

Airplane Stability and Control

SECOND EDITION

A History of the Technologies That Made Aviation Possible

*Malcolm J. Abzug
E. Eugene Larrabee*



CAMBRIDGE AEROSPACE SERIES

Contents

Preface

page xvii

1	Early Developments in Stability and Control	1
1.1	Inherent Stability and the Early Machines	1
1.2	The Problem of Control	1
1.3	Catching Up to the Wright Brothers	3
1.4	The Invention of Flap-Type Control Surfaces and Tabs	3
1.5	Handles, Wheels, and Pedals	4
1.6	Wright Controls	5
1.7	Blériot and Depéroussin Controls	5
1.8	Stability and Control of World War I Pursuit Airplanes	6
1.9	Contrasting Design Philosophies	7
1.10	Frederick Lanchester	9
1.11	G. H. Bryan and the Equations of Motion	9
1.12	Metacenter, Center of Pressure, Aerodynamic Center, and Neutral Point	11
2	Teachers and Texts	13
2.1	Stability and Control Educators	13
2.2	Modern Stability and Control Teaching Methods	14
2.3	Stability and Control Research Institutions	14
2.4	Stability and Control Textbooks and Conferences	17
3	Flying Qualities Become a Science	19
3.1	Warner, Norton, and Allen	19
3.2	The First Flying Qualities Specification	22
3.3	Hartley Soulé and Floyd Thompson at Langley	22
3.4	Robert Gilruth's Breakthrough	26
3.5	S. B. Gates in Britain	29
3.6	The U.S. Military Services Follow NACA's Lead	30
3.7	Civil Airworthiness Requirements	32
3.8	World-Wide Flying Qualities Specifications	32
3.9	Equivalent System Models and Pilot Rating	33
3.10	The Counterrevolution	34
3.11	Procurement Problems	35
3.12	Variable-Stability Airplanes Play a Part	35
3.13	Variable-Stability Airplanes as Trainers	36
3.14	The Future of Variable-Stability Airplanes	37
3.15	The V/STOL Case	39

3.16	Two Famous Airplanes	41
3.17	Changing Military Missions and Flying Qualities Requirements	43
3.18	Long-Lived Stability and Control Myths	44
4	Power Effects on Stability and Control	45
4.1	Propeller Effects on Stability and Control	45
4.2	Direct-Thrust Moments in Pitch	46
4.3	Direct-Thrust Moments in Yaw	47
4.4	World War II Twin-Engine Bombers	47
4.5	Modern Light Twin Airplanes	49
4.6	Propeller Slipstream Effects	50
4.7	Direct Propeller Forces in Yaw (or at Angle of Attack)	52
4.8	Jet and Rocket Effects on Stability and Control	53
4.8.1	Jet Intake Normal Force	53
4.8.2	Airstream Deviation Due to Inflow	54
4.9	Special VTOL Jet Inflow Effects	54
4.9.1	Jet Damping and Inertial Effects	55
5	Managing Control Forces	57
5.1	Desirable Control Force Levels	57
5.2	Background to Aerodynamically Balanced Control Surfaces	57
5.3	Horn Balances	60
5.4	Overhang or Leading-Edge Balances	61
5.5	Frise Ailerons	63
5.6	Aileron Differential	65
5.7	Balancing or Geared Tabs	66
5.8	Trailing-Edge Angle and Beveled Controls	66
5.9	Corded Controls	68
5.10	Spoiler Ailerons	69
5.10.1	Spoiler Opening Aerodynamics	70
5.10.2	Spoiler Steady-State Aerodynamics	70
5.10.3	Spoiler Operating Forces	71
5.10.4	Spoiler Aileron Applications	71
5.11	Internally Balanced Controls	72
5.12	Flying or Servo and Linked Tabs	74
5.13	Spring Tabs	75
5.14	Springy Tabs and Downsprings	77
5.15	All-Movable Controls	78
5.16	Mechanical Control System Design Details	78
5.17	Hydraulic Control Boost	79
5.18	Early Hydraulic Boost Problems	80
5.19	Irreversible Powered Controls	80
5.20	Artificial Feel Systems	81
5.21	Fly-by-Wire	82
5.22	Remaining Design Problems in Power Control Systems	86
5.23	Safety Issues in Fly-by-Wire Control Systems	87
5.24	Managing Redundancy in Fly-by-Wire Control Systems	88
5.25	Electric and Fly-by-Light Controls	89

6	Stability and Control at the Design Stage	90
6.1	Layout Principles	90
6.1.1	Subsonic Airplane Balance	90
6.1.2	Tail Location, Size, and Shape	91
6.2	Estimation from Drawings	92
6.2.1	Early Methods	92
6.2.2	Wing and Tail Methods	92
6.2.3	Bodies	93
6.2.4	Wing-Body Interference	93
6.2.5	Downwash and Sidewash	94
6.2.6	Early Design Methods Matured – DATCOM, RAeS, JSASS Data Sheets	95
6.2.7	Computational Fluid Dynamics	95
6.3	Estimation from Wind-Tunnel Data	97
7	The Jets at an Awkward Age	100
7.1	Needed Devices Are Not Installed	100
7.2	F4D, A4D, and A3D Manual Reversions	100
7.3	Partial Power Control	101
7.4	Nonelectronic Stability Augmentation	101
7.5	Grumman XF10F Jaguar	104
7.6	Successful B-52 Compromises	105
7.6.1	The B-52 Rudder Has Limited Control Authority	105
7.6.2	The B-52 Elevator Also Has Limited Control Authority	106
7.6.3	The B-52 Manually Controlled Ailerons Are Small	107
8	The Discovery of Inertial Coupling	109
8.1	W. H. Phillips Finds an Anomaly	109
8.2	The Phillips Inertial Coupling Technical Note	109
8.3	The First Flight Occurrences	112
8.4	The 1956 Wright Field Conference	115
8.5	Simplifications and Explications	116
8.6	The F4D Skyray Experience	118
8.7	Later Developments	120
8.8	Inertial Coupling and Future General-Aviation Aircraft	120
9	Spinning and Recovery	121
9.1	Spinning Before 1916	121
9.2	Advent of the Free-Spinning Wind Tunnels	121
9.3	Systematic Configuration Variations	124
9.4	Design for Spin Recovery	124
9.5	Changing Spin Recovery Piloting Techniques	126
9.5.1	Automatic Spin Recovery	128
9.6	The Role of Rotary Derivatives in Spins	128
9.7	Rotary Balances and the Steady Spin	129

9.8	Rotary Balances and the Unsteady Spin	130
9.9	Parameter Estimation Methods for Spins	131
9.10	The Case of the Grumman/American AA-IB	131
9.11	The Break with the Past	133
9.12	Effects of Wing Design on Spin Entry and Recovery	134
9.13	Drop and Radio-Controlled Model Testing	136
9.14	Remotely Piloted Spin Model Testing	137
9.15	Criteria for Departure Resistance	137
9.16	Vortex Effects and Self-Induced Wing Rock	141
9.17	Bifurcation Theory	142
9.18	Departures in Modern Fighters	142
10	Tactical Airplane Maneuverability	146
10.1	How Fast Should Fighter Airplanes Roll?	146
10.2	Air-to-Air Missile-Armed Fighters	148
10.3	Control Sensitivity and Overshoots in Rapid Pullups	148
10.3.1	Equivalent System Methods	148
10.3.2	Criteria Based on Equivalent Systems	149
10.3.3	Time Domain-Based Criteria	152
10.4	Rapid Rolls to Steep Turns	155
10.5	Supermaneuverability, High Angles of Attack	157
10.6	Unsteady Aerodynamics in the Supermaneuverability Regime	158
10.6.1	The Transfer Function Model for Unsteady Flow	158
10.7	The Inverse Problem	160
10.8	Thrust-Vector Control for Supermaneuvering	160
10.9	Forebody Controls for Supermaneuvering	160
10.10	Longitudinal Control for Recovery	161
10.11	Concluding Remarks	161
11	High Mach Number Difficulties	162
11.1	A Slow Buildup	162
11.2	The First Dive Pullout Problems	162
11.3	P-47 Dives at Wright Field	165
11.4	P-51 and P-39 Dive Difficulties	167
11.5	Transonic Aerodynamic Testing	168
11.6	Invention of the Sweptback Wing	169
11.7	Sweptback Wings Are Tamed at Low Speeds	172
11.7.1	Wing Leading-Edge Devices	172
11.7.2	Fences and Wing Engine Pylons	172
11.8	Trim Changes Due to Compressibility	175
11.9	Transonic Pitchup	176
11.10	Supersonic Directional Instability	179
11.11	Principal Axis Inclination Instability	181
11.12	High-Altitude Stall Buffet	181
11.13	Supersonic Altitude Stability	182
11.14	Stability and Control of Hypersonic Airplanes	186

12	Naval Aircraft Problems	187
12.1	Standard Carrier Approaches	187
12.2	Aerodynamic and Thrust Considerations	188
12.3	Theoretical Studies	189
12.4	Direct Lift Control	193
12.5	The T-45A Goshawk	195
12.6	The Lockheed S-3A Viking	196
12.7	Concluding Remarks	196
13	Ultralight and Human-Powered Airplanes	198
13.1	Apparent Mass Effects	198
13.2	Commercial and Kit-Built Ultralight Airplanes	199
13.3	The Gossamer and MIT Human-Powered Aircraft	200
13.4	Ultralight Airplane Pitch Stability	202
13.5	Turning Human-Powered Ultralight Airplanes	202
13.6	Concluding Remarks	204
14	Fuel Slosh, Deep Stall, and More	205
14.1	Fuel Shift and Dynamic Fuel Slosh	205
14.2	Deep Stall	209
14.3	Ground Effect	212
14.4	Directional Stability and Control in Ground Rolls	215
14.5	Vee- or Butterfly Tails	217
14.6	Control Surface Buzz	219
14.7	Rudder Lock and Dorsal Fins	220
14.8	Flight Vehicle System Identification from Flight Test	224
14.8.1	Early Attempts at Identification	224
14.8.2	Knob Twisting	224
14.8.3	Modern Identification Methods	225
14.8.4	Extensions to Nonlinearities and Unsteady Flow Regimes	228
14.9	Lifting Body Stability and Control	229
15	Safe Personal Airplanes	231
15.1	The Guggenheim Safe Airplane Competition	231
15.2	Progress after the Guggenheim Competition	231
15.3	Early Safe Personal Airplane Designs	233
15.4	1948 and 1966 NACA and NASA Test Series	234
15.5	Control Friction and Apparent Spiral Instability	235
15.6	Wing Levelers	237
15.7	The Role of Displays	237
15.8	Inappropriate Stability Augmentation	240
15.9	Unusual Aerodynamic Arrangements	240
15.10	Blind-Flying Demands on Stability and Control	241
15.10.1	Needle, Ball, and Airspeed	241
15.10.2	Artificial Horizon, Directional Gyro, and Autopilots	241

15.11	Single-Pilot IFR Operation	242
15.12	The Prospects for Safe Personal Airplanes	243
16	Stability and Control Issues with Variable Sweep	244
16.1	The First Variable-Sweep Wings – Rotation and Translation	244
16.2	The Rotation-Only Breakthrough	244
16.3	The F-111 Aardvark, or TFX	245
16.4	The F-14 Tomcat	246
16.5	The Rockwell B-1	246
16.6	The Oblique or Skewed Wing	247
16.7	Other Variable-Sweep Projects	251
17	Modern Canard Configurations	252
17.1	Burt Rutan and the Modern Canard Airplane	252
17.2	Canard Configuration Stall Characteristics	252
17.3	Directional Stability and Control of Canard Airplanes	253
17.4	The Penalty of Wing Sweepback on Low Subsonic Airplanes	253
17.5	Canard Airplane Spin Recovery	254
17.6	Other Canard Drawbacks	255
17.7	Pusher Propeller Problems	257
17.8	The Special Case of the Voyager	257
17.9	Modern Canard Tactical Airplanes	257
18	Evolution of the Equations of Motion	258
18.1	Euler and Hamilton	258
18.2	Linearization	262
18.3	Early Numerical Work	263
18.4	Glauert's and Later Nondimensional Forms	264
18.5	Rotary Derivatives	266
18.6	Stability Boundaries	267
18.7	Wind, Body, Stability, and Principal Axes	267
18.8	Laplace Transforms, Frequency Response, and Root Locus	270
18.9	The Modes of Airplane Motion	271
18.9.1	Literal Approximations to the Modes	273
18.10	Time Vector Analysis	274
18.11	Vector, Dyadic, Matrix, and Tensor Forms	274
18.12	Atmospheric Models	277
18.13	Integration Methods and Closed Forms	280
18.14	Steady-State Solutions	281
18.15	Equations of Motion Extension to Suborbital Flight	282
18.15.1	Heading Angular Velocity Correction and Initialization	284
18.16	Suborbital Flight Mechanics	284
18.17	Additional Special Forms of the Equations of Motion	284
19	The Elastic Airplane	286
19.1	Aeroelasticity and Stability and Control	286
19.2	Wing Torsional Divergence	287

19.3	The Semirigid Approach to Wing Torsional Divergence	287
19.4	The Effect of Wing Sweep on Torsional Divergence	288
19.5	Aileron-Reversal Theories	289
19.6	Aileron-Reversal Flight Experiences	290
19.7	Spoiler Ailerons Reduce Wing Twisting in Rolls	291
19.8	Aeroelastic Effects on Static Longitudinal Stability	291
19.9	Stabilizer Twist and Speed Stability	295
19.10	Dihedral Effect of a Flexible Wing	295
19.11	Finite-Element or Panel Methods in Quasi-Static Aeroelasticity	296
19.12	Aeroelastically Corrected Stability Derivatives	298
19.13	Mean and Structural Axes	299
19.14	Normal Mode Analysis	299
19.15	Quasi-Rigid Equations	300
19.16	Control System Coupling with Elastic Modes	300
19.17	Reduced-Order Elastic Airplane Models	302
19.18	Second-Order Elastic Airplane Models	302
19.19	Concluding Remarks	302
20	Stability Augmentation	303
20.1	The Essence of Stability Augmentation	303
20.2	Automatic Pilots in History	304
20.3	The Systems Concept	304
20.4	Frequency Methods of Analysis	304
20.5	Early Experiments in Stability Augmentation	305
20.5.1	The Boeing B-47 Yaw Damper	305
20.5.2	The Northrop YB-49 Yaw Damper	306
20.5.3	The Northrop F-89 Sideslip Stability Augmentor	308
20.6	Root Locus Methods of Analysis	308
20.7	Transfer-Function Numerators	310
20.8	Transfer-Function Dipoles	310
20.9	Command Augmentation Systems	310
20.9.1	Roll-Ratcheting	311
20.10	Superaugmentation, or Augmentation for Unstable Airplanes	312
20.11	Propulsion-Controlled Aircraft	314
20.12	The Advent of Digital Stability Augmentation	316
20.13	Practical Problems with Digital Systems	316
20.14	Time Domain and Linear Quadratic Optimization	316
20.15	Linear Quadratic Gaussian Controllers	317
20.16	Failed Applications of Optimal Control	319
20.17	Robust Controllers, Adaptive Systems	320
20.18	Robust Controllers, Singular Value Analysis	321
20.19	Decoupled Controls	321
20.20	Integrated Thrust Modulation and Vectoring	322
20.21	Concluding Remarks	322

21	Flying Qualities Research Moves with the Times	324
21.1	Empirical Approaches to Pilot-Induced Oscillations	324
21.2	Compensatory Operation and Model Categories	326
21.3	Crossover Model	327
21.4	Pilot Equalization for the Crossover Model	327
21.5	Algorithmic (Linear Optimal Control) Model	327
21.6	The Crossover Model and Pilot-Induced Oscillations	328
21.7	Gibson Approach	330
21.8	Neal-Smith Approach	330
21.9	Bandwidth-Phase Delay Criteria	331
21.10	Landing Approach and Turn Studies	332
21.11	Implications for Modern Transport Airplanes	333
21.12	Concluding Remarks	333
22	Challenge of Stealth Aerodynamics	335
22.1	Faceted Airframe Issues	335
22.2	Parallel-Line Planform Issues	337
22.3	Shielded Vertical Tails and Leading-Edge Flaps	338
22.4	Fighters Without Vertical Tails	340
23	Very Large Aircraft	341
23.1	The Effect of Higher Wing Loadings	341
23.2	The Effect of Folding Wings	341
23.3	Altitude Response During Landing Approach	342
23.4	Longitudinal Dynamics	342
23.5	Roll Response of Large Airplanes	343
23.6	Large Airplanes with Reduced-Static Longitudinal Stability	343
23.7	Large Supersonic Airplanes	343
23.8	Concluding Remarks	343
24	Work Still to Be Done	345
	<i>Short Biographies of Some Stability and Control Figures</i>	347
	<i>References and Core Bibliography</i>	357
	<i>Index</i>	377