
Aerodynamics

L J CLANCY
M.Sc., F.I.M.A.,
C. Eng., A.F.R.Ae.S

PITMAN PUBLISHING

Contents

Preface	xv
Introduction	xvii
Chapter 1 The Atmosphere	1
1.1 Introduction	1
1.2 The International Standard Atmosphere	2
1.3 Local and stream characteristics	7
Chapter 2 Units and Dimensions	9
2.1 Introduction	9
2.2 Consistent systems of units	9
2.3 Dimensions	10
2.4 Dimensional analysis	11
2.5 Rayleigh's formula	13
Chapter 3 Bernoulli's Theorem	16
3.1 Introduction	16
3.2 Definitions	17
3.3 Equation of continuity	17
3.4 Bernoulli's theorem for incompressible flow	19
3.5 Static, total and dynamic pressure	21
3.6 Pressure coefficient	22
3.7 Flow through a venturi tube	22
3.8 Measurement of airspeed	23
3.9 Errors and corrections	25
3.10 Equation of motion	26
3.11 Isentropic flow	28
3.12 Total pressure, density, temperature	29
3.13 Measurement of airspeed at higher speeds	31
3.14 One-dimensional duct flow	32
Chapter 4 Fundamentals of Air Flow	34
4.1 Introduction	34
4.2 The circulation theory of lift	34

4.3	Circular cylinder without circulation	35
4.4	Circulation	36
4.5	Circular cylinder with circulation	37
4.6	Magnus effect	38
4.7	Flow past a two-dimensional aerofoil	39
4.8	The Kutta condition	39
4.9	The wake	41
4.10	The boundary layer and drag	42
4.11	Types of boundary layer	44
4.12	Transition	45
4.13	Reynolds number	46
4.14	Separation	47
4.15	Dimensional analysis and scale effect	49
4.16	Geometric and dynamic similarity	51
4.17	Critical Reynolds number	51
4.18	Compressibility effect	54
Chapter 5 Characteristics of Low-speed Aerofoils		55
5.1	Introduction	55
5.2	The aerofoil section	55
5.3	Aerodynamic forces and moments on an aerofoil	56
5.4	Force and moment coefficients	57
5.5	Pressure distributions	58
5.6	Variation of pressure distribution with incidence	62
5.7	The lift curve	64
5.8	Maximum lift coefficient	65
5.9	Profile drag	65
5.10	Pitching moment	67
5.11	Movement of the centre of pressure	71
5.12	Three-dimensional aerofoils—The finite wing	71
5.13	Geometrical characteristics of a finite wing	72
5.14	Spanwise flow variations	73
5.15	Lift and downwash	76
5.16	The lift curve of a finite wing	77
5.17	Induced drag	79
5.18	The total drag of a wing	82
5.19	Effect on aerodynamic characteristics of change in aspect ratio	83
5.20	Pitching moment	88
5.21	The complete aircraft	89
5.22	The lift coefficient in straight and level flight	89
5.23	Total drag	90
5.24	Effect of Reynolds number	91
5.25	Variation of drag in straight and level flight	91
5.26	The minimum power condition	95
5.27	Minimum drag-velocity ratio	96
5.28	The stall	97
5.29	The effect of wing section	97

5.30	The effect of planform	98
5.31	The effect of protuberances	100
Chapter 6 High-lift Devices		101
6.1	Introduction	101
6.2	The trailing edge flap	102
6.3	The plain flap	102
6.4	The split flap	104
6.5	The slotted flap	105
6.6	The Fowler flap	106
6.7	Comparison of different types of flap	106
6.8	Further general comments on trailing edge flaps	107
6.9	The leading edge slot	109
6.10	The leading edge flap	110
6.11	Boundary layer control	112
6.12	Boundary layer blowing	112
6.13	Boundary layer suction	113
6.14	The jet flap	114
Chapter 7 Incompressible Potential Flow		115
7.1	Introduction	115
7.2	Flux	116
7.3	Equation of continuity	116
7.4	Equation of a streamline	118
7.5	Examples	119
7.6	The stream function	124
7.7	Examples	126
7.8	The principles of superposition	127
7.9	Examples	128
7.10	Circulation	131
7.11	Vorticity	132
7.12	Examples	134
7.13	Irrotational flow	135
7.14	Other flows	135
7.15	The velocity potential	136
7.16	Examples	138
7.17	Flow past a solid body in a uniform stream	139
7.18	A half-body	140
7.19	Rankine oval	141
7.20	Flow past a circular cylinder without circulation	142
7.21	Circular cylinder with circulation	144
7.22	Complex potential	147
7.23	Examples	149
7.24	Theorem of Blasius	151
7.25	Example	154
7.26	Corollary to Blasius' theorem	155
7.27	Conformal transformation	158
7.28	The Joukowski transformation	159

7.29	Flow past a flat plate at incidence α	162
7.30	Other Joukowski aerofoils	164
7.31	Modified Joukowski transformation	168
Chapter 8 Low-speed Aerofoil and Wing Theory		170
8.1	Introduction	170
8.2	Glauert thin aerofoil theory	170
8.3	Lift	174
8.4	Chordwise load distribution	175
8.5	Pitching moment	175
8.6	Thin symmetrical aerofoil at zero incidence	176
8.7	Velocity distribution	178
8.8	General two-dimensional aerofoil	179
8.9	The finite wing	179
8.10	The horseshoe vortex	181
8.11	Lanchester–Prandtl lifting line theory	185
8.12	Lift	188
8.13	Induced drag	188
8.14	Minimum induced drag	189
8.15	Wing of symmetrical planform	191
8.16	Rectangular aerofoil	192
8.17	Example	193
8.18	Pitching moment	194
8.19	Tapered aerofoils	195
8.20	Twisted wings	196
8.21	Lifting surface theories	196
Chapter 9 Viscous Flow and Boundary Layers		200
9.1	Introduction	200
9.2	Flow past a thin flat plate at zero incidence	201
9.3	Drag on a flat plate at zero incidence	203
9.4	Flow through a pipe	204
9.5	Velocity distribution across a pipe	204
9.6	Laminar flow in pipes	206
9.7	Turbulent flow in a pipe	208
9.8	Equations of motion of a viscous fluid	210
9.9	Laminar boundary layer on a flat plate at zero incidence	213
9.10	Boundary layer thickness	216
9.11	The momentum integral equation	217
9.12	Example	220
9.13	Laminar boundary layer with pressure gradient—Pohhausen's method	223
9.14	Turbulent boundary layers	226
9.15	Turbulent boundary layer on a flat plate at zero incidence	228
Chapter 10 Compressible Flow		232
10.1	Introduction	232
10.2	The speed of sound	233

10.3	Thermodynamics and gas dynamics	235
10.4	The equation of state	235
10.5	The first law of thermodynamics	235
10.6	Reversible and irreversible processes	236
10.7	Enthalpy	237
10.8	Specific heat	237
10.9	Entropy	239
10.10	Irreversible processes	240
10.11	The energy equation in adiabatic flow	240
10.12	Isentropic flow relationships	242
10.13	Mach lines and waves	247
10.14	Simple wave flow	250
10.15	The Prandtl–Meyer expansion	253
10.16	Normal shock waves	257
10.17	Pressure, density and temperature changes across a normal shock wave	261
10.18	Oblique shock waves	263
10.19	Supersonic flow round a corner	267
10.20	Isentropic flow in a duct	268
10.21	Flow through a nozzle	271
Chapter 11 High-speed Aerofoils		274
11.1	Introduction	274
11.2	High-speed subsonic flow past an aerofoil	274
11.3	The Prandtl–Glauert theory	275
11.4	Design of high-speed subsonic aerofoil sections	277
11.5	Transonic flow past an aerofoil	278
11.6	Critical Mach number	279
11.7	Movement of shocks with increasing Mach number	280
11.8	The shock stall	283
11.9	Pressure distributions in transonic flow	286
11.10	Centre of pressure position	286
11.11	Reducing or delaying the transonic drag rise	288
11.12	Wing section	289
11.13	Wing planform	289
11.14	Wing loading	291
11.15	The fuselage	292
11.16	The tailplane	292
11.17	Interference drag	293
11.18	Delta and crescent wings	294
11.19	Disadvantages of swept wings	294
11.20	The delta wing	296
11.21	The crescent wing	297
11.22	M and W wings	298
11.23	Supersonic flow past an aerofoil	298
11.24	Supersonic aerofoil sections	299
11.25	Supersonic flow past a flat plate	301

11.26	Supersonic flow past a double wedge aerofoil	303
11.27	Summary of double wedge results	311
11.28	Supersonic flow past a biconvex aerofoil	313
11.29	Biconvex aerofoil results using Ackeret theory	315
11.30	Finite supersonic wings	319
11.31	Swept wings	321
Chapter 12 Compressible Potential Flow Theory		325
12.1	Introduction	325
12.2	The potential flow equation	325
12.3	Perturbation velocity potential	327
12.4	Subsonic flow (Prandtl–Glauert theory)	330
12.5	Three dimensions	332
12.6	Supersonic flow (Ackeret theory)	333
12.7	Boundary conditions	334
12.8	Pressure distributions	336
12.9	Lift coefficient	337
12.10	Wave drag coefficient	338
12.11	Examples	338
12.12	Pitching moment coefficient	341
Chapter 13 Experimental Methods		342
13.1	Introduction	342
13.2	Low-speed wind tunnels	342
13.3	Types of low-speed wind tunnel	343
13.4	The working section	347
13.5	The diffuser	347
13.6	Gauzes and honeycombs	349
13.7	The contraction	349
13.8	The corners	349
13.9	The fan	349
13.10	Catchwires	350
13.11	Coolers	350
13.12	Measurement of tunnel speed	350
13.13	Power requirements	351
13.14	Manometers	352
13.15	Measurement of forces and moments	355
13.16	Pressure plotting	356
13.17	Measurement of profile drag by pitot traverse of the wake	357
13.18	Wind tunnel balances	360
13.19	Wind tunnel corrections	360
13.20	Solid blockage	361
13.21	Wake blockage	362
13.22	Lift effect	362
13.23	Effect of pressure gradient along the tunnel axis	364
13.24	Effect of supports	364
13.25	Effect of wind direction	364

13.26	Flow visualization techniques	364
13.27	The smoke technique	365
13.28	The hot wire technique	365
13.29	Boundary layer investigation	365
13.30	Optical methods	367
13.31	Supersonic wind tunnels	367
13.32	Liner and working section	368
13.33	Diffusers	369
13.34	Driers	372
13.35	Types of wind tunnel	372
13.36	Intermittent operation	373
13.37	Induced flow tunnels	374
13.38	Continuous operation	375
13.39	Return circuits	375
13.40	Choking	375
13.41	High-speed subsonic tunnels	376
13.42	Transonic wind tunnels	376
13.43	The shock tube	377
13.44	Hypersonic wind tunnels	378
13.45	Measurement of forces and moments	378
13.46	Optical methods of flow exploration	379
13.47	The shadowgraph system	380
13.48	The schlieren system	381
13.49	The interferometer	382
13.50	Measurement of fluid velocity	383
13.51	Total head measurement	384
13.52	Measurement of static pressure	385
13.53	Measurement of Mach number	386
13.54	Measurement of airspeed	388
13.55	The hot wire anemometer	388
13.56	Yawmeters	389
13.57	Special facilities	390
13.58	Flight tests	392
Chapter 14 Elementary Mechanics of Flight		393
14.1	Introduction	393
14.2	Steady, straight and level flight	393
14.3	Pull-outs	397
14.4	Gliding	400
14.5	Climbing	405
14.6	The steady, level, co-ordinated turn	406
14.7	Control in a turn	409
14.8	Manoeuvring boundaries	410
Chapter 15 Aircraft Performance		418
15.1	Introduction	418
15.2	Aircraft characteristics	419
15.3	Engine characteristics	425

15.4	Minimum speed	427
15.5	Maximum speed	430
15.6	The flight envelope	432
15.7	Excess power	433
15.8	Maximum rate of climb	434
15.9	Maximum angle of climb	436
15.10	Ceiling	437
15.11	Time to climb	441
15.12	Range and endurance	442
15.13	Specific fuel consumption	444
15.14	Specific air range	444
15.15	The estimation of range	446
15.16	The Breguet range equation	446
15.17	Endurance	449
15.18	Summary of results	451
15.19	Effect of wind on range and endurance	451
15.20	The cruise climb of a jet-engined aircraft	453
15.21	The general performance equation	457
15.22	Take-off performance	459
15.23	Landing distance	461
15.24	The non-dimensional presentation of aircraft performance	463
15.25	The energy height method	467
15.26	Non-dimensional presentation of climbing performance	473
Chapter 16 Aircraft Stability and Control		475
16.1	Introduction	475
16.2	Static stability	475
16.3	Dynamic stability	477
16.4	Aircraft control	479
16.5	Simplifying assumptions	480
16.6	Axes of reference and notation	481
16.7	Equations of motion—Aerodynamic derivatives	483
16.8	Longitudinal stability	485
16.9	Wing alone	488
16.10	Wing and horizontal tail	491
16.11	Factors affecting the tail contribution	495
16.12	Neutral point and static margin	496
16.13	The stick-fixed condition	497
16.14	Determination of neutral point by flight test	500
16.15	The stick-free condition	502
16.16	Determination of stick-free neutral point	505
16.17	Relationship between stick-fixed and stick-free static stability	506
16.18	Forward C.G. limit	507
16.19	General effects of other components	509
16.20	Manoeuvring stability	510
16.21	The stick-fixed aspect	511

16.22	The stick-free aspect	515
16.23	Limitations	517
16.24	The phugoid	518
16.25	Longitudinal control	520
16.26	The elevator and trim tab	520
16.27	Stick force and stick gearing	521
16.28	Variation of stick force with airspeed	522
16.29	Effect of pitching velocity on tail incidence	524
16.30	A note on tail fin and rudder	524
16.31	Lateral and directional stability and control	525
16.32	Directional static stability	527
16.33	The fuselage	528
16.34	Vertical tail fin	529
16.35	Propeller effects	531
16.36	The wing	531
16.37	Damping in yaw	532
16.38	Directional control	534
16.39	Asymmetric power	534
16.40	Lateral static stability	535
16.41	Effect of wing dihedral	536
16.42	Effect of wing sweepback	536
16.43	Fuselage and vertical tail	537
16.44	Damping in roll	538
16.45	Strip theory	538
16.46	Cross-coupling	541
16.47	Dynamic effects	543
16.48	Autorotation	545
16.49	The spin	546
16.50	Aerodynamic balancing	547
16.51	The set-back hinge	548
16.52	The horn balance	549
16.53	The Frise aileron	549
16.54	The sealed nose balance	550
16.55	The geared balance tab	550
16.56	Powered controls	551
16.57	Aeroelastic effects	551
16.58	Wing torsional divergence	552
16.59	Control reversal	553
16.60	Control surface flutter	553
16.61	Longitudinal dynamic stability	555
16.62	Solution of the stability quartic	558
16.63	Stability criteria	559
16.64	Lateral-directional stability	560
16.65	Non-dimensional aerodynamic derivatives	561
Chapter 17 Elementary Theory of Propellers		564
17.1	Introduction	564

17.2	Geometry of the propeller	564
17.3	Airscrew coefficients	566
17.4	The Rankine-Froude momentum theory of propulsion	569
17.5	Ideal efficiency	572
17.6	Slipstream velocity	575
17.7	Effect of pitch on airscrew performance	576
17.8	Blade element theory	580
17.9	Rotational inflow and outflow factors	580
17.10	Performance of a blade element	581
17.11	Inflow factors	585
17.12	Compressibility effects	587
Appendix I	The Glauert Integral	589
Appendix II	The Prandtl-Meyer Formula	593
Appendix III	Metrication	596
	List of symbols	600
	Index	603