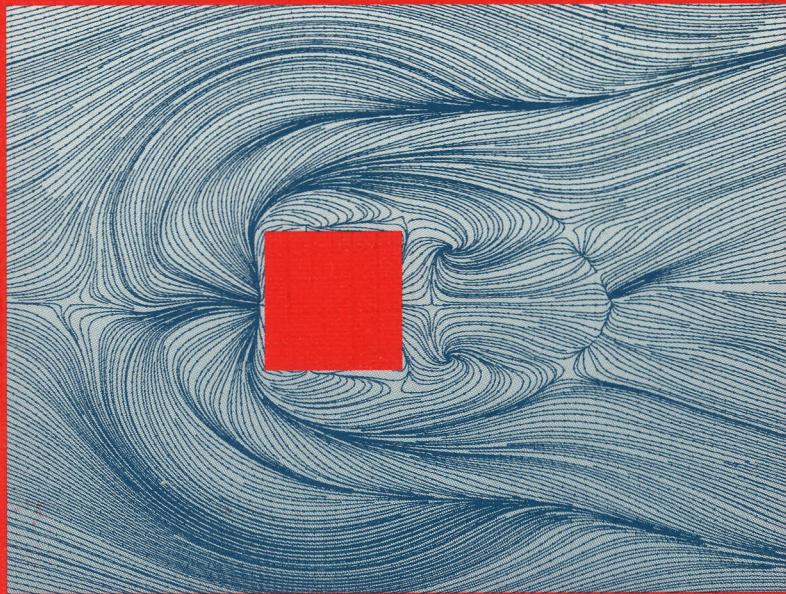


Joel H. Ferziger · Milovan Perić

Computational Methods for Fluid Dynamics



Springer

J. H. Ferziger · M. Perić

Computational Methods for Fluid Dynamics

With 95 Figures

312/3895 INSTITUT
FÜR METEOROLOGIE U. KLIMATOLOGIE
UNIVERSITÄT HANNOVER
HERRENHÄUSER STR. 2 · 30419 HANNÖVER



Springer

Table of Contents

Preface	V
1. Basic Concepts of Fluid Flow	1
1.1 Introduction	1
1.2 Conservation Principles	3
1.3 Mass Conservation	4
1.4 Momentum Conservation	5
1.5 Conservation of Scalar Quantities	9
1.6 Dimensionless Form of Equations	11
1.7 Simplified Mathematical Models	12
1.7.1 Incompressible Flow	12
1.7.2 Inviscid (Euler) Flow	13
1.7.3 Potential Flow	13
1.7.4 Creeping (Stokes) Flow	14
1.7.5 Boussinesq Approximation	14
1.7.6 Boundary Layer Approximation	15
1.7.7 Modeling of Complex Flow Phenomena	15
1.8 Mathematical Classification of Flows	16
1.8.1 Hyperbolic Flows	17
1.8.2 Parabolic Flows	17
1.8.3 Elliptic Flows	17
1.8.4 Mixed Flow Types	18
1.9 Plan of This Book	18
2. Introduction to Numerical Methods	21
2.1 Approaches to Fluid Dynamical Problems	21
2.2 What is CFD?	23
2.3 Possibilities and Limitations of Numerical Methods	23
2.4 Components of a Numerical Solution Method	25
2.4.1 Mathematical Model	25
2.4.2 Discretization Method	25
2.4.3 Coordinate and Basis Vector Systems	26
2.4.4 Numerical Grid	26
2.4.5 Finite Approximations	30

X Table of Contents

2.4.6	Solution Method	30
2.4.7	Convergence Criteria	30
2.5	Properties of Numerical Solution Methods	31
2.5.1	Consistency	31
2.5.2	Stability	31
2.5.3	Convergence	32
2.5.4	Conservation	32
2.5.5	Boundedness	33
2.5.6	Realizability	33
2.5.7	Accuracy	34
2.6	Discretization Approaches	35
2.6.1	Finite Difference Method	35
2.6.2	Finite Volume Method	35
2.6.3	Finite Element Method	36
3.	Finite Difference Methods	39
3.1	Introduction	39
3.2	Basic Concept	39
3.3	Approximation of the First Derivative	42
3.3.1	Taylor Series Expansion	42
3.3.2	Polynomial Fitting	46
3.4	Approximation of the Second Derivative	47
3.5	Approximation of Mixed Derivatives	50
3.6	Approximation of Other Terms	50
3.7	Implementation of Boundary Conditions	50
3.8	An Introduction to Spectral Methods	52
3.8.1	Basic Concept	52
3.8.2	Another View of Discretization Error	53
3.9	The Algebraic Equation System	55
3.10	Discretization Errors	58
3.11	Example	60
4.	Finite Volume Methods	67
4.1	Introduction	67
4.2	Approximation of Surface Integrals	68
4.3	Approximation of Volume Integrals	70
4.4	Interpolation Practices	72
4.4.1	Upwind Interpolation (UDS)	72
4.4.2	Linear Interpolation (CDS)	73
4.4.3	Quadratic Upwind Interpolation (QUICK)	74
4.4.4	Higher-Order Schemes	75
4.4.5	Other Schemes	76
4.5	Deferred Correction	76
4.6	Implementation of Boundary Conditions	77
4.7	The Algebraic Equation System	77

4.8 Examples	78
5. Solution of Linear Equation Systems	85
5.1 Introduction	85
5.2 Direct Methods	86
5.2.1 Gauss Elimination	86
5.2.2 LU Decomposition	88
5.2.3 Tridiagonal Systems	89
5.2.4 Cyclic Reduction	90
5.3 Iterative Methods	91
5.3.1 Basic Concept	91
5.3.2 Convergence	92
5.3.3 Some Basic Methods	94
5.3.4 Incomplete LU Decomposition: Stone's Method	95
5.3.5 ADI and Other Splitting Methods	99
5.3.6 Conjugate Gradient Methods	101
5.3.7 Biconjugate Gradients and CGSTAB	104
5.3.8 Multigrid Methods	106
5.3.9 Other Iterative Solvers	110
5.4 Coupled Equations and Their Solution	110
5.4.1 Simultaneous Solution	111
5.4.2 Sequential Solution	111
5.5 Non-Linear Equations and their Solution	113
5.5.1 Newton-like Techniques	113
5.5.2 Other Techniques	115
5.6 Convergence Criteria	115
5.7 Examples	120
6. Methods for Unsteady Problems	127
6.1 Introduction	127
6.2 Methods for Initial Value Problems in ODEs	127
6.2.1 Two-Level Methods	127
6.2.2 Predictor-Corrector and Multipoint Methods	130
6.2.3 Runge-Kutta Methods	132
6.2.4 Other Methods	133
6.3 Application to the Generic Transport Equation	134
6.3.1 Explicit Methods	135
6.3.2 Implicit Methods	140
6.3.3 Other Methods	143
6.4 Examples	143

7. Solution of the Navier-Stokes Equations	149
7.1 Special Features of the Navier-Stokes Equations	149
7.1.1 Discretization of Convective and Viscous Terms	149
7.1.2 Discretization of Pressure Terms and Body Forces	150
7.1.3 Conservation Properties	152
7.2 Choice of Variable Arrangement on the Grid	156
7.2.1 Colocated Arrangement	157
7.2.2 Staggered Arrangements	158
7.3 Calculation of the Pressure	159
7.3.1 The Pressure Equation and its Solution	159
7.3.2 A Simple Explicit Time Advance Scheme	160
7.3.3 Implicit Pressure-Correction Methods	162
7.4 Other Methods	168
7.4.1 Fractional Step Methods	168
7.4.2 Streamfunction-Vorticity Methods	170
7.4.3 Artificial Compressibility Methods	172
7.5 Solution Methods for the Navier-Stokes Equations	176
7.5.1 Implicit Scheme Using Pressure-Correction and a Staggered Grid	176
7.5.2 Treatment of Pressure for Colocated Variables	184
7.5.3 SIMPLE Algorithm for a Colocated Variable Arrangement	188
7.6 Note on Pressure and Incompressibility	191
7.7 Boundary Conditions for the Navier-Stokes Equations	192
7.8 Examples	195
8. Complex Geometries	205
8.1 The Choice of Grid	205
8.1.1 Stepwise Approximation Using Regular Grids	205
8.1.2 Overlapping Grids	206
8.1.3 Boundary-Fitted Non-Orthogonal Grids	207
8.2 Grid Generation	207
8.3 The Choice of Velocity Components	209
8.3.1 Grid-Oriented Velocity Components	209
8.3.2 Cartesian Velocity Components	210
8.4 The Choice of Variable Arrangement	210
8.4.1 Staggered Arrangements	211
8.4.2 Colocated Arrangement	212
8.5 Finite Difference Methods	212
8.6 Finite Volume Methods	215
8.6.1 Approximation of Convective Fluxes	215
8.6.2 Approximation of Diffusive Fluxes	217
8.6.3 Approximation of Source Terms	223
8.6.4 Three-Dimensional Grids	224
8.6.5 Unstructured Grids	225

8.7	Control-Volume-Based Finite Element Methods	226
8.8	Pressure-Correction Equation	228
8.9	Axisymmetric Problems	233
8.10	Implementation of Boundary Conditions	235
8.10.1	Inlet	236
8.10.2	Outlet	236
8.10.3	Impermeable Walls	237
8.10.4	Symmetry Planes	239
8.10.5	Specified Pressure	239
8.11	Examples	240
9.	Turbulent Flows	247
9.1	Introduction	247
9.2	Direct Numerical Simulation (DNS)	249
9.2.1	Example: Spatial Decay of Grid Turbulence	255
9.3	Large Eddy Simulation (LES)	257
9.3.1	Smagorinsky and Related Models	258
9.3.2	Dynamic Models	260
9.3.3	Example: Flow Over a Wall-Mounted Cube	262
9.4	RANS Models	264
9.4.1	Reynolds Averaged Navier-Stokes (RANS) Equations .	265
9.4.2	Simple Turbulence Models and their Application . .	267
9.4.3	Example: Flow Around a Valve	273
9.5	Reynolds Stress Models	275
10.	Compressible Flow	277
10.1	Introduction	277
10.2	Pressure-Correction Methods for Arbitrary Mach Number .	278
10.2.1	Pressure–Velocity–Density Coupling	279
10.2.2	Boundary Conditions	283
10.2.3	Examples	287
10.3	Methods Designed for Compressible Flow	292
10.3.1	An Overview of Some Specific Methods	293
11.	Efficiency and Accuracy Improvement	297
11.1	Multigrid Methods for Flow Calculation	297
11.2	Adaptive Grid Methods and Local Grid Refinement . .	305
11.3	Parallel Computing in CFD	309
11.3.1	Iterative Schemes for Linear Equations	309
11.3.2	Domain Decomposition in Space	312
11.3.3	Domain Decomposition in Time	315
11.3.4	Efficiency of Parallel Computing	316

XIV Table of Contents

12. Special Topics	321
12.1 Moving Grids	321
12.2 Free Surface Flows.....	327
12.3 Heat Transfer	335
12.4 Flow With Variable Fluid Properties	337
12.5 Meteorological and Oceanographic Applications.....	338
12.6 Combustion	339
A. Appendeces	341
A.1 List of Computer Codes and How to Access Them	341
A.2 List of Frequently Used Abbreviations	342