



Stephen Corda

Introduction to Aerospace Engineering

with a Flight Test Perspective

Aerospace Series

Editors Peter Belobaba, Jonathan Cooper
and Allan Seabridge



WILEY

**INTRODUCTION TO
AEROSPACE
ENGINEERING
WITH A FLIGHT TEST
PERSPECTIVE**

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Stephen Corda

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*To Glenn, Gerard, and Marta.
“Blue skies and tailwinds.”*

Table of Contents

About the Author	xv
Series Preface	xvii
Preface	xix
About the Companion website	xxi
1 First Flights	1
1.1 Introduction	2
1.1.1 <i>Organization of the Book</i>	3
1.1.2 <i>FTT: Your Familiarization Flight</i>	4
1.2 Aircraft	12
1.2.1 <i>Classification of Aircraft</i>	12
1.2.2 <i>The Airplane</i>	13
1.2.3 <i>Rotorcraft: the Helicopter</i>	26
1.2.4 <i>Lighter-Than-Air Aircraft: Balloon and Airship</i>	35
1.2.5 <i>The Unmanned Aerial Vehicle</i>	43
1.3 Spacecraft	45
1.3.1 <i>Classification of Spacecraft</i>	46
1.3.2 <i>Parts of a Spacecraft</i>	52
1.3.3 <i>Unmanned Spacecraft</i>	57
1.3.4 <i>Manned Spacecraft</i>	69
1.3.5 <i>Space Access Systems and Vehicles</i>	77
References	96
2 Introductory Concepts	98
2.1 Introduction	98
2.2 Introductory Mathematical Concepts	99
2.2.1 <i>Units and Unit Systems</i>	99
2.2.2 <i>Measurement and Numerical Uncertainty</i>	107
2.2.3 <i>Scalars and Vectors</i>	113
2.3 Introductory Aerospace Engineering Concepts	114
2.3.1 <i>Aircraft Body Axes</i>	115
2.3.2 <i>Angle-of-Attack and Angle-of-Sideslip</i>	116

2.3.3	<i>Aircraft Stability Axes</i>	118
2.3.4	<i>Aircraft Location Numbering System</i>	119
2.3.5	<i>The Free-Body Diagram and the Four Forces</i>	120
2.3.6	<i>FTT: the Trim Shot</i>	125
2.3.7	<i>Mach Number and the Regimes of Flight</i>	129
2.3.8	<i>The Flight Envelope</i>	132
2.3.9	<i>The V-n Diagram</i>	144
2.3.10	<i>Aircraft Weight and Balance</i>	150
2.3.11	<i>Aerospace Vehicle Designations and Naming</i>	157
2.4	Introductory Flight Test Concepts	161
2.4.1	<i>What is a Flight Test?</i>	161
2.4.2	<i>The Flight Test Process</i>	165
2.4.3	<i>Flight Test Techniques</i>	169
2.4.4	<i>Roles of Test Pilot, Flight Test Engineer, and Flight Test Analyst</i>	173
2.4.5	<i>Flight Test Safety and Risk Assessment</i>	174
	References	177
	Problems	178
3	Aerodynamics	181
3.1	Introduction	182
3.2	Fundamental Physical Properties of a Fluid	183
3.2.1	<i>The Fluid Element</i>	183
3.2.2	<i>Thermodynamic Properties of a Fluid</i>	184
3.2.3	<i>Kinematic Properties of a Flow</i>	186
3.2.4	<i>Streamlines, Pathlines, and Flow Visualization</i>	187
3.2.5	<i>FTT: In-Flight Flow Visualization</i>	188
3.2.6	<i>Transport Properties of a Fluid</i>	192
3.3	Types of Aerodynamic Flows	195
3.3.1	<i>Continuum and Non-Continuum Flows</i>	195
3.3.2	<i>Steady and Unsteady Flows</i>	196
3.3.3	<i>Incompressible and Compressible Flows</i>	197
3.3.4	<i>Inviscid and Viscous Flows</i>	198
3.4	Similarity Parameters	201
3.4.1	<i>Mach Number</i>	202
3.4.2	<i>Reynolds Number</i>	203
3.4.3	<i>Pressure Coefficient</i>	205
3.4.4	<i>Force and Moment Coefficients</i>	205
3.4.5	<i>Ratio of Specific Heats</i>	206
3.4.6	<i>Prandtl Number</i>	206
3.4.7	<i>Other Similarity Parameters</i>	206
3.4.8	<i>Summary of Similarity Parameters</i>	212
3.5	A Brief Review of Thermodynamics	213
3.5.1	<i>Thermodynamic System and State</i>	213
3.5.2	<i>Connecting the Thermodynamic State: The Equation of State</i>	215
3.5.3	<i>Additional Thermodynamic Properties: Internal Energy, Enthalpy, and Entropy</i>	223
3.5.4	<i>Work and Heat</i>	224
3.5.5	<i>The Laws of Thermodynamics</i>	229

3.5.6	<i>Specific Heats of an Ideal Gas</i>	232
3.5.7	<i>Isentropic Flow</i>	236
3.6	Fundamental Equations of Fluid Motion	239
3.6.1	<i>Conservation of Mass: The Continuity Equation</i>	239
3.6.2	<i>Newton's Second Law: The Momentum Equation</i>	241
3.6.3	<i>Conservation of Energy: The Energy Equation</i>	246
3.6.4	<i>Summary of the Governing Equations of Fluid Flow</i>	247
3.7	Aerodynamic Forces and Moments	248
3.7.1	<i>Lift</i>	251
3.7.2	<i>Drag</i>	258
3.7.3	<i>GTT: Drag Cleanup</i>	269
3.7.4	<i>GTT: Wind Tunnel Testing</i>	270
3.7.5	<i>GTT: Computational Fluid Dynamics</i>	286
3.7.6	<i>FTT: Lift and Drag in Steady, Gliding Flight</i>	292
3.8	Two-Dimensional Lifting Shapes: Airfoils	298
3.8.1	<i>Airfoil Construction and Nomenclature</i>	303
3.8.2	<i>Airfoil Numbering Systems</i>	305
3.8.3	<i>Airfoil Lift, Drag, and Pitching Moment</i>	307
3.8.4	<i>Pressure Coefficient</i>	308
3.8.5	<i>Airfoil Lift, Drag, and Moment Curves</i>	310
3.8.6	<i>Data for Selected Symmetric and Cambered Airfoils</i>	315
3.8.7	<i>Comparison of Symmetric and Cambered Airfoils</i>	322
3.9	Three-Dimensional Aerodynamics: Wings	325
3.9.1	<i>Finite Wings</i>	325
3.9.2	<i>Lift and Drag Curves of Finite Wings</i>	338
3.9.3	<i>High-Lift Devices</i>	341
3.9.4	<i>FTT: Aeromodeling</i>	347
3.9.5	<i>Wings in Ground Effect</i>	354
3.10	Compressible, Subsonic and Transonic Flows	359
3.10.1	<i>The Speed of Sound</i>	360
3.10.2	<i>The Critical Mach Number and Drag Divergence</i>	363
3.10.3	<i>Compressibility Corrections</i>	365
3.10.4	<i>The "Sound Barrier"</i>	370
3.10.5	<i>Breaking the Sound Barrier: the Bell X-1 and the Miles M.52</i>	371
3.11	Supersonic Flow	377
3.11.1	<i>Isentropic Flow Relations</i>	378
3.11.2	<i>Shock and Expansion Waves</i>	381
3.11.3	<i>FTT: Visualizing Shock waves in Flight</i>	387
3.11.4	<i>Sonic Boom</i>	391
3.11.5	<i>Lift and Drag of Supersonic Airfoils</i>	396
3.11.6	<i>Supercritical Airfoils</i>	399
3.11.7	<i>Wings for Supersonic Flight</i>	401
3.11.8	<i>Transonic and Supersonic Area Rule</i>	417
3.11.9	<i>Internal Supersonic Flows</i>	422
3.12	Viscous Flow	429
3.12.1	<i>Skin Friction and Shearing Stress</i>	430
3.12.2	<i>Boundary Layers</i>	431
3.12.3	<i>Skin Friction Drag</i>	440

3.12.4	<i>Aerodynamic Stall and Departure</i>	444
3.12.5	<i>FTT: Stall, Departure, and Spin Flight Testing</i>	458
3.13	Hypersonic Flow	463
3.13.1	<i>Hypersonic Vehicles</i>	464
3.13.2	<i>Effects of High Mach Number</i>	467
3.13.3	<i>Effects of High Temperature</i>	470
3.13.4	<i>Viscous Hypersonic Flow</i>	473
3.13.5	<i>Effects of Low Density</i>	476
3.13.6	<i>Approximate Analyses of Inviscid Hypersonic Flow</i>	476
3.13.7	<i>Aerodynamic Heating</i>	481
3.13.8	<i>FTT: Hypersonic Flight Testing</i>	485
3.14	Summary of Lift and Drag Theories	495
	References	497
	Problems	500
4	Propulsion	504
4.1	Introduction	504
4.1.1	<i>The Concept of Propulsive Thrust</i>	505
4.1.2	<i>Engine Station Numbering</i>	509
4.2	Propulsive Flows with Heat Addition and Work	511
4.3	Derivation of the Thrust Equations	513
4.3.1	<i>Force Accounting</i>	514
4.3.2	<i>Uninstalled Thrust for the Rocket Engine</i>	515
4.3.3	<i>Uninstalled Thrust for the Ramjet and Turbojet</i>	518
4.3.4	<i>Installed Thrust for an Air-Breathing Engine</i>	520
4.3.5	<i>Thrust Equation for a Propeller</i>	521
4.4	Thrust and Power Curves for Propeller-Driven and Jet Engines	525
4.4.1	<i>FTT: In-Flight Thrust Measurement</i>	526
4.5	Air-Breathing Propulsion	531
4.5.1	<i>Air-Breathing Propulsion Performance Parameters</i>	532
4.5.2	<i>The Ramjet</i>	538
4.5.3	<i>The Gas Generator</i>	542
4.5.4	<i>The Turbojet Engine</i>	548
4.5.5	<i>The Turbofan Engine</i>	555
4.5.6	<i>The Turboprop and Turboshift Engines</i>	558
4.5.7	<i>More about Inlets and Nozzles for Air-Breathing Engines</i>	560
4.5.8	<i>The Reciprocating, Piston Engine–Propeller Combination</i>	570
4.5.9	<i>Summary of Thermodynamic Cycles for Air-Breathing Engines</i>	585
4.5.10	<i>GTT: the Engine Test Cell and Test Stand</i>	585
4.5.11	<i>FTT: Flying Engine Testbeds</i>	588
4.6	Rocket Propulsion	589
4.6.1	<i>Thrust Chamber Thermodynamics</i>	590
4.6.2	<i>Rocket Propulsion Performance Parameters</i>	592
4.6.3	<i>Liquid-Propellant Rocket Propulsion</i>	601
4.6.4	<i>Solid-Propellant Rocket Propulsion</i>	604
4.6.5	<i>Hybrid-Propellant Rocket Propulsion</i>	607
4.6.6	<i>Types of Rocket Nozzles</i>	611

4.7	Other Types of Non-Air-Breathing Propulsion	613
4.7.1	<i>Nuclear Rocket Propulsion</i>	614
4.7.2	<i>Electric Spacecraft Propulsion</i>	616
4.7.3	<i>Solar Propulsion</i>	623
4.8	Other Types of Air-Breathing Propulsion	627
4.8.1	<i>The Scramjet</i>	627
4.8.2	<i>Combined Cycle Propulsion</i>	629
4.8.3	<i>Unsteady Wave Propulsion</i>	630
	References	634
	Problems	635
5	Performance	637
5.1	Introduction	638
5.2	Altitude Definitions	641
5.3	Physical Description of the Atmosphere	644
5.3.1	<i>Chemical Composition of the Atmosphere</i>	645
5.3.2	<i>Layers of the Atmosphere</i>	646
5.3.3	<i>GTT: Cabin Pressurization Test</i>	649
5.4	Equation of Fluid Statics: The Hydrostatic Equation	651
5.5	The Standard Atmosphere	655
5.5.1	<i>Development of the Standard Atmosphere Model</i>	656
5.5.2	<i>Temperature, Pressure, and Density Ratios</i>	661
5.6	Air Data System Measurements	663
5.6.1	<i>The Pitot-Static System</i>	664
5.6.2	<i>Measurement of Altitude</i>	665
5.6.3	<i>Measurement of Airspeed</i>	667
5.6.4	<i>Types of Airspeed</i>	672
5.6.5	<i>Pitot-Static System Errors</i>	678
5.6.6	<i>Other Air Data Measurements</i>	681
5.6.7	<i>FTT: Altitude and Airspeed Calibration</i>	684
5.7	The Equations of Motion for Unaccelerated Flight	690
5.8	Level Flight Performance	692
5.8.1	<i>Thrust Required in Level, Unaccelerated Flight</i>	693
5.8.2	<i>Velocity and Lift Coefficient for Minimum Thrust Required</i>	697
5.8.3	<i>Thrust Available and Maximum Velocity</i>	698
5.8.4	<i>Power Required and Power Available</i>	701
5.8.5	<i>Velocity and Lift Coefficient for Minimum Power Required</i>	705
5.8.6	<i>Range and Endurance</i>	707
5.8.7	<i>FTT: Cruise Performance</i>	712
5.9	Climb Performance	722
5.9.1	<i>Maximum Angle and Maximum Rate of Climb</i>	722
5.9.2	<i>Time to Climb</i>	725
5.9.3	<i>FTT: Climb Performance</i>	727
5.10	Glide Performance	731
5.11	The Polar Diagram	733
5.12	Energy Concepts	735
5.12.1	<i>FTT: Specific Excess Power</i>	745

5.13	Turn Performance	748
	5.13.1 <i>The Level Turn</i>	748
	5.13.2 <i>Turns in the Vertical Plane</i>	758
	5.13.3 <i>Turn Performance and the V–n Diagram</i>	762
	5.13.4 <i>FTT: Turn Performance</i>	763
5.14	Takeoff and Landing Performance	766
	5.14.1 <i>Takeoff Distance</i>	771
	5.14.2 <i>Landing Distance</i>	772
	5.14.3 <i>Solution</i>	773
	5.14.4 <i>FTT: Takeoff Performance</i>	774
	References	778
	Problems	779
6	Stability and Control	782
6.1	Introduction	783
6.2	Aircraft Stability	784
	6.2.1 <i>Static Stability</i>	785
	6.2.2 <i>Dynamic Stability</i>	785
6.3	Aircraft Control	787
	6.3.1 <i>Flight Controls</i>	787
	6.3.2 <i>Stick-Fixed and Stick-Free Stability</i>	788
6.4	Aircraft Body Axes, Sign Conventions, and Nomenclature	789
6.5	Longitudinal Static Stability	793
	6.5.1 <i>The Pitching Moment Curve</i>	793
	6.5.2 <i>Configurations with Longitudinal Static Stability and Balance</i>	797
	6.5.3 <i>Contributions of Aircraft Components to the Pitching Moment</i>	801
	6.5.4 <i>Neutral Point and Static Margin</i>	814
6.6	Longitudinal Control	817
	6.6.1 <i>Elevator Effectiveness and Control Power</i>	818
	6.6.2 <i>Calculation of New Trim Conditions Due to Elevator Deflection</i>	823
	6.6.3 <i>Elevator Hinge Moment</i>	825
	6.6.4 <i>Stick-Free Longitudinal Static Stability</i>	827
	6.6.5 <i>Longitudinal Control Forces</i>	828
	6.6.6 <i>FTT: Longitudinal Static Stability</i>	831
6.7	Lateral-Directional Static Stability and Control	837
	6.7.1 <i>Directional Static Stability</i>	838
	6.7.2 <i>Directional Control</i>	843
	6.7.3 <i>Lateral Static Stability</i>	845
	6.7.4 <i>Roll Control</i>	849
	6.7.5 <i>FTT: Lateral-Directional Static Stability</i>	851
6.8	Summary of Static Stability and Control Derivatives	856
6.9	Dynamic Stability	857
	6.9.1 <i>Long Period or Phugoid</i>	858
	6.9.2 <i>Short Period</i>	861
	6.9.3 <i>Dutch Roll</i>	862
	6.9.4 <i>Spiral Mode</i>	864
	6.9.5 <i>Roll Mode</i>	865
	6.9.6 <i>FTT: Longitudinal Dynamic Stability</i>	866

6.10	Handling Qualities	872
	6.10.1 FTT: Variable-Stability Aircraft	873
6.11	FTT: First Flight	876
	References	880
	Problems	880
	Appendix A Constants	882
A.1	Miscellaneous Constants	882
A.2	Properties of Air at Standard Sea Level Conditions	882
	Appendix B Conversions	883
B.1	Unit Conversions	883
B.2	Temperature Unit Conversions	884
	Appendix C Properties of the 1976 US Standard Atmosphere	885
C.1	English Units	885
C.2	SI Units	887
	Index	891

About the Author

Stephen Corda was born in Newburg, New York on February 3, 1958. He attended the University of Maryland, graduating in 1980 with a Bachelor of Science degree in Aerospace Engineering. He continued with graduate studies in hypersonic aerodynamics at the University of Maryland, graduating with a Master of Science degree in 1982 and a PhD in 1988, both in Aerospace Engineering. From 1983 to 1984, he attended the Von Karman Institute for Fluid Dynamics in Rhode-Saint-Genese, Belgium, graduating with an Aeronautics Diploma in 1984. In 1988, he accepted a position with the Hypersonic Propulsion Group at The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland. From 1990 to 2001 and then from 2004 to 2006, he served in various positions at the NASA Dryden (now Armstrong) Flight Research Center, Edwards, California, including project engineer, flight test engineer, project manager, and Chief of the Propulsion and Performance Branch. He was an instructor and flight test engineer in the Performance Branch at the U.S. Air Force Test Pilot School, Edwards, California from 2001 to 2002. From 2003 to 2004, he was an Assistant Professor in the Aerospace Engineering Department, U.S. Naval Academy, Annapolis, Maryland. He was Associate Professor and Chairman of the Aviation Systems and Flight Research Program at the University of Tennessee Space Institute, Tullahoma, Tennessee, from 2006 to 2012. Returning to the Mojave Desert in 2012, he was the engineering manager of Flight Sciences at Virgin Galactic-The Spaceship Company until 2014. Dr. Corda is currently a private engineering consultant.

Series Preface

The field of aerospace is multi-disciplinary and wide-ranging, covering a large variety of products, disciplines, and domains, not merely in engineering but in many related supporting activities. These combine to enable the aerospace industry to produce innovative and technologically advanced vehicles. The wealth of knowledge and experience that has been gained by expert practitioners in the various aerospace fields needs to be passed on to others working in the industry and also to researchers, teachers, and students in universities.

The *Aerospace Series* aims to be a practical, topical, and relevant series of books aimed at people working in the aerospace industry, including engineering professionals and operators, engineers in academia, and allied professionals such as commercial and legal executives. The topics are wide-ranging, covering design and development, manufacture, operation and support of aircraft, and topics such as infrastructure operations and current advances in research and technology.

The design of future aircraft will depend not only on a deep understanding of the fundamental scientific disciplines that provide the foundations for aerospace engineering, but also on the test techniques that enable verification and validation of novel designs.

This book, *Introduction to Aerospace Engineering with a Flight Test Perspective*, provides a comprehensive introduction to the fundamentals of aerodynamics, propulsion, performance, and stability and control, as required for the design of fixed-wing aircraft. It is a welcome addition to the Wiley Aerospace Series, complementing many of the other books in the Series. Of particular note is the inclusion of various ground and flight testing techniques that relate to the various sections of the book, an area that is rarely documented in textbooks.

Peter Belobaba, Jonathan Cooper and Allan Seabridge

Preface

This book is an introductory level text in aerospace engineering with a unique perspective. Flight test, where dreams of aircraft and space vehicles take to the sky, is the bottom line in the application of aerospace engineering theories and principles. Designing and flying the real machines is often the reason that these theories and principles were developed in the first place. This book provides a solid foundation in many of the fundamentals of aerospace engineering, while illuminating many aspects of real-world flight. Fundamental aerospace engineering subjects that are covered include aerodynamics, propulsion, performance, and stability and control.

The test perspective provides an applied, hands-on engineering flavor to the book. The reader comes away with engineering insights about how to do many different types of aerospace testing, topics that are seldom covered or integrated into a university aerospace engineering curriculum. These topics are essential to becoming a well-rounded aerospace engineer, regardless of what discipline or role one may have in aerospace.

The text is suitable for use in an introductory, undergraduate course in aerospace engineering. The addition of the sections dealing with testing provides the opportunity to introduce these important subjects, especially for those aerospace programs that do not have a dedicated flight test course. In addition, the text may be used to support a dedicated flight test course.

The text can also serve working engineers who seek to broaden their aerospace engineering “toolbox”, to include some of the fundamentals of flight testing. The text can be helpful to those engaged in flight test, as a convenient reference source in fundamental aerospace engineering theory and applied flight test practice. The flight test perspective can also provide the non-engineer, aviation professional, or enthusiast with a deeper understanding of aerospace and flight test. However, the text should not be used as a “how to” manual for the non-professional to attempt their own flight testing.

Sections entitled Flight Test Techniques (FTTs) and Ground Test Techniques (GTTs) present test methods used in applying the aerospace engineering theories and concepts discussed in the previous sections. Rather than presenting a step-by-step list of procedures, the FTTs are described in a unique manner, by placing the reader “in the cockpit” of different aircraft, giving them an exciting perspective for learning about flight test concepts, test techniques, and in-flight data collection. A collateral benefit of this approach is that the reader learns about several different types of aircraft. This approach is a unique and interesting way to learn about aerospace engineering and flight testing, short of actually flying the real airplanes!

Other useful resources may be found online at the companion Wiley website associated with the text (www.wiley.com/go/corda/aerospace_engg_flight_test_persp), where you will find a collection of technical papers and information, which are referenced in the text. These are organized by chapter and by reference to flight test techniques. Instructors may also access complete solutions to all of the homework problems on the website.

In many ways, a textbook is autobiographical in nature, drawing on the author's personal career experiences, interactions, and lessons learned. The material for this book is derived from the author's experience as an aerospace engineer, flight test engineer, flight research pilot, and educator at the NASA Dryden (now Armstrong) Flight Research Center, The Johns Hopkins University Applied Physics Laboratory, the US Air Force Test Pilot School, the US Naval Academy, the University of Tennessee Space Institute, and Virgin Galactic – The Spaceship Company. I owe a great debt to the many engineers, scientists, students, technicians, managers, administrators, and test pilots that I have worked and flown with over my career, who have helped me to learn my trade.

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If you have comments, questions, suggestions, or corrections for the next edition of the book, please email them to scaos@gmail.com.

Stephen Corda
Rosamond, California

About the Companion website

This book is accompanied by a companion website:

www.wiley.com/go/corda/aerospace_engg_flight_test_persp

The website includes:

- Chapters 1 - 6 PDF files
- Homework problems solution manual
- Flight Test Techniques papers

1

First Flights



The first controlled flight of a heavier-than-air airplane, 17 December 1903. (Source: *W. Wright, O. Wright, and J. Daniels, 1903, US Library of Congress.*)

“Wilbur, having used his turn in the unsuccessful attempt on the 14th, the right to the first trial now belonged to me. After running the motor a few minutes to heat it up, I released the wire that held the machine to the track, and the machine started forward in the wind. Wilbur ran at the side of the machine, holding the wing to balance it on the track. Unlike the start on the 14th, made in a calm, the machine, facing a 27-mile wind, started very slowly. Wilbur was able to stay with it till it lifted from the track after a forty-foot run. One of the Life Saving men snapped the camera for us, taking a picture just as the machine had reached the end of the track and had risen to a height

of about two feet.¹ The slow forward speed of the machine over the ground is clearly shown in the picture by Wilbur's attitude. He stayed along beside the machine without any effort.

The course of the flight up and down was exceedingly erratic, partly due to the irregularity of the air, and partly to lack of experience in handling this machine. The control of the front rudder was difficult on account of its being balanced too near the center. This gave it a tendency to turn itself when started; so that it turned too far on one side and then too far on the other. As a result the machine would rise suddenly to about ten feet, and then as suddenly dart for the ground. A sudden dart when a little over a hundred feet from the end of the track, or a little over 120 ft from the point at which it rose into the air, ended the flight. As the velocity of the wind was over 35 ft per second and the speed of the machine over the ground against this wind ten feet per second, the speed of the machine relative to the air was over 45 ft per second, and the length of the flight was equivalent to a flight of 540 feet made in calm air. This flight lasted only 12 seconds, but it was nevertheless the first in the history of the world in which a machine carrying a man had raised itself by its own power into the air in full flight, had sailed forward without reduction of speed and had finally landed at a point as high as that from which it started.”

Orville Wright writing about the first successful flight of a heavier-than-air flying machine from Kill Devil Hills, North Carolina, on 17 December, 1903²

1.1 Introduction

The history of aerospace engineering is full of firsts, such as the first balloon flight, the first airplane flight, the first helicopter flight, the first artificial satellite flight, the first manned spacecraft flight, and many others. In this first chapter, these many firsts are discussed in the context of the aerospace engineering involved in making these historic events happen. The first flight of a new vehicle design is a significant achievement and milestone. It is usually the culmination of years of hard work by many people, including engineers, technicians, managers, pilots, and other support personnel. First flights often represent firsts in the application of new aerospace engineering concepts or theories that are being validated by the actual flight.

As an aerospace engineer, you have the opportunity to contribute to the first flight of a new aircraft, a new spacecraft, or a new technology. Aerospace engineers are involved in all facets of the design, analysis, research, development, and testing of aerospace vehicles. This encompasses many different aerospace engineering discipline specialties, including aerodynamics, propulsion, performance, stability, control, structures, systems, and others. Several of these fundamental disciplines of aerospace engineering are introduced in this text. The aerospace engineer tests the vehicle, on the ground and in flight, to verify that it can perform as predicted and to improve its operating

¹ John Thomas Daniels, Jr. (1873–1948) snapped the iconic photograph of the Wright brothers' historic first flight. Daniels was a member of the Kill Devil Hills, North Carolina, Life Saving Station, which relied on volunteers to respond to the frequent shipwrecks in this barrier island area. The Wright's *Flyer* made four flights on 17 December 1903, three of which were photographed. After the fourth and final flight, a gust of wind caught the airplane and Daniels grabbed a wing strut, attempting to hold the airplane down. He was caught between the biplane wings when the *Flyer* flipped over in the wind. Although the *Flyer I* was destroyed, Daniels was unhurt, and he would later recount that he had “survived the first airplane crash”.

² Orville Wright, *How We Made the First Flight* (1986) Federal Aviation Administration, Office of Public Affairs, Aviation Education Program, US Department of Transportation.

characteristics. Flight testing is usually the final test to be performed on the complete vehicle or system.

In many areas of engineering and technology, there is sometimes a perception that there is “nothing left to be done”, or that “there is nothing left to be invented”. The impressive successes of our aerospace past may appear, to some, to dim the prospects for future innovations. Aerospace engineers have indeed designed, built, and flown some of the most innovative, complex, and amazing machines known to humanity. However, there is still ample room for creativity and innovation in the design of aerospace vehicles, and opportunities for technological breakthroughs to make the skies and stars far more accessible. By the end of this textbook, you will have greatly increased your knowledge of aerospace engineering, but you will also be humbled by how much more there is to be discovered.

1.1.1 Organization of the Book

Aerospace engineering encompasses the fields of aeronautical and astronautical engineering. As a broad generalization, the aeronautical field tends to deal with vehicles that fly through the sensible atmosphere, that is, *aircraft*. Astronautics deals with vehicles that operate in the airless space environment, that is, *spacecraft*. Aerospace engineering is, in many ways, a merging of these two fields, and includes aircraft, spacecraft, and other vehicles that operate in both the air and space environments. In the coming sections, we get more precise with the definitions of the various types of aerospace vehicles, such as aircraft and spacecraft.

The material in the text is organized in an academic building-block fashion as shown in Figure 1.1. In Chapter 1, we start by defining and discussing some of the many different types of aircraft and spacecraft. Many first flights of these different types of aerospace vehicles are described, providing insights and perspectives into the development and evolution of aerospace engineering. The terms *aircraft* and *spacecraft* are clearly defined, along with definitions of the various parts, components, and assemblies that make up various examples of these types of vehicles. The reader also makes a literary “first flight” in a modern, supersonic jet airplane, which introduces many of the areas to be discussed in the coming chapters.

In Chapter 2, several *introductory concepts* in aerospace engineering and flight test are discussed. This chapter gives the reader some of the basic concepts and terminology, in aerospace

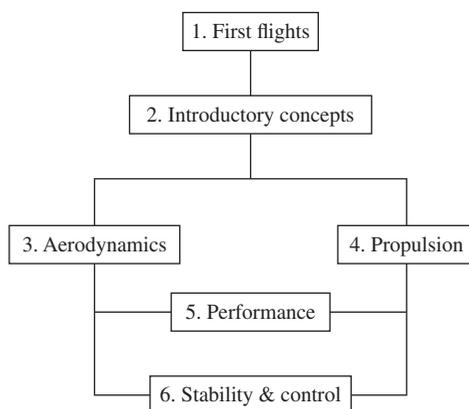


Figure 1.1 Academic building blocks followed in the text.

engineering and flight test, from which to learn the material in the subsequent chapters. Some basic mathematical ideas, definitions, and concepts are reviewed, which starts to fill our engineering toolbox with the basic tools required to analyze and design aerospace vehicles. Basic aerospace engineering concepts, relating to the flight of aerospace vehicles, are introduced, including aircraft axis systems, free-body diagrams, the regimes of flight, and the flight envelope. Basic flight test concepts are introduced, including the different types of flight test, the flight test process, the players involved, and the use of flight test techniques.

The fundamental disciplines of *aerodynamics* and *propulsion* are discussed in Chapters 3 and 4, respectively. The study of aerodynamics, in Chapter 3, provides the theories and tools required to analyze the flow of air over aerospace vehicles, the flow that produces aerodynamic forces such as lift and drag. We discover how and why these aerodynamic forces are created, and how this affects the design of aerodynamic surfaces such as airfoils and wings. In studying propulsion in Chapter 4, we learn about the devices that generate the thrust force to propel aerospace vehicles both in the atmosphere and in space. We develop a deeper understanding of how thrust is produced, regardless of the type of machinery that is used.

The study of *performance*, in Chapter 5, builds upon an understanding of aerodynamics and propulsion, as shown graphically in Figure 1.1. Performance deals with the linear motion of the vehicle caused by the aerodynamic forces (lift and drag) and propulsive force (thrust) acting upon it. Performance seeks to determine how fast, how high, how far, and how long a vehicle can fly.

In Chapter 6, the study of *stability and control* also builds upon the fundamental disciplines of aerodynamics and propulsion. Stability and control deals with the angular motion of the vehicle caused by the aerodynamic and propulsive moments acting on it. We investigate the vehicle's stability when disturbed from its equilibrium condition and seek to understand the impacts of various vehicle configurations and geometries. We also look at the means by which the vehicle can be controlled throughout its flight regime.

Many examples of ground and flight testing are integrated throughout the text, in sections entitled *Ground Test Techniques* and *Flight Test Techniques*. The flight test techniques are described in a unique manner, by placing the reader "in the cockpit" of different aircraft as the test pilot or flight test engineer. The reader obtains an intimate knowledge of the engineering concepts, test techniques, and in-flight data collection by "flying" the flight test techniques. A collateral benefit of this approach is that the reader is familiarized with several different types of real aircraft.

1.1.2 FTT: Your Familiarization Flight

This is the first of many flight test techniques (FTTs) that are "flown" in the text. The FTT is a precise and standardized method, used to efficiently collect data during flight test, research, and evaluation of aerospace vehicles. The FTT process is discussed in more detail in a later section of this chapter.

This first FTT introduces you to aerospace engineering in an exciting way, by taking a flight in a supersonic jet aircraft. A flight test engineer (FTE) often flies a *familiarization flight* in an aircraft prior to performing test flights, especially if this is an aircraft that is new to the FTE. As the name implies, this flight serves to *familiarize* the FTE with the aircraft and the flight environment. The areas of familiarization usually include the aircraft's performance, flying qualities, cockpit environment, avionics, or other special test equipment and instrumentation. The present FTT provides a general description of a familiarization flight, but the primary objective is to introduce you to a wide range of aerospace engineering and test concepts that are explored in later chapters. Your familiarization flight will raise many technical questions about aerospace engineering and flight test, and this provides motivation to seek answers in the chapters to come.



Figure 1.2 McDonnell Douglas F/A-18B *Hornet* supersonic fighter. (Source: *Courtesy of the author.*)

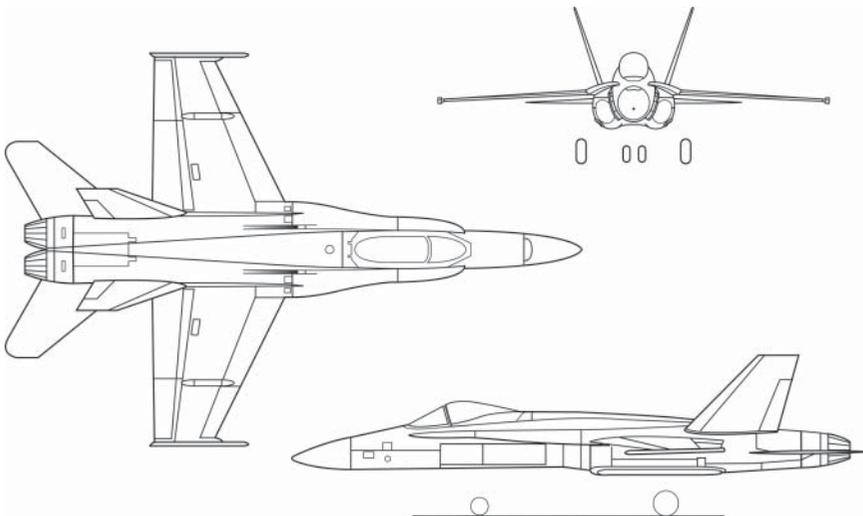


Figure 1.3 Three-view drawing of the McDonnell Douglas F/A-18A *Hornet* (single-seat version shown). (Source: NASA.)

For your familiarization flight, you will be flying the McDonnell Douglas (now Boeing) F/A-18B *Hornet* supersonic jet aircraft, shown in Figure 1.2. The F/A-18B is a two-seat, twin-engine, supersonic fighter jet aircraft, designed for launching from and landing on an aircraft carrier. Almost all aerospace vehicles are designated with letters and numbers, which we will decipher in a later section. A three-view drawing of the F/A-18A is shown in Figure 1.3. You will get very familiar

Table 1.1 Selected specifications of the McDonnell Douglas F/A-18B *Hornet*.

Item	Specification
Primary function	All-weather, supersonic fighter/attack jet aircraft
Manufacturer	McDonnell Douglas Aircraft, St Louis, Missouri
First flight	18 November 1978
Crew	1 pilot + 1 instructor pilot or flight test engineer
Powerplant	2 × F404-GE-400 afterburning turbofan engine
Thrust, MIL (ea. engine)	10,700 lb (47,600 N), military power
Thrust, MAX (ea. engine)	17,700 lb (78,700 N), maximum afterburner
Empty weight	~25,000 lb (11,300 kg)
Maximum takeoff weight	51,900 lb (23,500 kg)
Length	56 ft (17.1 m)
Height	15 ft 4 in (4.67 m)
Wingspan	37 ft 6 in (11.4 m)
Wing area	400 ft ² (37.2 m ²)
Airfoil, wing root	NACA 65A005 modified
Airfoil, wingtip	NACA 65A003.5 modified
Maximum speed	1190 mph (1915 km/h), Mach 1.7+
Service ceiling	>50,000 ft (>15,240 m)
Load factor limits	+7.5 g, -3.0 g

with these types of drawings of aerospace vehicles, where typically side, top, and front views of the vehicle are depicted. Selected specifications of the F-18 *Hornet* are given in Table 1.1. The chapters to come will help you understand all of the technical details in these specifications, such as what defines a “low bypass turbofan jet engine with an afterburner” or why wing area, maximum weights, or load factor limits are important.

Before you can go flying in an F-18, you need to be properly dressed. You don an olive-green flight suit, black flight boots, and an anti-G suit, an outer garment that fits snugly over the lower half of your body. Inflatable bladders, sewn into the anti-G suit, inflate with pressurized air to prevent blood from pooling in your lower extremities, keeping the blood in your head, so that you do not lose consciousness when the aircraft is maneuvering at high load factors or g’s. You slip your arms into a parachute harness that buckles around your chest and both legs. You are wearing the harness for the parachute, but not the actual parachute, as you will buckle this harness into your ejection seat, which contains your emergency parachute in the headrest.

With your flight helmet, oxygen mask, and kneeboard, a small clipboard-type writing surface, in your helmet bag, you walk out to the airport ramp, where the jet is parked. As you walk up to the aircraft, you note its general configuration. The aircraft has a slender fuselage with a low-mounted, thin wing, aft-mounted horizontal tail, twin vertical tails, and tricycle landing gear, comprising two main wheels, extending from either side of the fuselage, and a fuselage nosewheel. You observe that the landing gear looks quite sturdy, designed for harsh aircraft carrier landings. The jet is powered by twin engines, with semicircular air inlets on each side of the fuselage and side-by-side exhaust nozzles at the aft end of the fuselage. The two aviators sit in a tandem configuration, beneath a long “bubble” canopy that is hinged behind the aft cockpit. Your test pilot will be seated in the front cockpit and you will be in the aft cockpit.

You approach the aircraft from its left side, next to the cockpit, as shown in Figure 1.4. Before you climb into the cockpit, you perform a walk-around of the jet to learn a little more about it. Underneath the left wing, near the fuselage, you look into the left engine inlet, which is a semicircular