

Contents

Foreword	v
1 Introduction	1
2 Description of Flows at High Angles of Attack	8
2.1. The Finite Lifting Wing of Medium and High AR at Low Subsonic Speeds	10
2.2. The Low AR Rectangular Wing at Low Subsonic Speeds	12
2.3. The Slender Delta Type Wings	13
2.3.1. Sharp Edges Delta Wings at Low Subsonic Speeds	15
2.3.2. Spiral Type Separations on Delta Wings at Very High Angles of Attack at Low Speeds	16
2.3.3. Slender Delta Wings in Supersonic Flows	21
2.4. The Flow Over Elongated Slender Bodies	23
2.4.1. The Symmetric Vortex Flows over Slender Bodies in Subsonic Flows	23
2.4.2. The Asymmetric Vortex Flow over Slender Bodies in Subsonic Flow	25
2.4.3. Symmetric and Asymmetric Vortex Flows over Elongated Bodies in Supersonic Flows	30
2.5. Aircraft Type Configurations	34
2.5.1. Aircraft Aerodynamics Characteristics	35
2.5.1.1. Effects of Symmetrical Vortex Flows at Subsonic Speeds	35
2.5.1.2. Effects of Asymmetric Vortex Flows at Zero Sideslip in Subsonic Flow	35
2.5.1.3. Effect of LEX at High Angles of Attack at Subsonic Flow	41
2.5.1.4. Closed Coupled Canard-Wing Configurations at High Angles of Attack at Subsonic Flows	41
2.5.1.5. Effect of Sideslip at Subsonic Speeds	41
2.6. Vortex Breakdown	47
2.7. Nonsteady Aerodynamics at High Angles of Attack on Slender Configurations	52

2.8. Effect of Separation at High Angles of Attack in Hypersonic Flows	56
References	59
3 The Topology of Separating and Reattaching Vortical Flows	62
3.1. Equations for Vortical Flows	62
3.1.1. The Vorticity Transport Equation	63
3.1.2. The Biot-Savart Law	63
3.2. Topological Concepts for the Analysis of Vortical Flows	63
3.2.1. Attached and Separated Flows	64
3.2.2. The Equations for Surface Stream Lines and Surface Vortex Lines of Three-Dimensional Flows	68
3.2.3. The Characteristics of the Singular Point	68
3.2.4. Skin Friction Lines Near Separation in Three-Dimensional Flows	69
3.2.5. Rules of Topology Applied to Three-Dimensional Separated Flows	72
References	76
4 Linear Aerodynamics of Wings and Bodies	78
4.1. Equations for Potential Subsonic Flows	79
4.2. Equations for the Lifting Wing at Low Speeds	81
4.3. The Linear Panel Methods for the Calculation of the Subsonic Aerodynamic Coefficients for Wings and Bodies	84
4.3.1. The Multhop Method	84
4.3.2. The Surface-Source Distribution Method	85
4.3.3. The Linear Vortex Lattice Method	96
4.4. Low and High Order Linear Panel Methods for Subsonic and Supersonic Flows	99
4.4.1. Low Order Method - USSAERO	100
4.4.2. Low Order Method - Supersonic Linear VLM-VORLAX	103
4.4.3. High Order Method - PAN AIR	112
4.5. Comparison of the Various Panel Methods	119
References	127
5 Vortex Flows and the Rolled Up Vortex Wake	131
5.1. Vortex Core of the Rolled Up Wake	133
5.2. The Rolled Up Tip Vortices	134
5.3. The Rolling-Up of the Vortex Wake Behind Wings	135
5.3.1. The Rolling-Up of the Vortex Lines of the Zero Thickness Vortex Sheet	137
5.3.2. The Rolling-Up of a Finite Thickness Vortex Sheet	142
5.4. The "Bursting" of the Rolled Up Vortices	147
References	147

6 Nonlinear Aerodynamics of Wings and Bodies at High Angles of Attack	150
6.1. Analytical and Semi-Empirical Methods for Calculations of the Nonlinear Aerodynamic Characteristics	151
6.1.1. Cross Flow Model	151
6.1.2. Nonlinear Lifting Surface Theory for Low AR Wings	152
6.1.3. Leading Edge Vortex Models for Slender Delta Wing	158
6.1.3.1. Concentrated Line Vortices with Plane Feeding Sheet	159
6.1.3.2. The Spiral Vortex Sheet	163
6.1.4. Leading-Edge Suction Analogy	166
6.1.5. Semi-Empirical Correlation for the Nonlinear Lift of Low AR Wings	171
References	174
 7 The Nonlinear Panel Methods for Aircraft and Missile Configurations at High Angles of Attack	 177
7.1. The Nonlinear Vortex Lattice Method (NLVLM) for Subsonic Flows	180
7.1.1. Mathematical Formulation of the NLVLM	182
7.1.2. The Nonlinear Calculation Method for Lifting Surfaces	183
7.1.2.1. Calculations of the Source and Vortex Strengths Distributions and the Trajectories of the Free Vortices	183
7.1.2.2. Calculations of the Pressure Distribution and Aerodynamic Coefficients	185
7.1.2.3. Schemes for Division of Delta Wing Surfaces to Panels	186
7.1.2.4. The Relative Merit of the Various Panelling Schemes	187
7.1.3. Results of the NLVLM Calculations for Subsonic Flows	188
7.1.3.1. Rectangular and Trapezoidal Wings with or without Sweep	188
7.1.3.1.1. High Aspect Ratio Wings	189
7.1.3.1.2. Low Aspect Ratio Rectangular Wings	191
7.1.3.2. Delta Wings in Subsonic Flows	194
7.1.3.3. Multi Lifting Surfaces Configurations in Subsonic Flows	200
7.1.3.3.1. The Wing-Canard Configuration at Subsonic Speed	200
7.1.3.3.2. The Strake-Delta Wing Configuration at Subsonic Speed	206
7.1.4. Calculations of Subsonic Flows over Bodies at High Angles of Attack	210
7.1.4.1. The Position of Separation on Elongated Bodies	213
7.1.4.2. Calculation of the Aerodynamic Characteristics for Symmetric and Asymmetric Vortex Separation over Elongated Bodies	218

7.1.4.2.1. Symmetric Vortex Separation	218
7.1.4.2.2. Asymmetric Vortex Separation	223
7.2. The Free Vortex Sheet (FVS) Method for Subsonic Flows	226
7.2.1. The Theoretical Model	227
7.2.1.1. Method of Computation	230
7.2.2. Results of the FVS Method Calculations	233
7.2.2.1. Delta Wings	233
7.3. The NLVLM for Supersonic Flow	241
7.3.1. Method of Calculations	241
References	245
 8 Solutions of the Euler Equations for Flows over Configurations at High Angles of Attack	 249
8.1. The Euler Equations	250
8.2. Numerical Methods of Solution of the Euler Equations	251
8.2.1. Methods for Grid Generation	252
8.2.1.1. Grid Topology	253
8.2.1.2. Body Aligned Grid Systems	253
8.2.2. Finite Volume Methods	256
8.2.2.1. The Finite Volume Method of Jameson	256
8.2.2.1.1. Artificial Dissipation	258
8.2.2.1.2. Time Stepping	259
8.2.2.1.3. Methods of Accelerating Convergence to Steady State	260
8.2.2.1.4. Boundary Conditions	262
8.2.2.1.5. Mesh Generation Around Aircraft Configuration	262
8.2.2.2. The Finite Volume Method of Rizzi and Eriksson	263
8.2.2.2.1. Grid Generation	263
8.2.2.2.2. Numerical Procedure	265
8.2.2.2.3. The Trailing Edge Vorticity Generation – Kutta Condition	270
8.2.3. Finite Difference Methods	272
8.2.3.1. The Governing Equations	272
8.2.3.2. Numerical Solution Methods	273
8.2.3.3. Mesh Generation and Boundary Conditions	275
8.2.4. Finite Element Methods	276
8.2.4.1. Governing Equations	276
8.2.4.1.1. Artificial Dissipation Model	278
8.2.4.2. Mesh Generation	279
8.2.5. Multigrid Calculations with Cartesian Grids and Local Refinements	279
8.2.5.1. Numerical Scheme	280
8.2.5.2. Boundary Conditions	281
8.2.5.3. Computer Code	282

8.2.6. Results of Euler Computations on Three-Dimensional Configurations at High Angles of Attack	282
8.2.6.1. Delta Wings with Sharp and Rounded Edges	283
8.2.6.1.1. Calculation of Vortex Structure over Delta Wing	291
8.2.6.2. Strake-Wing-Body Configuration	293
8.2.6.3. Euler Solution Over Aircraft Missile Configuration	298
References	306
9 Solutions to the Navier-Stokes Equations for Flows over Configurations at High Angles of Attack	315
9.1. Formulation of the Navier-Stokes Equations	316
9.1.1. The Navier-Stokes Equations in Cartesian Coordinates	316
9.1.2. Nondimensional Navier-Stokes Equations in Generalized Curvilinear Coordinates	317
9.1.3. Thin-Layer Approximation	320
9.1.4. The Parabolized Navier-Stokes Equations	321
9.1.5. The Reynolds-Averaged Equations and Turbulence Models	322
9.2. Numerical Methods for Solutions of the Navier-Stokes Equations	326
9.2.1. Solution of the Compressible Navier-Stokes Equations by a Time-Dependent Method	327
9.3. Method of solution of the Thin-Layer Equations	327
9.4. Grid Topology, Boundary and Initial Conditions	329
9.5. Solutions of the Navier-Stokes Equations for Flows over Three-Dimensional Configurations at High Angles of Attack	330
9.5.1. Navier-Stokes Solutions for Flows over Elongated Axisymmetric Bodies at High Angles of Attack	331
9.5.1.1. Flow on Prolate Spheroid and Ellipsoid in Subsonic Flow	331
9.5.1.2. Flow on Pointed Axisymmetric Bodies	335
9.5.1.2.1. Subsonic Flow Solutions	336
9.5.1.2.2. Supersonic Flow Solutions	341
9.5.1.3. Flow over Delta and Strake-Delta Wings	345
9.5.1.3.1. Subsonic Flow Calculations	345
9.5.1.3.2. Supersonic flow calculations	352
9.5.1.4. Calculation of Vortex Breakdown on Delta Type Wings	357
9.5.1.5. Flow over Canard-Wing-Body Configuration	361
9.5.1.6. Calculations on Aircraft Configurations	365
References	378
Credits	385
Author Index	387
Subject Index	395