

THEORY AND COMPUTATION OF HYDRODYNAMIC STABILITY

W. O. CRIMINALE, T. L. JACKSON, R. D. JOSLIN



CAMBRIDGE
UNIVERSITY PRESS

Contents

<i>Figures</i>	<i>page</i> x
<i>Tables</i>	xix
<i>Preface</i>	xxi
1 Introduction and problem formulation	1
1.1 History, background, and rationale	1
1.2 Initial-value concepts and stability bases	9
1.3 Classical treatment: modal expansions	12
1.4 Transient dynamics	17
1.5 Asymptotic behavior	18
1.6 Role of viscosity	19
1.7 Geometries of relevance	21
1.8 Spatial stability bases	22
2 Temporal stability of inviscid incompressible flows	24
2.1 General equations	24
2.1.1 Nondimensionalization	25
2.1.2 Mean plus fluctuating components	27
2.1.3 Linearized disturbance equations	27
2.1.4 Recourse to complex functions	31
2.1.5 Three-dimensionality	35
2.1.6 Squire transformation	37
2.2 Kelvin-Helmholtz theory	39
2.2.1 Interface conditions	40
2.3 Piecewise linear profile	42
2.3.1 Unconfined shear layer	42
2.3.2 Confined shear layer	45
2.4 Inviscid temporal theory	48
2.5 Critical layer concept	56

2.5.1	Reynolds shear stress	58
2.6	Continuous profiles	59
2.6.1	Hyperbolic tangent profile	60
2.6.2	Laminar mixing layer	63
2.7	Exercises	67
2.8	Appendix: numerical computation	73
3	Temporal stability of viscous incompressible flows	76
3.1	Discussion	76
3.2	Channel flows	77
3.2.1	Plane Poiseuille flow	77
3.2.2	Plane Couette flow	79
3.2.3	Generalized channel flow	82
3.3	Blasius boundary layer	84
3.4	Falkner-Skan flow family	86
3.5	Unbounded flows	88
3.6	Discrete and continuous spectra	90
3.7	Exercises	97
3.8	Appendix: compound matrix method	99
4	Spatial stability of incompressible flows	102
4.1	Discussion	102
4.2	Gaster's transformation	103
4.3	Incompressible inviscid flow	105
4.3.1	Hyperbolic tangent profile	105
4.3.2	Symmetric jet	108
4.3.3	Symmetric wake	110
4.4	Absolute and convective instabilities	116
4.4.1	Mixing layer revisited	120
4.5	Incompressible viscous flow	121
4.5.1	Spatial stability	121
4.5.2	Gaster transformation	122
4.5.3	Wave packets	124
4.6	Discrete and continuous spectra	125
4.7	Exercises	130
5	Stability of compressible flows	132
5.1	Introduction	132
5.2	Compressible mixing layer	133
5.2.1	Mean flow	136
5.2.2	Inviscid fluctuations	138
5.2.3	Linear stability	141

5.2.4	Compressible vortex sheet	149
5.2.5	Bounded compressible mixing layer	152
5.3	Compressible boundary layer	155
5.3.1	Mean flow	156
5.3.2	Inviscid fluctuations	161
5.3.3	Viscous fluctuations	166
5.4	Exercises	170
6	Centrifugal stability	173
6.1	Polar coordinates	173
6.2	Taylor problem	175
6.3	Görtler vortices	182
6.4	Pipe flow	184
6.5	Rotating disk	187
6.6	Trailing vortex	190
6.7	Round jet	192
6.8	Exercises	194
7	Geophysical flow	196
7.1	General properties	196
7.2	Stratified flow	197
7.3	Effects of rotation	213
7.4	The Ekman layer	220
7.5	Exercises	227
8	Transient dynamics	229
8.1	The Initial-Value problem	229
8.2	Laplace transforms	233
8.3	Moving coordinates and exact solutions	236
8.4	Multiple scale, multiple time analysis	244
8.5	Numerical solution of governing partial differential equations	248
8.5.1	Channel flows	248
8.5.2	Blasius boundary layer	250
8.6	Optimizing initial conditions	252
8.6.1	Perturbation energy	252
8.6.2	Optimization scheme	257
8.6.3	Concluding remarks	260
8.7	Exercises	261
9	Nonlinear stability	263
9.1	Energy equation	263
9.2	Weakly nonlinear theory	265
9.3	Secondary instability theory	267

9.4	Resonant wave interactions	276
9.5	PSE theory	283
9.6	Exercises	289
10	Transition and receptivity	291
10.1	Introduction	291
10.2	Influence of free stream turbulence and receptivity	291
10.3	Tollmien-Schlichting breakdown	295
10.4	Oblique wave breakdown	296
10.5	Crossflow vortex breakdown	299
10.6	Dean-Taylor-Görtler vortex breakdown	303
10.7	Transition prediction	305
10.7.1	Granville criterion	307
10.7.2	C1 and C2 criteria	307
10.7.3	Linear Stability Theory and e^N	308
10.7.4	Parabolized stability equations theory	316
10.7.5	Transition prediction coupled to turbulence modeling	317
10.8	Exercises	319
11	Direct numerical simulation	320
11.1	Introduction	320
11.2	Governing equations	320
11.3	Temporal DNS formulation	324
11.4	Spatial DNS formulation	325
11.4.1	Boundary and initial conditions	326
11.4.2	Time marching methods	329
11.4.3	Spatial discretization methods	331
11.4.4	Influence matrix method	332
11.5	Large eddy simulation	336
11.6	Applications	337
11.6.1	Tollmien-Schlichting wave propagation	337
11.6.2	Subharmonic breakdown	339
11.6.3	Oblique wave breakdown	340
11.6.4	Attachment line flow	343
11.7	Summary	351
11.8	Exercises	352
11.9	Appendix: numerical methods	354
11.9.1	Chebyshev series formulas	354
11.9.2	Other numerical tools	359
12	Flow control and optimization	362
12.1	Introduction	362

12.2	Effects of flexible boundaries	363
12.2.1	Primary wave model	364
12.2.2	Primary instability results	368
12.2.3	Secondary instability theory	374
12.3	Wave-induced forcing	378
12.4	Feed forward and feedback control	380
12.5	Optimal control theory	383
12.5.1	Optimization methodology	384
12.5.2	The state equations	385
12.5.3	The objective functional and the optimization problem	386
12.5.4	The adjoint system	387
12.5.5	The optimality conditions	391
12.5.6	Finite computational domains	392
12.5.7	The optimality system for channel flow	392
12.5.8	The optimality system for boundary layer flow	393
12.5.9	Numerical experiments	394
12.5.10	Summary	399
12.6	Exercises	399
13	Investigating hydrodynamic instabilities with experiments	401
13.1	Experimental facility	401
13.2	Model configuration	403
13.3	Inducing hydrodynamics instabilities	404
13.3.1	Natural disturbances	404
13.3.2	Artificial disturbances	404
13.4	Measurement instrumentation	405
13.4.1	Liquid crystals	405
13.4.2	Smoke wires	406
13.4.3	Bubbles and dyes	406
13.4.4	Thermo-anemometry	406
13.5	Signal analysis	408
13.6	Summary	409
<i>References</i>		410
<i>Author index</i>		434
<i>General index</i>		439