
Contents

List of Acronyms	xvii
Preface.....	xix
Author.....	xxiii
1 Introduction to Flight Vehicles.....	1
1.1 Introduction	1
1.2 Components of an Aeroplane.....	1
1.2.1 Fuselage.....	1
1.2.2 Wings.....	2
1.2.3 Tail Surfaces or Empennage.....	2
1.2.4 Landing Gear.....	3
1.3 Basic Principles of Flight.....	3
1.3.1 Forces Acting on an Aeroplane.....	3
1.3.2 Drag and Its Reduction	5
1.3.3 Aerodynamically Conforming Shapes: Streamlining.....	6
1.3.4 Stability and Balance	6
1.4 Flying Control Surfaces: Elevator, Ailerons and Rudder	7
1.4.1 Flaps, High-Lift and Flow Control Devices	10
1.4.2 Introducing Boundary Layers.....	12
1.4.3 Spoilers	15
1.5 Pilot's Controls: The Throttle, the Control Column and Yoke, the Rudder Pedals and the Toe Brakes	16
1.6 Modes of Flight.....	16
1.6.1 Static and In-Flight Stability Margins.....	18
1.7 Power Plant	19
1.7.1 Propeller-Driven Aircraft	19
1.7.2 Jet Propulsion	19
1.8 Avionics, Instrumentation and Systems.....	20
1.9 Geometry of Aerofoils and Wings.....	21
1.9.1 Aerofoil Geometry	21
1.9.2 Chord Line	21
1.9.3 Camber	22
1.9.4 Leading and Trailing Edges	22
1.9.5 Specifying Aerofoils	23
1.9.6 Equations Defining Mean Camber Line.....	24
1.9.7 Aerofoil Thickness Distributions	24
1.9.8 Wing Geometry.....	26
Chapter Highlights.....	30

Exercises	30
Answers to Selected Exercises	32
References	32
2 Basic Principles Governing Aerodynamic Flows	33
2.1 Introduction	33
2.2 Continuity Principle	33
2.2.1 Streamlines and Stream Tubes	34
2.3 Bernoulli's Principle.....	34
2.4 Laminar Flows and Boundary Layers	34
2.5 Turbulent Flows.....	35
2.6 Aerodynamics of Aerofoils and Wings	35
2.6.1 Flow around an Aerofoil.....	36
2.6.2 Mach Number and Subsonic and Supersonic Flows.....	36
2.7 Properties of Air in the Atmosphere.....	38
2.7.1 Composition of the Atmosphere: The Troposphere, Stratosphere, Mesosphere, Ionosphere and Exosphere	38
2.7.2 Air Density	39
2.7.3 Temperature.....	39
2.7.4 Pressure	39
2.7.5 Effects of Pressure and Temperature	40
2.7.6 Viscosity	40
2.7.7 Bulk Modulus of Elasticity	41
2.7.8 Temperature Variations with Altitude: The Lapse Rate..	41
2.8 International Standard Atmosphere (from ESDU 77021, 1986)	41
2.9 Generation of Lift and Drag	45
2.10 Aerodynamic Forces and Moments	47
2.10.1 Aerodynamic Coefficients	50
2.10.2 Aerofoil Drag.....	53
2.10.3 Aircraft Lift Equation and Lift Curve Slope	54
2.10.4 Centre of Pressure.....	57
2.10.5 Aerodynamic Centre	57
2.10.6 Pitching Moment Equation.....	58
2.10.7 Elevator Hinge Moment Coefficient.....	60
Chapter Highlights	61
Exercises	63
Answers to Selected Exercises	65
References	66
3 Mechanics of Equilibrium Flight.....	67
3.1 Introduction	67
3.2 Speeds of Equilibrium Flight	71
3.3 Basic Aircraft Performance.....	73
3.3.1 Optimum Flight Speeds.....	73
3.4 Conditions for Minimum Drag.....	76

Contents

3.5	Stability in the Vicinity of the Minimum Drag Speed	77
3.6	Range and Endurance Estimation	77
3.7	Trim	79
3.8	Stability of Equilibrium Flight	82
3.9	Longitudinal Static Stability	84
3.9.1	Neutral Point (Stick-Fixed)	85
3.9.2	Neutral Point (Stick-Free)	85
3.10	Manoeuvrability	86
3.10.1	Pull-Out Manoeuvre	86
3.10.2	Manoeuvre Margin: Stick-Fixed	87
3.10.3	Manoeuvre Margin: Stick-Free	89
3.11	Lateral Stability and Stability Criteria	89
3.12	Experimental Determination of Aircraft Stability Margins	91
3.13	Summary of Equilibrium- and Stability-Related Equations	92
	Chapter Highlights	95
	Exercises	97
	Answers to Selected Exercises	101
	References	102
4	Aircraft Non-Linear Dynamics: Equations of Motion	103
4.1	Introduction	103
4.2	Aircraft Dynamics	103
4.3	Aircraft Motion in a 2D Plane	104
4.4	Moments of Inertia	109
4.5	Euler's Equations and the Dynamics of Rigid Bodies	111
4.6	Description of the Attitude or Orientation	115
4.7	Aircraft Equations of Motion	119
4.8	Motion-Induced Aerodynamic Forces and Moments	122
4.9	Non-Linear Dynamics of Aircraft Motion and the Stability Axes	125
4.9.1	Equations of Motion in Wind Axis Coordinates, V_D , α and β	130
4.9.2	Reduced-Order Modelling: The Short Period Approximations	135
4.10	Trimmed Equations of Motion	137
4.10.1	Non-Linear Equations of Perturbed Motion	139
4.10.2	Linear Equations of Motion	140
	Chapter Highlights	141
	Exercises	142
	References	143
5	Small Perturbations and the Linearised, Decoupled Equations of Motion	145
5.1	Introduction	145
5.2	Small Perturbations and Linearisations	145

5.3	Linearising the Aerodynamic Forces and Moments: Stability Derivative Concept	148
5.4	Direct Formulation in the Stability Axis	152
5.5	Decoupled Equations of Motion	158
5.5.1	Case I: Motion in the Longitudinal Plane of Symmetry ...	158
5.5.2	Case II: Motion in the Lateral Direction, Perpendicular to the Plane of Symmetry	160
5.6	Decoupled Equations of Motion in terms of the Stability Axis Aerodynamic Derivatives.....	161
5.7	Addition of Aerodynamic Controls and Throttle	164
5.8	Non-Dimensional Longitudinal and Lateral Dynamics	173
5.9	Simplified State-Space Equations of Longitudinal and Lateral Dynamics	179
5.10	Simplified Concise Equations of Longitudinal and Lateral Dynamics	181
	Chapter Highlights	182
	Exercises	182
	Reference	184
6	Longitudinal and Lateral Linear Stability and Control	185
6.1	Introduction	185
6.2	Dynamic and Static Stability	185
6.2.1	Longitudinal Stability Analysis.....	185
6.2.2	Lateral Dynamics and Stability	196
6.3	Modal Description of Aircraft Dynamics and the Stability of the Modes.....	201
6.3.1	Slow-Fast Partitioning of the Longitudinal Dynamics.....	201
6.3.2	Slow-Fast Partitioning of the Lateral Dynamics.....	204
6.3.3	Summary of Longitudinal and Lateral Modal Equations.....	213
6.3.3.1	Phugoid or Long Period	213
6.3.3.2	Short Period.....	214
6.3.3.3	Third Oscillatory Mode.....	214
6.3.3.4	Roll Subsidence.....	215
6.3.3.5	Dutch Roll.....	215
6.3.3.6	Spiral	215
6.4	Aircraft Lift and Drag Estimation	216
6.4.1	Fuselage Lift and Moment Coefficients	219
6.4.2	Wing-Tail Interference Effects	220
6.4.3	Estimating the Wing's Maximum Lift Coefficient.....	220
6.4.4	Drag Estimation	221
6.5	Estimating the Longitudinal Aerodynamic Derivatives	225
6.6	Estimating the Lateral Aerodynamic Derivatives.....	232
6.6.1	Perturbation Analysis of Trimmed Flight.....	238

Contents

6.6.2	Perturbation Analysis of Longitudinal Trimmed Flight.....	238
6.6.3	Perturbation Analysis of Lateral Trimmed Flight.....	243
6.6.3.1	Control Settings for Steady Sideslip	243
6.6.3.2	Control Settings for Turn Coordination and Banking.....	245
6.6.4	Perturbations of Coupled Trimmed Flight.....	250
6.6.5	Simplified Analysis of Complex Manoeuvres: The Sidestep Manoeuvre	250
	Chapter Highlights	252
	Exercises	255
	Answers to Selected Exercises	263
	References	264
7	Aircraft Dynamic Response: Numerical Simulation and Non-Linear Phenomenon	265
7.1	Introduction	265
7.2	Longitudinal and Lateral Modal Equations.....	265
7.3	Methods of Computing Aircraft Dynamic Response.....	269
7.3.1	Laplace Transform Method	270
7.3.2	Aircraft Response Transfer Functions	270
7.3.3	Direct Numerical Integration.....	275
7.4	System Block Diagram Representation.....	277
7.4.1	Numerical Simulation of Flight Using MATLAB®/Simulink®	283
7.5	Atmospheric Disturbance: Deterministic Disturbances	284
7.6	Principles of Random Atmospheric Disturbance Modelling.....	291
7.6.1	White Noise: Power Spectrum and Autocorrelation	291
7.6.2	Linear Time-Invariant System with Stochastic Process Input	293
7.7	Application to Atmospheric Turbulence Modelling	296
7.8	Aircraft Non-Linear Dynamic Response Phenomenon	299
7.8.1	Aircraft Dynamic Non-Linearities and Their Analysis	302
7.8.2	High-Angle-of-Attack Dynamics and Its Consequences.....	305
7.8.3	Post-Stall Behaviour.....	306
7.8.4	Tumbling and Autorotation.....	307
7.8.5	Lateral Dynamic Phenomenon	307
7.8.6	Flat Spin and Deep Spin	308
7.8.7	Wing Drop, Wing Rock and Nose Slice	309
7.8.8	Fully Coupled Motions: The Falling Leaf	309
7.8.9	Regenerative Phenomenon	311
	Chapter Highlights.....	312
	Exercises	312
	References	330

8 Aircraft Flight Control	333
8.1 Automatic Flight Control Systems: An Introduction.....	333
8.2 Functions of a Flight Control System.....	336
8.3 Integrated Flight Control System.....	347
8.3.1 Guidance System: Interfacing to the Automatic Flight Control System.....	352
8.3.2 Flight Management System.....	353
8.4 Flight Control System Design	354
8.4.1 Block Diagram Algebra.....	357
8.4.2 Return Difference Equation	360
8.4.3 Laplace Transform	362
8.4.4 Stability of Uncontrolled and Controlled Systems	362
8.4.5 Routh's Tabular Method.....	365
8.4.6 Frequency Response.....	366
8.4.7 Bode Plots.....	369
8.4.8 Nyquist Plots	369
8.4.9 Stability in the Frequency Domain	369
8.4.10 Stability Margins: The Gain and Phase Margins.....	370
8.4.11 Mapping Complex Functions and Nyquist Diagrams ...	370
8.4.12 Time Domain: The State Variable Representation	371
8.4.13 Solution of the State Equations and the Controllability Condition	373
8.4.14 State-Space and Transfer Function Equivalence	375
8.4.15 Transformations of State Variables.....	376
8.4.16 Design of a Full-State Variable Feedback Control Law ...	377
8.4.17 Root Locus Method	379
8.4.18 Root Locus Principle	381
8.4.19 Root Locus Sketching Procedure.....	381
8.4.20 Producing a Root Locus Using MATLAB®	385
8.4.21 Application of the Root Locus Method: Unity Feedback with a PID Control Law.....	387
8.5 Optimal Control of Flight Dynamics.....	390
8.5.1 Compensating Full-State Feedback: Observers and Compensators.....	391
8.5.2 Observers for Controller Implementation.....	392
8.5.3 Observer Equations	393
8.5.4 Special Cases: The Full- and First-Order Observers.....	393
8.5.5 Solving the Observer Equations	395
8.5.6 Luenberger Observer.....	396
8.5.7 Optimisation Performance Criteria.....	396
8.5.8 <i>Good Handling Domains of Modal Response</i> Parameters	397
8.5.9 Cooper–Harper Rating Scale	400

Contents

8.6	Application to the Design of Stability Augmentation Systems and Autopilots.....	401
8.6.1	Design of a Pitch Attitude Autopilot Using PID Feedback and the Root Locus Method	401
8.6.2	Example of Pitch Attitude Autopilot Design for the Lockheed F104 by the Root Locus Method	405
8.6.3	Example of Pitch Attitude Autopilot Design, Including a Stability Augmentation Inner Loop, by the Root Locus Method	405
8.6.4	Design of an Altitude Acquire-and-Hold Autopilot.....	408
8.6.5	Design of a Lateral Roll Attitude Autopilot.....	416
8.6.6	Design of a Lateral Yaw Damper.....	419
8.6.7	Design of a Lateral Heading Autopilot.....	421
8.6.8	Turn Coordination with Sideslip Suppression	423
8.6.9	Application of Optimal Control to Lateral Control Augmentation Design	425
8.7	Performance Assessment of a Command or Control Augmentation System	428
8.8	Linear Perturbation Dynamics Flight Control Law Design by Partial Dynamic Inversion	429
8.8.1	Design Example of a Longitudinal Autopilot Based on Partial Dynamic Inversion	434
8.9	Design of Controllers for Multi-Input Systems.....	437
8.9.1	Design Example of a Lateral Turn Coordination Using the Partial Inverse Dynamics Method	437
8.9.2	Design Example of the Simultaneously Operating Auto-Throttle and Pitch Attitude Autopilot	439
8.9.3	Two-Input Lateral Attitude Control Autopilot	441
8.10	Decoupling Control and Its Application: Longitudinal and Lateral Dynamics Decoupling Control.....	446
8.11	Full Aircraft Six-DOF Flight Controller Design by Dynamic Inversion.....	448
8.11.1	Control Law Synthesis	459
8.11.2	Example of Linear Control Law Synthesis by Partial Dynamic Inversion: The Fully Propulsion-Controlled MD11 Aircraft	462
8.11.3	Example of Quasi-Non-Linear Control Law Synthesis by Partial Dynamic Inversion: The Fully Propulsion-Controlled MD11 Aircraft	464
8.11.4	Full Aircraft Orientation Control Law Design by Dynamic Inversion.....	468
8.11.5	Aircraft Flight Control Synthesis in Wind Axes Coordinates, V_T , β and α	471

Chapter Highlights	474
Exercises	475
Answers to Selected Exercises	484
References	485
9 Piloted Simulation and Pilot Modelling	487
9.1 Introduction	487
9.2 Piloted Flight Simulation	488
9.2.1 Full Moving-Base Simulation: The Stewart Platform	491
9.2.2 Kinematics of Motion Systems	492
9.2.3 Principles of Motion Control	493
9.2.4 Motion Cueing Concepts	493
9.3 Principles of Human Pilot Physiological Modelling	497
9.3.1 Auricular and Ocular Sensors	498
9.4 Human Physiological Control Mechanisms	502
9.4.1 Crossover Model	504
9.4.2 Neal–Smith Criterion	507
9.4.3 Pilot-Induced Oscillations	508
9.4.4 PIO Categories	509
9.4.5 PIOs Classified under Small Perturbation Modes	510
9.4.6 Optimal Control Models	510
9.4.7 Generic Human Pilot Modelling	511
9.4.8 Pilot–Vehicle Simulation	515
9.5 Spatial Awareness	516
9.5.1 Visual Displays	517
9.5.2 Animation and Visual Cues	518
9.5.3 Visual Illusions	520
Chapter Highlights	522
Exercises	522
References	528
10 Flight Dynamics of Elastic Aircraft	529
10.1 Introduction	529
10.2 Flight Dynamics of Flexible Aircraft	529
10.3 Newton–Euler Equations of a Rigid Aircraft	530
10.4 Lagrangian Formulation	536
10.4.1 Generalised Coordinates and Holonomic Dynamic Systems	537
10.4.2 Generalised Velocities	537
10.4.3 Virtual Displacements and Virtual Work	538
10.4.4 Principle of Virtual Work	539
10.4.5 Euler–Lagrange Equations	540
10.4.6 Potential Energy and the Dissipation Function	543
10.4.7 Euler–Lagrange Equations of Motion in Quasi-Coordinates	545

Contents

10.4.8	Transformation to Centre of Mass Coordinates	550
10.4.9	Application of the Lagrangian Method to a Rigid Aircraft.....	553
10.5	Vibration of Elastic Structures in a Fluid Medium	559
10.5.1	Effects of Structural Flexibility in Aircraft Aeroelasticity	563
10.5.2	Wing Divergence.....	563
10.5.3	Control Reversal.....	565
10.5.4	Wing Flutter	566
10.5.5	Aerofoil Flutter Analysis.....	567
10.6	Unsteady Aerodynamics of an Aerofoil	575
10.7	Euler–Lagrange Formulation of Flexible Body Dynamics.....	582
10.8	Application to an Aircraft with a Flexible Wing Vibrating in Bending and Torsion.....	595
10.8.1	Longitudinal Small Perturbation Equations with Flexibility.....	595
10.8.2	Lateral Small Perturbation Equations with Flexibility.....	599
10.9	Kinetic and Potential Energies of the Whole Elastic Aircraft... ..	601
10.9.1	Kinetic Energy	601
10.9.2	Simplifying the General Expression.....	604
10.9.3	Mean Axes.....	604
10.9.4	Kinetic Energy in terms of Modal Amplitudes	605
10.9.5	Tisserand Frame	607
10.10	Euler–Lagrange Matrix Equations of a Flexible Body in Quasi-Coordinates	611
10.11	Slender Elastic Aircraft.....	614
10.12	Aircraft with a Flexible Flat Body Component.....	618
10.12.1	Elastic Large Aspect Ratio <i>Flying Wing</i> Model.....	618
10.12.2	Flexible Aircraft in Roll	620
10.13	Estimating the Aerodynamic Derivatives: Modified Strip Analysis	622
	Chapter Highlights	627
	Exercises	627
	Answers to Selected Exercises	648
	References	649
	Index	651