

Table of Contents

Preface and Acknowledgments	1
1 Introductory comments and summary	3
1.1 Introduction	3
1.2 Summary of the chapters	4
1.3 Conclusions	7
2 Finite differences	8
2.1 Introduction	8
2.2 Difference operators	8
2.2.1 Space discretization	8
2.2.2 Non-uniform grids	10
2.2.3 Coordinate transformations	12
2.2.3a Two walls clustering	12
2.2.3b Uniform in the center, stretched in the far field	12
2.2.3c Clustered in the center	13
2.2.3d Clustered around two inner regions	13
2.2.3e Clustered near two walls and at the center	14
2.2.3f Clustered in one region and stretched elsewhere	14
2.2.4 Non-uniform grids boundary conditions	15
2.3 Parabolic equations in time	18
2.3.1 Crank–Nicholson implicit scheme	19
2.3.2 Adams–Bashfort explicit	20
2.3.3 Low storage third–order Runge–Kutta Explicit	20
2.3.4 Hybrid third–order Runge–Kutta/Crank–Nicholson	22
2.3.5 Third order Runge–Kutta <i>vs</i> Adams–Bashfort.	23
2.4. FFT for elliptic partial differential equations.	24
2.4.1 Solution by FFT	25
2.4.2 Two periodic directions	26
2.4.3 sinFFT	29
2.4.4 cosFFT centered	31
2.4.5 cosFFT ”staggered”	32
2.5 Multigrid methods for elliptic partial differential equations	34
2.5.1 Multigrid method	34
2.6 Conclusions	39
3 The Burgers equation	40
3.1 Physical considerations	40
3.2 Spatial discretization	44
3.3 Time discretization	44
3.4 Results	45
3.5 Conclusions	48
4 Two-dimensional flows in Cartesian coordinates	51
4.1. Introduction	51

4.2	The equations in vorticity-streamfunction formulation	51
4.3	Vorticity boundary conditions	52
4.3a	Periodicity	52
4.3b	Free-slip	52
4.3c	No-slip	52
4.3d	Outlet	53
4.4	Streamfunction boundary conditions	54
4.5	Physical aspects of nonlinear terms	55
4.6	Arakawa's scheme	57
4.7	Nonlinear terms in primitive variables	58
4.8	Viscous terms and factorization	60
4.9	Boundary conditions	61
4.10	Test of ω, ψ formulation	62
4.11	Code PSOMGBC	63
4.11a	Input data	64
4.11b	Initial conditions	66
4.11b.a	Lamb dipole	66
4.11b.b	Stern dipole	67
4.11b.c	Isolated vortex	67
4.11b.d	Monopole in a β plane	68
4.11b.e	Flow near a coast with topography slopes	69
4.11b.f	Time developing mixing layer	69
4.11b.g	Space developing mixing layer	69
4.12	Results by the code <i>PSOMGBC</i>	70
4.12.1	General suggestion	70
4.12.2	Flow phenomena simulations	71
4.12.2a	Lamb dipoles	71
4.12.2b	Modons	75
4.12.2c	Tripoles	77
4.12.2d	Monopoles in a β plane	79
4.12.2e	Flow over topographic slopes	81
4.12.2f	Time developing mixing layers	82
4.12.2g	Roll-up	84
4.12.2h	The pairing	85
4.12.2i	Arakawa scheme effects	86
4.12.2j	Space developing mixing layer s	90
4.13	Conclusions	91
5	Two-dimensional flows in general curvilinear coordinates	93
5.1	Introduction	93
5.2	Equations	94
5.3	Laplacian discretization	96
5.4	Nonlinear terms discretization	97
5.5	Boundary conditions	98
5.6	Time discretization	98

5.7 Code PSOMCUR	99
5.8 Results	102
5.8a Inviscid dipole moving close to a bump	102
5.8b Dipole impinging a semicircular cavity	104
5.8c Stream around a Gaussian hill	106
5.9 Conclusions	108
6 Two-dimensional turbulence	110
6.1. Introduction	110
6.2 Arakawa fourth order scheme	110
6.3 Initial conditions	111
6.4 Code <i>TURB2D</i>	112
6.5 Results	114
6.5.1 Resolution check	114
6.5.2 Global conservation properties	116
6.6 Conclusions	117
7 Axisymmetric flows	119
7.1 Introduction	119
7.2 Equations for the vorticity formulation	119
7.3 Results	121
7.3a Vortex ring formation	121
7.3b Vortex ring in the presence of solid body rotation	127
7.3c Vortex rings impacting free-slip walls	131
7.3d Vortex rings impacting no-slip walls	135
7.3e Space developing coaxial jet	138
7.4 Conclusions	143
8 Three-dimensional flows with three periodic directions	145
8.1 Introduction	145
8.2 Governing equations	146
8.3 Space and time discretization	146
8.4 Discretization of the non-linear terms	147
8.5 Fractional step	148
8.6 Factorization in the \hat{u}_i equations	150
8.7 Solution of the Poisson equation for ϕ	151
8.8 Initial conditions	152
8.8.1 Isotropic turbulence	152
8.8.2 Lamb dipole stability	153
8.9 Numerical checks of the code <i>ISO</i>	154
8.10 Definition of turbulent quantities	157
8.11 Isotropic turbulence with and without rotation	159
8.11a Isotropic turbulence	160
8.11b Isotropic turbulence subjected to uniform rotation	161
8.12 Physics of turbulence from data	165
8.12.a Correlation tensor	166
8.12.b Probability Density Functions	168

8.12.b.1 PDF of velocity and vorticity components	170
8.12.b.2 PDF of pressure field	170
8.12.b.3 PDF of angle between velocity and vorticity vectors	173
8.12.b.4 Velocity structure functions	175
8.13 Stability of the Lamb dipole to three dimensional disturbances	181
8.14 Conclusions	187
9 Flows with walls in Cartesian coordinates	188
9.1 Introduction	188
9.2 Adimensionalization	191
9.3 Space and time discretization	192
9.4 Initial conditions	196
9.5 Wall boundaries for turbulence control	196
9.6 Definition of turbulent quantities	197
9.7 Check of the code <i>CHADS</i>	198
9.8 Wall-boundary conditions effects	201
9.9 Analysis of the data	204
9.9a Velocity statistics	205
9.9b Vorticity statistics	206
9.9c Production and dissipation rate	207
9.9d Velocity vorticity tensor	208
9.9e Velocity vorticity spectra	213
9.9f Velocity and vorticity cospectra	217
9.9g Velocity and vorticity two-point correlations	218
9.9h Joint PDF of velocity and vorticity correlations in one point	221
9.9i Vortex stretching	222
9.9j Budget in the one-point closure equations	225
9.10 Conclusions	229
10 Flows in cylindrical coordinates with one wall	231
10.1 Introduction	231
10.2 Governing equations	232
10.3. Numerical method	234
10.4. Treatment of the axis	237
10.5 Code informations	238
10.5a Calculation of \hat{q}_i (first step)	238
10.5b Calculation of q_i^{n+1} (second step)	239
10.5c Initial conditions	240
10.6 Results	241
10.6a Check of axis accuracy	241
10.6b Check of energy conservation	241
10.6c Turbulent non-rotating pipe, coarse solution	243
10.6b Turbulent rotating pipe, coarse solution	246
10.7 Conclusions	252
11 Flows in cylindrical coordinates with two walls	253
11.1 Introduction	253

11.2	Governing equations and numerical model	254
11.3	Code general informations	257
11.3a	Description of the file tr3dnuma.f	258
11.3b	Description of the file fr3dnuge.f	258
11.3c	Description of the file tr3dnuco.f	259
11.3d	Description of the file tr3dnuintr.f	259
11.3e	Description of the file tr3dnuinri.f	259
11.3f	Description of the file tr3dnuhn.f	260
11.3g	Description of the file tr3dnutn.f	260
11.3h	Description of the file tr3dnutr.f	261
11.3i	Description of the file tr3dnutu.f	261
11.3j	Description of the file tr3dnuio.f	261
11.4	Results	261
11.4a	Three-dimensional tripole formation	262
11.4b	Three-dimensional impact of a vortex ring on a wall.	268
11.5	Conclusions	272
12	Large eddy simulations	275
12.1.	Introduction	275
12.2.	Filtering	277
12.3.	Equations	278
12.4.	Subgrid models	280
12.4a	Smagorinsky model for the residual stress	280
12.4b	Structure function model	281
12.4c	Dynamic subgrid model	282
12.4d	Similarity scale models	283
12.5	Equations for density-Related problems	284
12.6	Subgrid model for thermal flows	285
12.7	Code informations	288
12.7a	Description of the file isolesma.f	288
12.7b	Description of the file isolesnn.f	289
12.7c	Description of the file isoleshn.f	289
12.7d	Description of the file isoletn.f	289
12.7e	Description of the file isoletnsi.f	290
12.7f	Description of the file isolesintu.f	290
12.7g	Description of the file isolesinsi.f	290
12.7h	Description of the file isolesph.f	290
12.7i	Description of the file isolessp.f	290
12.7j	Description of the file isolessst.f	290
12.7k	Description of the file isolestr.f	290
12.7l	Description of the file isolesio.f	291
12.7m	Description of the file isolesiosif	291
12.7n	Subgrid-models	291
12.8	Results	291
12.8a	Grid turbulence at intermediate R_λ	291

12.8b Isotropic turbulence at high R_λ	296
12.8c Isotropic turbulence with a passive scalar	298
12.8d Buoyancy-generated turbulence	300
12.8e Turbulence with buoyancy and stratification	306
12.9 Conclusions	310
13 Large eddy simulations of wall-bounded flows	312
13.1. Introduction	312
13.2. Equations	312
13.3. Results	314
13.3.a Results at low Reynolds number	315
13.3.a Results at high Reynolds numbers	319
13.4 Conclusions	325
References	326
Diskette information	347
Plates Section	349