the Governing Equations	150
4.3.1	Strong Conservation Form.	150
4.3.2	Mass Conservation	151
4.3.3	Momentum Conservation.	151
4.4	Basic Variables and Coordinate System	153
4.5	Incompressible Flow Solvers Using Collocated Grids.	157
4.6	Spatial Discretization of Pressure Gradient Term	160
4.6.1	Pressure Gradient Term.	160
4.6.2	Pressure Poisson Equation.	163
4.6.3	Iterative Solver for the Pressure Poisson Equation.	165
4.7	Spatial Discretization of Advection Term.	166
4.7.1	Compatibility and Conservation	166
4.7.2	Upwinding Schemes	168
4.8	Spatial Discretization of Viscous Term.	170
4.9	Boundary Conditions	170
4.10	High-Order Accurate Spatial Discretization	172
4.11	Evaluation of Coordinate Transform Coefficients	173
4.12	Remarks	175
4.13	Exercises.	176
	References.	177
5	Immersed Boundary Methods	179
5.1	Introduction	179
5.2	Continuous Forcing Approach	180
5.2.1	Discrete Delta Functions	182
5.2.2	Original Immersed Boundary Method	188
5.2.3	Immersed Boundary Projection Method.	190
5.3	Discrete Forcing Approach	193
5.3.1	Direct Forcing Method	193
5.3.2	Consistent Direct Forcing Method.	194
5.3.3	Cut-Cell Immersed Boundary Method.	197

5.4	Applications of Immersed Boundary Methods	198
5.4.1	Flow Around a Circular Cylinder	199
5.4.2	Turbulent Flow Through a Nuclear Rod Bundle	199
5.5	Remarks	201
5.6	Exercises.	202
	References.	204
6	Numerical Simulation of Turbulent Flows.	207
6.1	Introduction	207
6.2	Direct Numerical Simulation of Turbulent Flows	208
6.2.1	Reynolds Number	208
6.2.2	Full Turbulence Simulation	210
6.2.3	Direct Numerical Simulation of Turbulence	212
6.2.4	Turbulence Simulation with Low Grid Resolution.	213
6.3	Representation of Turbulent Flows	218
6.3.1	Turbulence Models	218
6.3.2	Governing Equations for Turbulent Flow	220
6.3.3	Turbulence Modeling Approaches	221
6.3.4	Visualization of Vortical Structures	222
6.3.5	Coherent Structure Function	225
6.3.6	Rotational Invariance.	226
6.3.7	Modal Decomposition of Turbulent Flows	227
6.4	Remarks	231
6.5	Exercises.	232
	References.	233
7	Reynolds-Averaged Navier–Stokes Equations	237
7.1	Introduction	237
7.2	Reynolds-Averaged Equations	237
7.2.1	Reynolds Average	237
7.2.2	Reynolds Stress Equation	239
7.3	Modeling of Eddy Viscosity	241
7.4	k - ε Model	246
7.4.1	Treatment of Near-Wall Region	249
7.4.2	Computational Details of the k - ε Model	252
7.4.3	Features and Applications of the k - ε Model	254
7.5	Other Eddy-Viscosity Models	256
7.6	Reynolds Stress Equation Model	259
7.6.1	Basic Form of the Stress Equation	259
7.6.2	Features of the Stress Equation Model	263
7.7	Remarks	263
7.8	Exercises.	265
	References.	267

8 Large-Eddy Simulation	269
8.1 Introduction	269
8.2 Governing Equations for LES.	269
8.2.1 Filtering.	270
8.2.2 Governing Equations for Large-Eddy Simulation	274
8.3 Smagorinsky Model	276
8.3.1 Local Equilibrium and Eddy-Viscosity Assumptions.	276
8.3.2 Derivation of the Smagorinsky Model.	277
8.3.3 Properties of the Smagorinsky Model	278
8.3.4 Modification in the Near-Wall Region.	279
8.4 Scale-Similarity Model	282
8.4.1 Bardina Model.	282
8.4.2 Mixed Model.	283
8.5 Dynamic Model	284
8.5.1 Dynamic Eddy-Viscosity Model	285
8.5.2 Extensions of the Dynamic Model	288
8.6 Other SGS Eddy-Viscosity Models.	289
8.6.1 Structure Function Model	289
8.6.2 Coherent Structure Model	290
8.6.3 One-Equation SGS Model.	292
8.7 Numerical Methods for Large-Eddy Simulation	294
8.7.1 Computation of SGS Eddy Viscosity	294
8.7.2 Implementation of Filtering.	297
8.7.3 Boundary and Initial Conditions	300
8.7.4 Influence of Numerical Accuracy	302
8.8 Remarks	303
8.9 Exercises.	305
References.	306
Appendix A: Generalized Coordinate System	309
Appendix B: Fourier Analysis of Flow Fields	325
Appendix C: Modal Decomposition Methods	339
Index	353

Computational Fluid Dynamics

Incompressible Turbulent Flows

Kajishima, T.; Taira, K.

2017, XV, 358 p. 107 illus., Hardcover

ISBN: 978-3-319-45302-6