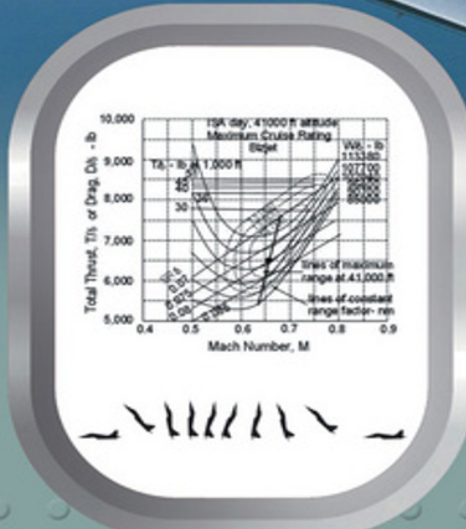

Ajoy Kumar Kundu,
Mark A. Price and David Riordan

Theory and Practice of Aircraft Performance

Aerospace Series
Editors Peter Belobaba, Jonathan Cooper and Allan Seabridge

WILEY

Theory and Practice of Aircraft Performance

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Theory and Practice of Aircraft Performance

AJOY KUMAR KUNDU
Queen's University Belfast
Belfast
UK

MARK A. PRICE
Queen's University Belfast
Belfast
UK

DAVID RIORDAN
Bombardier
Belfast
UK

WILEY

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Preface

This book is about estimating and appreciating the performance of conventional fixed winged aircraft of given designs. It is primarily meant for undergraduates, taking from introductory to advanced intensive courses on aircraft performance. It will also be useful for those in industry as training courses. Practising engineers will also find it helpful, especially for retraining and for those wishing to broaden their knowledge beyond their main area of specialization. We have left out treating VTOL/STOL and helicopters in their entirety – these are subjects by themselves, which require voluminous extensive treatment. We have also left out tilted rotor/vector thrust aircraft, UAVs and high-altitude aircraft performance analyses.

Today's engineers must have strong analytical and applied abilities to convert ideas into profitable products. We hope that this book will serve this cause by combining analytical methods and engineering practices, and adapting them to aircraft performance. New engineers are expected to contribute to the system almost immediately, with minimal supervision, and to do it "right-first-time." The methodology adopted herein is in line with what is practised in industry; the simplifications adopted for classroom use are supported by explanations so that an appreciation of industrial expectations will not be lost. The singular aim of this book is to prepare the reader, as far as possible, for industry-standard engineering practices: to enable new graduates to join industry seamlessly and to become productive as soon as possible. Technology can be purchased, but progress must be earned. We hope to prepare readers to contribute to progress.

The readers are assumed to have exposure to undergraduate engineering mathematics, aerodynamics and mechanics coursework. It is also assumed the reader will have some aircraft design experience. While the book is not on aircraft design, those design topics affecting aircraft performance are included here.

The presentation begins with the derivation of aircraft performance equations, followed by industry standard worked examples. Supporting materials are provided in the Appendices. Examples from engineering practice and "experience" are included. We would be grateful to receive suggestions and criticisms from readers; please contact the publisher or email to a.kundu@qub.ac.uk or M.Price@qub.ac.uk with any relevant information.

There are many excellent books treating the subject matter at various levels; all offer valuable exposure to aircraft performance. There are those that approach the topic classically, treating close-form analyses of exact equations obtained through assumptions. The examples do not represent real aircraft, but are close enough and powerful enough to represent capabilities and characteristics of the aircraft quickly and extensively. At the other extreme, there are simpler books appropriate to an undergraduate curriculum, exposing the barest essentials of aircraft performance. Our goal is to produce a new textbook reflecting some of the advances and presenting relatively detailed analyses as used in industry, tailored to an academic curriculum.

This book can be used in preparing an aircraft performance manual, which is nowadays computerized. Therefore, some operational aspects of commercial transport aircraft are included.

We thank Professor Michael Niu, Professor Jan Roskam (DARcorp), Professor Egbert Torenbeek, Dr Bill Gunston, the late Dr John McMasters (Boeing Aircraft Company), and the late Dr L. Pazmany. Richard Ferrier, Yevgeny Pashnin and Pablo Quispe Avellaneda allowed us to use their figures.

We are indebted to Jane's *All the World Aircraft Manual*, Flightglobal, BAE Systems, Europa Aircraft Company, Airbus, NASA, MIT, Boeing, Defense Advanced Research Projects Agency, Hamilton Standards, Virginia Tech Aerospace and Ocean Engineering, and General Atomics for allowing us to use their figures free of cost. All names are duly credited in their figures.

We offer our sincere thanks to Ms Anne Hunt, Associate Commissioning Editor, Mechanical Engineering, of John Wiley & Sons Ltd, the publisher of this book. Her clear, efficient and prompt support proved vital to reaching our goal. Dr. Samantha Jones's editing made substantial improvement to our book - our heartfelt thanks to her. Also, we thank Mr. Radjan Lourde Selvanadin of SPi Global for managing so efficiently and courteously the publication process.

There are many excellent web sites in the public domain. We gratefully acknowledge benefiting from them. We apologize if we have inadvertently infringed on any proprietary diagrams for educational purposes.

Ajoy K. Kundu
Mark A. Price
David Riordan

Series Preface

The field of aerospace is multidisciplinary 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 onto others working in the industry, including those just entering from university.

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 professions such as commercial and legal executives. The range of topics is intended to be wide-ranging, covering design and development, manufacture, operation and support of aircraft, as well as topics such as infrastructure operations and current advances in research and technology.

Aircraft performance concerns the prediction of how well an aircraft functions throughout its operation, and provides most of the key considerations for aircraft design, leading to the configurations and geometries that we see in today's modern aircraft. The topic is inherently multidisciplinary, requiring not only an understanding of a wide range of individual disciplines such as aerodynamics, flight mechanics, power plant, loads, and so on, but also an appreciation of how these fields interact with each other.

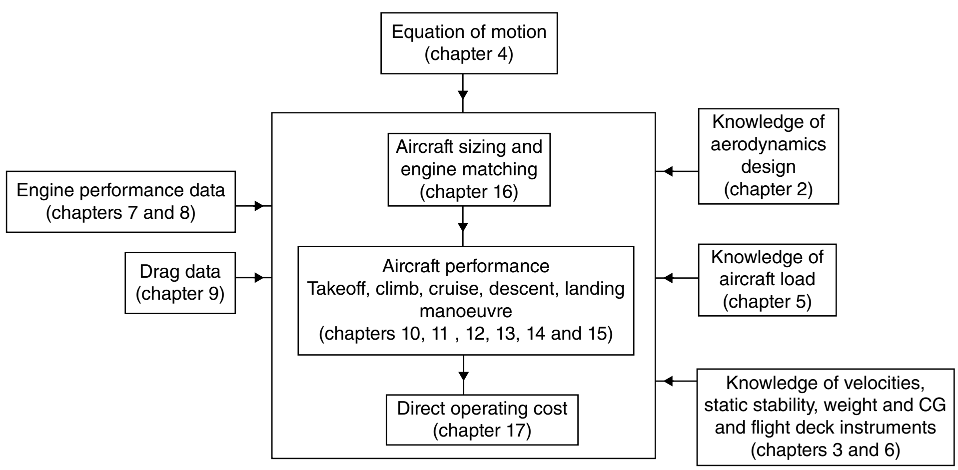
This book, *Theory and Practice of Aircraft Performance*, is a welcome addition to the Wiley Aerospace Series and complements a number of other titles. It tackles the subject from an industrial viewpoint, but is written in such a way as to be very suitable for the curriculum of undergraduate aero engineering courses. Following a comprehensive introductory section covering some fundamentals and background, a complete range of relevant topics is examined, including: aircraft design considerations, loads, stability, power plant, aerodynamics, operational performance and costing. Each chapter contains the appropriate detailed analysis combined with plenty of industrial-standard worked studies and classroom examples.

Peter Belobaba
Jonathan Cooper
Alan Seabridge

Road Map of the Book

Organization

In a step-by-step manner, I have developed a road map to learning industry standard aircraft performance methodology that can be followed in classrooms. Except for Chapter 1, the book is written in formal third-person grammatical usage. The chapters are arranged quite linearly, and there is not much choice in tailoring a course. While the course material progresses linearly, the following diagram depicts how the topics are interlinked.



Chapter 1 introduces some background material to prepare readers on the scope of aeronautical engineering. It gives broad coverage of some historical perspective, future trends, role of marketing, project phases from conception to completion, role of airworthiness requirements, and some miscellaneous topics. The main purpose of this chapter is to motivate readers to explore and learn about aircraft.

Chapter 2 covers atmosphere, aircraft aerodynamics and design considerations that influence aircraft performance and must be known to the engineers. This is the only chapter that could be browsed, as these topics are normally covered separately in academies. Chapter 3 introduces the definitions of various kinds of aircraft velocities, related topics on static stability, and some related flight deck instruments. The equations of motion for a flat stationary Earth are derived in Chapter 4, and classroom work starts from here. Next, the aircraft load limits are introduced in Chapter 5, as these define the aircraft performance envelope. Stability considerations are dealt with in Chapter 6; understanding aircraft stability is essential to performance analyses. Aircraft performance computations cannot start without engine performance data, and they are dealt with in Chapters 7 and 8. Aircraft drag data is evaluated in Chapter 9.

Chapters 10 to 15 present the core treatment of aircraft performance. Aircraft sizing and engine matching are done by aircraft performance engineers, and dealt with in Chapter 16 in a formal manner after completing studies on performance. The methodology is treated uniquely in close conformation with industry practices, and is an indispensable part of analyses at the conceptual design phase of a project, as it finalizes aircraft configuration and demonstrates compliance with customer specifications. The procedure offers a "satisfying" solution to generating a family of aircraft variants. This approach is widely practised by all major aircraft manufacturing organizations. The chapter also permits parametric sensitivity studies, which will eventually prove the key to success through balancing comfort with cost in a fiercely competitive market. Readers are encouraged to study aircraft design considerations along with performance analyses. It is to be stressed all the time that aircraft safety is never compromised. Each chapter starts with an overview, a summary of what is learnt, and the classroom work content.

Direct operating cost estimates are looked at in Chapter 17. For commercial aircraft the economic factors are the most important considerations, and for military aircraft it is the performance. Safety and reliability is never sacrificed. The importance of developing the configurations in a family concept is emphasized. The variants can emerge at a low cost by retaining component commonality and covering a wider market area: one might say, lightheartedly, "Design one and get the second at half the development cost". Finally, Chapter 18 concludes by discussing some miscellaneous topics related to aircraft performance.

Appendices A and B give the conversion factors and the ISA day atmospheric tables for both the SI and Imperial systems. Appendix C covers some important formulae. Appendix D gives a basic review on matrices and determinants required to study equations of motion and some important equations. Appendix E gives the problem sets for the pertinent chapters. It is recommended that these should be worked out. Appendix F gives a case study of the class Airbus 320 aircraft. Finally, Appendix G considers some interesting aerofoil in wide usage. This book is meant to reflect what aircraft performance engineers do in industry and airline operation.

Jane's Aircraft Manual [1] is an indispensable book for the vital statistics of aircraft geometries, design data and relevant performance details. This yearly publication has served many generations of aeronautical engineers around the world for more than half a century. The data from *Jane's Aircraft Manual* can be used to compare classroom work on similar types of aircraft. Flightglobal.com is another good source to study cutaway diagrams of aircraft and engines. Products from different origins do show similarities, and this is picked up as a strong statistical pattern, which can help to give an idea of what is to be expected in a new design (Section 18.9). Readers should prepare their own statistics for the type of aircraft under study. Other useful publications are [2] to [5]. I would recommend the readers to look at the Virginia Tech web site on Aircraft Design Bibliographies [6]. Their compilation of aircraft design information sources is comprehensive. Related web sites also give useful data.

Many categories of aircraft have been designed. I have chosen the important ones that will broadly cover a wide range of classroom exercises; these will provide adequate exposure for the students. The associated examples in the book would be those of four cases: (i) a turbofan powered Learjet 45 class business jet (Bizjet); (ii) a turboprop powered propeller-driven Tucano class military trainer aircraft (TPT); (iii) a military advanced jet trainer (AJT) in the class of BAe Hawk that has a close support role variant; and (iv) performance computation of a high subsonic jet in the class of Boeing 737/Airbus 320 aircraft is given in Appendix E. These are the types recommended as the most suitable for classroom projects. Classroom methodology should be in harmony with industrial practices, otherwise the gap between academy and industry might widen.

Case studies are indispensable in the course of learning in the classroom. Example exercises must bear high fidelity with the real ones – I take some satisfaction in providing real world examples modified to classroom usage to maintain commercial confidence. These are not from any academic projects, but follow the designs of the real ones worked out by myself. At this point, I highlight that the results are not those from the industry, but have been compared with the performance data available. Industry is not liable for what I present here.

The book gives full coverage of worked-out examples. Instructors have the flexibility to generate problem assignment sets at the level of class requirements. I strongly recommend the adoption of manual computation, leaving the repetitive aspects to spreadsheets to be developed by the students as part of their learning process. This is essential if students are to develop a feel for numbers and to learn the labour content of a design (it is expensive to make mid-course changes). Also, extensive theoretical treatment is embedded for research workers to extend their analytical work. It is common nowadays to provide CDs as companion software. I have elected not to follow this practice because the supplied software to handle repetitive tasks constrains students to interact more deeply with the governing equations, which is an important part of the learning experience.

If students elect to use off-the-shelf software, then let it be the reputable ones. However, these are more meaningful after the subject is well understood, that is, after completing the course with manual computation. This will lead to an appreciation of how realistic the computer output is and how to make changes in input to improve results. It is better to postpone the usage of aircraft performance software until one joins industry. In academia, a student can use computational fluid dynamics (CFD) and finite element method (FEM) analyses as computer-aided engineering (CAE). Today's students are proficient with computers and can generate their own programs.

Suggested Structure for the Coursework

The author suggests a typical pathway for one term of 36 hours of classroom contact hours – 24 hours of lectures and 12 hours of tutorials. [A note of caution: what is done in about 36 hours of classroom lectures takes about 36 weeks in industry.]

		Classroom lecture (contact) hours
1.	Coverage of Chapter 1 and some topics from Chapter 2 as selected by the instructor (other topics are to be sandwiched as and when required).	1
2.	Chapter 3 – to cover velocities, stability criteria, etc.	1.5
3.	Equation of motion – Chapter 4.	2
4.	Aircraft load – Chapter 5.	1
5.	Air stability, weights and CG – Chapter 9.	0.5
6.	Engine performance (establish engine data) – Chapters 7 and 8.	2.5
7.	Drag estimation – Chapter 9.	2
8.	Fundamentals of aircraft performance analyses, payload range – Chapter 10.	2.5
9.	Field performance (takeoff and landing) – Chapter 11.	2

(*Continued*)

(*Continued*)

		Classroom lecture (contact) hours
10.	Climb and descent performance – Chapter 12.	2
11.	Cruise performance – Chapter 13.	2
12.	Aircraft mission analyses – Chapter 14.	2
13.	Manoeuvre – Chapter 15.	1
14.	Aircraft sizing and engine matching – Chapter 16.	1.5
15.	Aircraft operating costs– Chapter 17.	1
16.	Miscellaneous (optional) – Chapter 18.	0.5
	Total	25 lecture hours

Of course, instructors are free to plan their course as it suits them.

Ajoy K. Kundu

Acknowledgements

By A.K. Kundu

Throughout my career, which began in the 1960s and continues in the twenty-first century, I have had the good fortune of witnessing many aerospace achievements, especially putting mankind on the Moon. A third of my career has been spent in academia and two-thirds in industry. I owe a lot to many.

I thank my teachers, heads of establishments/supervisors, colleagues, students, shop-floor workers, and all those who taught and supported me during my career. I remember the following (in no particular order) who have influenced me – the list is compact for the sake of brevity, and there are many more individuals to whom I owe my thanks.

***Teachers/Academic Supervisors/Instructors*:**

The late Professor Triguna Sen of Jadavpur University.

The late Professor Holt Ashley and Professor Samuel McIntosh of Stanford University.

Professor Arthur Messiter and Professor Martin Sichel of University of Michigan.

Professor James Palmer of Cranfield University.

The late Squadron Leader Ron Campbell, RAF, of Cranfield University (Chief Flying Instructor).

***Heads of Establishments/Supervisors*:**

The late Dr Vikram Sarabhai, Indian Space Research Organisation.

James Fletcher, Short Brothers and Harland, Belfast.

Robin Edwards, Canadair Limited, Montreal.

Kenneth Hoefs, Head of the New Airplane Project group of Boeing Company, Renton, USA.

Wing Commander Baljit Kapur, Chairman of Hindustan Aeronautics Limited (HAL), Bangalore.

The late Mr Raj Mahindra, MD (D&D), Hindustan Aeronautics Limited (HAL), Bangalore.

Tom Johnston, Director and Chief Engineer, Bombardier Aerospace-Shorts (BAS), Belfast.

Dr Tom Cummings, Chief Aerodynamicist, Bombardier Aerospace-Shorts (BAS), Belfast.

I am grateful to Boeing Company, Hindustan Aeronautics Ltd (*HAL*) and Bombardier Aerospace-Short (*BAS*) and proud to be associated with them. I learnt a lot from them. I started my aeronautical career with BAS (then Short Brothers and Harland Ltd), and after a long break rejoined and then retired from the company, the first aerospace company to celebrate its centenary. Many of my examples are based on my work in those companies.

I am indebted to my long-time friend and ex-colleague at Boeing Company, Mr Stephen Snyder, a registered Professional Engineer and now independent aviation consultant. I offer my thanks to Anthony Hays of Aircraft Design and Consulting, San Clemente, for his help in professional matters. Suggestions by Professor (Emeritus) Bernard Etkin of the University of Toronto and Professor Dieter Scholz of Hamburg University are gratefully appreciated with thanks. I thank my present and former colleagues (Rev. Dr John Watterson and Dr Theresa Robinson) and former students (Dr Mark Bell and Christina Fanthorpe) for their help.

I am thankful to have my former colleagues Colin Elliott, Vice President of Engineering and Business Development, James Tweedie and Lesley Carson, both Senior Engineers, BAS, help me bring out an industry-standard book.

I offer my thanks to Cambridge University Press for allowing me to use some of the materials of my earlier book entitled *Aircraft Design* (ISBN 978-0-521-88516-4), assisted by the support of their Senior Editor Mr Peter Gordon.

My grandfather, the late Dr Kunja Behari Kundu, my father the late Dr Kamakhya Prosad Kundu, and my cousin-brother the late Dr Gora Chand Kundu are long gone, but they kept me inspired and motivated to remain studious. My wife Gouri's tireless support saved me from being a hunter-gatherer, keeping me comfortable while sparing the time to write this book. Would mere thanks be enough for them?

I had my aeronautical education in the UK and in the USA; I worked in India, the UK and North America. In today's world of cooperative ventures among countries, especially in the defence sector, the methodologies adopted in this book should apply. I dedicate this book to all those organizations (listed under acknowledgements) where I learnt a lot, and that is what I have included in this book. These organizations gave me the best education, their best jobs and their best homes.

I am very fortunate to be able to join with my long-standing colleagues Professor Mark Price, Pro-Vice-Chancellor for the Faculty of Engineering and Physical Sciences at Queen's University Belfast. Formerly, he was the Head of School of Mechanical and Aerospace Engineering. (Queen's University, Belfast) and Mr David Riordan, Senior Engineering Advisor, Nacelles Design and Powerplant Integration (Bombardier Aerospace, Belfast) as co-authors. I have gained a lot from these two brilliant young friends, beyond being just colleagues, and naturally sought their contributions to get this old man supported.

By Mark Price

Before taking up an academic position in the late 1990s, I spent a number of years in industry applying what knowledge I had gained to a variety of design and analysis problems. Often this was with difficulty, and often with that feeling of weakness than any engineer feels in the formative stages of their career, in the depth and extent of their knowledge. However, the challenges that come with bringing a working product to life help to mature an engineer, forcing them to understand the limits of their ability, and the theory on which they have based their decisions. It drives them to strive for better. And it was this desire for improvement that brought me into academia, where I encountered Ajoy, someone with the same motivation and commitment to always do things better, except he had vast experience and so much more knowledge. I have learned much from him, in both detail and approach, and it has been fun, challenging our way of thinking.

It is therefore a real honour for me to join with him in his publication ventures, but moreover I am delighted to do so. The concept of this book is to provide that bridge in knowledge between the undergraduate curriculum and the complex world within which a professional engineer exists. This is something which is lacking in most textbooks, and something which we all recognize we can do better. In this book Ajoy brings this combination of an intelligent approach with practical examples, and real scenarios, to the student. It both challenges and excites, creating a learning experience that will accelerate the formation of an engineer by embedding them from the start within real-world applications. I have learned much by being involved with the book, and I hope that all of you who read it will similarly learn, and that this book will be your stepping stone to developing your engineering knowledge to the highest standards.

I am thankful to Queens University, Belfast, for providing an environment supportive of educational development, and in particular the noble aim to provide graduates valuable to industry. Together with Ajoy, my contribution in this effort has been to shape the book to offer course material in line with industrial standard treatise.

I have many people to thank who have supported me in my career and my life thus far. My mentors, Mr Sam Sterling, Professor Raghu Raghunathan, and Professor Cecil Armstrong provided much in the way of guidance, wise words and sharp wit, in addition to standing as exemplars of their profession, providing excellence in education and research. My colleague Dr Adrian Murphy has worked alongside me from the start and has shared the many risks we took in developing new ideas to bring to a sceptical world. We have learned much together as we trod the path of mistakes and blind alleys. I thank the outstanding team of academics and support staff in Mechanical and Aerospace Engineering who make work such an enjoyable part of my life. I cannot thank enough my family, my wife Denise and my daughter Rachel, who have patience beyond their calling in allowing me space and time to fulfil my dreams. And lastly, my late father, Matt, instilled in me the virtue of delivering to the customer what they actually need, and hence my enthusiasm for this book, to fulfil a need for industry and the graduates they need.

By David Riordan

I count it a privilege to have been invited by Ajoy to contribute to this textbook. The enthusiasm of Ajoy in writing the book has been impressive, and at the same time inspiring to recognize that his motivation has solely been to share an accumulated lifetime's worth of knowledge and experience with the younger generation who may choose aerospace as a career, and subsequently contribute to the further development of aircraft design.

I first met Ajoy when, in the late 1980s as a relatively young engineer, I was assigned to the Aerodynamics department at Short Brothers PLC, Belfast. Even then, Ajoy was recognized as one who would not only provide technical direction and advice when required to help progress the task, but who would also help to ensure you understood the basic fundamentals of aerodynamics and the relevance of the assigned task to the development of new aircraft designs. Reflecting on those times of new aircraft design concepts for regional jet aircraft design, it is amazing to realise what was achieved at a time when computer-based analysis tools were not as prolific as they are today.

Each chapter of this textbook has necessitated many long hours of effort and research for Ajoy. The content reflects Ajoy's broad exposure to the many specialist disciplines required to integrate a successful new aircraft design. For me, the explanations of aircraft aerodynamic drag are the best to appear in contemporary textbooks. With this new book, Ajoy's contribution to both academic and industrial learning is admirable. I trust that those reading the book will both benefit therefrom and at the same time appreciate the abilities and diligence of its principal author, who I have found to be a true gentleman: a colleague and friend.

I am thankful to my employer, Bombardier Aerostructures and Engineering Services, Belfast (Short Brothers PLC), who has afforded me the opportunity to work with many different aerospace companies and engineering professionals from all over the world, since I started with the company in September 1978. No other career could have been so enjoyable or as rewarding.

The patient support of my wife, Hazel, over the years, and also of my two sons, Matthew and Jack, has been appreciated. They have each taught me to realise that, no matter what enjoyment aerospace engineering might bring, nothing surpasses the pleasure of having a supporting family with which to share life's experiences.

Nomenclature

Symbols

A	area
A_1	intake highlight area
APR	augmented power rating
A_{th}	throat area
A_W	wetted area
AR	aspect ratio
A_W	wetted area
a	speed of sound, acceleration
ā	average acceleration at $0.7\,V_2$
ac	aerodynamic centre
b	span
C_R, C_B	root chord
C_D	drag coefficient
C_{Di}	induced drag coefficient
C_{Dp}	parasite drag coefficient
C_{Dpmin}	minimum parasite drag coefficient
C_{Dw}	wave drag coefficient
C_v	specific heat at constant volume
C_F	overall skin friction coefficient, force coefficient
C_f	local skin friction coefficient, coefficient of friction
C_L	lift coefficient
C_l	sectional lift coefficient, rolling moment coefficient
C_{Li}	integrated design lift coefficient
$C_{L\alpha}$	lift curve slope
$C_{L\beta}$	side-slip curve slope
C_M	pitching moment coefficient
C_n	yawing moment coefficient
C_p	pressure coefficient, power coefficient, specific heat at constant pressure
C_T	thrust coefficient
C_{HT}	horizontal tail volume coefficient
C_{VT}	vertical tail volume coefficient
C_{xxxx}	cost with subscript identifying parts assembly
C'_{xxxx}	cost heading for the type
CC	combustion chamber

CG	centre of gravity
c	chord
c_{root}	root chord
c_{tip}	tip chord
cp	centre of pressure
D	drag, diameter
D_{skin}	skin friction drag
D_{press}	pressure drag
d	diameter
E	modulus of elasticity
e	Oswald's factor
F	force
f	flat plate equivalent of drag, wing span
f_c	ratio of speed of sound (altitude to sea level)
F_{ca}	aft fuselage closure angle
F_{cf}	front fuselage closure angle
F_B	body axis
F_I	inertial axis
F_W	wind axis
F_{xxx}	component mass fraction, subscript identifies the item
F/m_a	specific thrust
FR	fineness ratio
g	acceleration due to gravity
H	height
h	vertical distance, height
J	advance ratio
k	constant, sometimes with subscript for each application
L	length, lift
L_{FB}	nacelle fore-body length
L_N	nacelle length
L_{VT}	vertical tail-arm
L_{HT}	horizontal tail-arm
L	length
M	mass, moment
M_f	fuel mass
M_i	component group mass, subscript identifies the item
M_{xxx}	component item mass, subscript identifies the item
m	mass
$\dot{m}_a$	air mass flow rate
$\dot{m}_f$	fuel mass flow rate
$\dot{m}_p$	primary (hot) air mass flow rate (turbofan)
$\dot{m}_s$	secondary (cold) air mass flow rate (turbofan)
N	number of blades, normal force
N_e	number of engines
n	revolutions per minute, load factor
nm	nautical miles
P, p	static pressure
p'	angular velocity about Y-axis
p_e	exit plane static pressure
p_∞	atmospheric (ambient) pressure

P_t, p_t	total pressure
Q	heat energy of the system
q	dynamic head, heat energy per unit mass
q'	angular velocity about Z-axis
R	gas constant, reaction
Re	Reynolds number
Re_{crit}	critical Reynolds number
r	radius, angular velocity
r'	angular velocity about X-axis
S	area, most of the time with subscript identifying the component
S_H	horizontal tail reference area
S_n	maximum cross-sectional area
S_W	wing reference area
S_V	vertical tail reference area
sfc	specific fuel consumption
T	temperature, thrust, time
T_C	non-dimensional thrust
T_F	non-dimensional force (for torque)
T_{SLS}	sea-level static thrust at takeoff rating
T/W	thrust loading
t/c	thickness to chord ratio
tf	turbofan
U_g	vertical gust velocity
U_∞	freestream velocity
u	local velocity along X-axis
V	freestream velocity
V_A	aircraft stall speed at limit load
V_B	aircraft speed at upward gust
V_C	aircraft maximum design speed
V_D	aircraft maximum dive speed
V_S	aircraft stall speed
V_e	exit plane velocity (turbofan)
V_{ep}	primary (hot) exit plane velocity (turbofan)
V_{es}	secondary (cold) exit plane velocity (turbofan)
W	weight, width
W_A	useful work done on aircraft
W_E	mechanical work produced by engine
W/S_w	wing loading
x	distance along X-axis
y	distance along Y-axis
z	vertical distance

Greek Symbols

α	angle of attack
β	CG angle with vertical at main wheel, blade pitch angle, side-slip angle
Γ	dihedral angle, circulation
γ	ratio of specific heat, fuselage clearance angle
Δ	increment measure
δ	boundary layer thickness
ε	downwash angle

η_t	thermal efficiency
η_p	propulsive efficiency
η_o	overall efficiency
Λ	wing sweep, subscript indicates at the chord line
λ	taper ratio
μ	friction coefficient, wing mass
ρ	density
θ	elevation angle, flight path angle, fuselage upsweep angle
π	constant = 3.14
σ	atmospheric density ratio
τ	thickness parameter
υ	velocity
ϕ	roll angle, bank angle
ψ	azimuth angle, yaw angle
ω	angular velocity

Subscripts

[In many cases the subscripts are spelled out and not listed here.]

a	aft
ave	average
ep	primary exit plane
es	secondary exit plane
f	front, fuselage
f_b	blockage factor for drag
f_h	drag factor for nacelle profile drag (propeller driven)
fus	fuselage
HT	horizontal tail
M	middle
N, nac	nacelle
o	freestream condition
p	primary (hot) flow
s	stall, secondary (cold) flow
t, tot	total
w	wing
VT	vertical tail
∞	freestream condition

Abbreviations

AB	afterburner
ACAS	advanced close air support
ACM	air combat manoeuvre
ACT	active control technology
ADC	air data computer
AEA	Association of European Airlines
AEW	airborne early warning
AF	activity factor
AFM	aircraft flight-track monitoring, aircraft flight manual
AGARD	Advisory Group for Aerospace Research and Development
AGL	average ground level

AHM	aircraft health monitoring
AIAA	American Institute for Aeronautics and Astronautics
AJT	advanced jet trainer
ALD	actual landing distance
AMPR	aeronautical manufacturer's planning report
AO	angle off
AOA	angle of attack
AOB	angle of bank
APM	aircraft performance monitoring/management
APR	augmented power rating
APU	auxiliary power unit
AR	aspect ratio
ARINC	Aircraft Radio Inc.
ASD	accelerate-stop distance
ASDA	accelerate-stop distance available
ASI	airspeed indicator
AST	Air Staff Target
ATA	Aircraft Transport Association
ATC	air traffic control
ATF	advanced tactical fighter
AVGAS	aviation gasoline (petrol)
AVTUR	aviation turbine fuel (kerosene)
BAS	Bombardier Aerospace–Shorts
BFL	balanced field length
BFM	basic fighter manoeuvre
BHP	brake horse power
BOM	bill of material
BPR	bypass ratio
BRM	brake release mass
BVR	beyond visual range
BWB	blended-wing body
CAA	Civil Aviation Authority (UK)
CAD	computer-aided design
CAE	computer-aided engineering
CAM	computer-aided manufacture
CAS	close air support, calibrated air speed, control augmentation system
CAT	clear air turbulence
cc/c	flap chord to aerofoil chord ratio
CCV	control configured vehicle
CFC	chlorofluorocarbon
CFD	computational fluid dynamics
CFL	critical field length
CFR	Code of Federal Regulation
CG	centre of gravity
COC	cash operating cost
CS	Certification Standard
CTOL	conventional takeoff and landing
CV	control volume
CWY	clearway
DCPR	defence contractor's planning report

DBT	design built team
DF	drift angle
DFFS	design for Six Sigma
DFM/A	design for manufacture/assembly
DLM	design landing mass
DOC	direct operating cost
DOM	dry operational mass
DOT	Department of Transport
EAS	equivalent airspeed
EASA	European Aviation Safety Agency
ECS	environmental control system
ED	engine display
EF	endurance factor
EFIS	electronic flight information system
EGT	exhaust gas temperature
EI	emissions index
EPA	Environmental Protection Agency
EPNL	effective perceived noise level
EPR	exhaust pressure ratio, engine pressure ratio
ESHP	equivalent SHP (shaft horse power)
ETOPS	extended twin-engine operations
ETP	equal time point
EW	electronic warfare
FAA	Federal Aviation Administration
FADEC	full authority digital engine control
FAR	Federal Aviation Regulation
FBL	fly-by-light
FBW	fly-by-wire
FCOM	flight crew operating manual
FE	field elevation
FEM	finite element method
FF	fuel flow
FI	Fatigue Index
FL	flight level
FOC	fixed operating cost
FPS	foot, pound, second
FR	fineness ratio
FS	factor of safety
FTM	flight test manual
HMD	helmet-mounted display
HOTAS	hands-on throttle and stick
HP	horse power, high pressure
HSC	high-speed cruise
HST	hypersonic transport
H-tail	horizontal tail
HUD	head-up display
IA	indicated altitude
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IGE	in-ground effect

ILS	instrument landing system
INCOSE	International Council of Systems Engineering
IOC	indirect operating cost
IPPD	integrated product and process development
ISA	International Standard Atmosphere
JAA	Joint Aviation Authorities
JAR	Joint Airworthiness Requirements
JPT	jet pipe temperature
JUCAS	Joint Unmanned Combat Air System
KE	kinetic energy
KEAS	knots equivalent air speed
LCA	light combat aircraft
LCC	life cycle cost
LCD	liquid crystal display
LCN	load classification number
LCR	lip contraction ratio
L/D	lift-to-drag (ratio)
LDA	landing distance available
LE	leading edge
LF	load factor
LFL	landing field length
LO	low observable
LOH	liquid hydrogen
LP	low pressure
LPO	long period oscillation
LRC	long-range cruise
MAC	mean aerodynamic chord
MDA	multidisciplinary analysis
MDO	multidisciplinary optimization
MEM (W)	manufacturer's empty mass (weight)
MFD	multifunctional display
MFR	mass flow rate
MGC	mean geometric chord
MLM	maximum landing mass
MoD	Ministry of Defence
MOGAS	motor gasoline (petrol)
MPM	manufacturer process management
MRM (W)	maximum ramp mass (weight)
MTBF	mean time before failure
MTM	maximum taxi mass
MTOM (W)	maximum takeoff mass (weight)
MTTR	mean time to repair
NACA	National Advisory Committee for Aeronautics
nam	nautical air miles
NASA	National Aeronautics and Space Administration
NBAA	National Business Aviation Association
NCS	normal climb speed
ND	navigational display
nm	nautical miles
NP	neutral point

NRC	non-recurring cost
NTC	normal training configuration
OAT	outside air temperature
OEM (W)	operating empty mass (weight)
OEMF	operating empty mass fraction
OGE	out-of-ground effect
OPR	overall pressure ratio
PCU	power control unit
PE	potential energy
PFD	primary flight display
PHA	positive high angle of attack
PIA	positive intermediate angle of attack
PLA	positive low angle of attack
PLM	product life cycle management
PNL	perceived noise level
PNR	point of no-return
PPR	product, process and resource
psfc	power specific fuel consumption
RAeS	Royal Aeronautical Society
RAF	Royal Air Force
RAE	Royal Aircraft Establishment
RAT	ram air turbine
RC	recurring cost
RCS	radar cross-section
RF	range factor
RFP	Request for Proposal
RJ	regional jet
RLD	required landing distance
RPM	revolutions per minute, revenue passenger miles
RPS	revolutions per second
RPV	remotely piloted vehicle
RSA	runway safety area
RTOW	regulatory takeoff weight
SAS	stability augmentation system
SAT	static air temperature
SD	system display
SE	specific energy
SEP	specific excess power
sfc	specific fuel consumption
SHP	shaft horse power
SI	Système International
SPL	sound pressure level
SPO	short period oscillation
SR	specific range
SST	supersonic transport
STOL	short takeoff and landing
SWY	stopway
TA	true altitude
TAF	total activity factor
TAS	true airspeed

TAT	total air temperature
TBO	time between overhauls
TE	trailing edge
TET	turbine entry temperature
TGT	turbine guide-vane temperature
TOC	total operating cost
TOD	takeoff distance
TODA	takeoff distance available
TOFL	takeoff field length
TOR	takeoff run
TORA	takeoff run available
TPT	turboprop trainer
TQM	total quality management
TR	thrust reverser
tsfc	thrust specific fuel consumption
TTOM	typical takeoff mass (military)
T&E	training and evaluation
UAV	unmanned air vehicle
UBFL	unbalanced field length
UCA	unmanned combat aircraft
UHBPR	ultra-high bypass ratio
UHC	unburned hydrocarbon
ULD	unit load device
VSI	vertical speed indicator
V-tail	vertical tail
VTOL	vertical takeoff and landing
WAT	weight, altitude and temperature
WS	wind speed
ZFM (W)	zero fuel mass (weight)

CHAPTER 1

Introduction

1.1 Overview

This book begins with a brief historical introduction, surveying our aeronautical legacy to motivate readers by describing the remarkable progress we have made from mythical conceptions of flight to high-performance aircraft with capabilities unimagined by early aeronautical pioneers. This chapter continues with offering a brief introduction to aircraft fundamentals and aircraft flight mechanics, which form the basics of aircraft performance. The chapter also presents the issues involved with units and dimensions in this context.

1.2 Brief Historical Background

Many books cover the broad sweep of aeronautical history, while others discuss specific accomplishments and famous people's achievements in aeronautics. References [1] to [4] are good places to start your exploration. Innumerable web sites on historical topics and technological achievements exist; simply enter keywords such as Airbus, Boeing, or anything that piques your curiosity, and you will find a wealth of information.

1.2.1 Flight in Mythology

People's desire to fly is ancient – every civilization has their early imaginations embedded in mythologies. In human efforts there are the well-known examples such as Daedalus/Icarus, vimanas (aircraft), flying carpets, flying chariots, and so on. In creatures, there are the bird-men (Garuda), flying horses (Pegasus/Sleipnir), flying dragons – our imagination of flight is universal.

History is unfortunately more "down to earth" than mythology, with stories about early pioneers who leapt from towers and cliffs, only to leave the Earth in a different but predictable manner because they did not respect natural laws. Our dreams and imagination became reality only a little over a century ago on 17 December 1903, when the Wright brothers succeeded with the first powered heavier-than-air flight. It only took 65 years from that date to land a man on the Moon.

1.2.2 Fifteenth to Nineteenth Centuries

Tethered kites are recorded to have flown in China as long ago as 600 BC. However, the first scientific attempts to design a mechanism for aerial navigation are credited to Leonardo da Vinci (1452–1519). He was the true "grandfather" of modern aviation, even if none of his

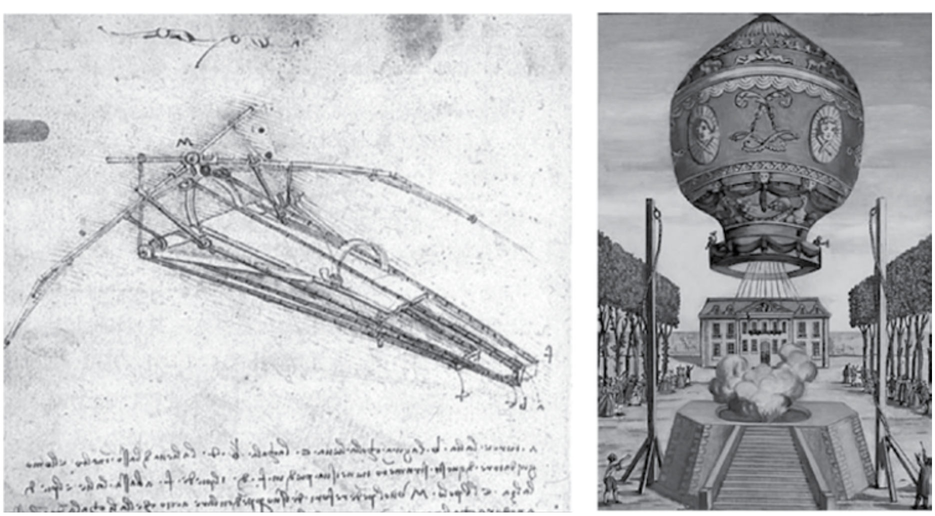
Theory and Practice of Aircraft Performance, First Edition. Ajoy Kumar Kundu, Mark A. Price and David Riordan.

machines ever defied gravity (Figure 1.1), because he sketched many contraptions in his attempt to make a mechanical bird. Birds possess such refined design features that the initial human path into the skies could not take that route, but today's micro-air devices are increasingly exploring natural designs. After da Vinci, there was an apparent lull for more than a century until Sir Isaac Newton (1642–1727), who computed the power required to make sustained flight. Perhaps we lack the documentary evidence, but we are convinced that the human fascination with and endeavour for flight did not abate. Flight is essentially a practical matter, so real progress paralleled other industrial developments (e.g. isolating gas required for buoyancy).

While it appears that Bartolomeu de Gusmao may have demonstrated balloon flight in 1709 [4] in Portugal, information on this event is still lean. So we credit Jean-François Pilâtre de Rozier and François Laurent d'Arlandes as the first people to effectively defy gravity, using a Montgolfier balloon (Figure 1.1) in France in 1783. For the first time, it was possible to sustain and somewhat control flight above the ground at will. However, these balloon pioneers were subject to the prevailing winds and were thus limited in their navigational options. To become airborne was an important landmark in human history. The Montgolfier brothers (Joseph and Etienne) should be considered among the "fathers" of aviation. In 1784, Jean-Pierre Blanchard (France) with Dr John Jeffries (USA) added a hand-powered propeller to a balloon and made the first aerial crossing of the English Channel on 7 January 1785. (Jules Verne's fictional balloon trip around the world in 80 days became a reality when the late Steve Fossett circumnavigated the globe in fewer than 15 days in 2002.) In 1855, Joseph Pline was the first to use the word *aeroplane* in a paper he wrote proposing a gas-filled dirigible glider with a propeller.

It was not until 1804 that the first recorded controllable heavier-than-air machine to stay freely airborne was recorded when Englishman Sir George Cayley constructed and flew a kite-like glider (Figure 1.2) with movable control surfaces. In 1842, the English engineer Samuel Henson secured a patent on an aircraft design that was driven by a steam engine.

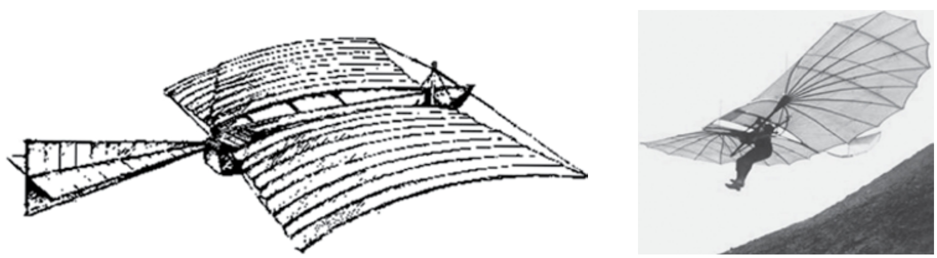
With his brother Gustav, Otto Lilienthal was successfully flying gliders (Figure 1.2) in Berlin more than a decade (1890) before the Wright Brothers' first experiments. His flights



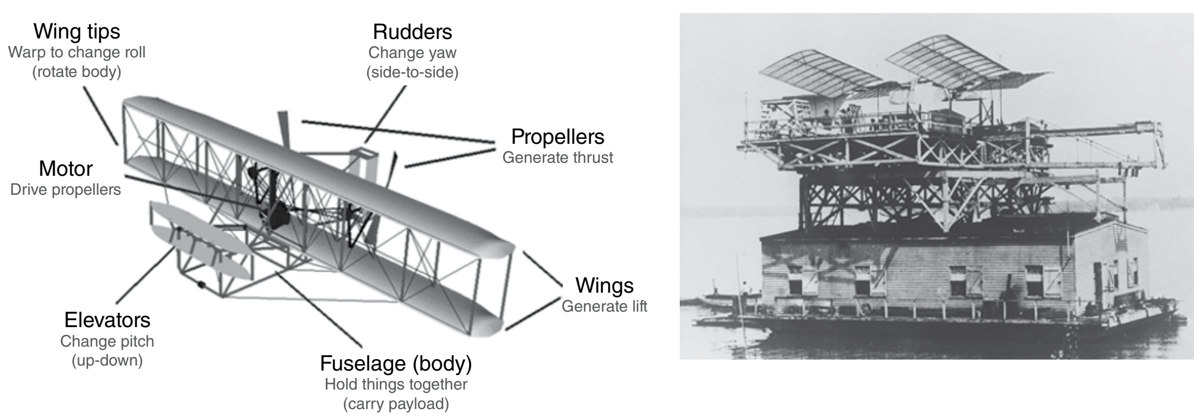
■ **FIGURE 1.1** **Early concepts and reality of flying: Leonardo da Vinci's flying machine, and the Montgolfier Balloon (reproduced with permission of NASA)** were controlled but not sustained. The early flight machine designs were hampered by an overestimation of the power requirement needed for sustained flight. This mistake (based in part on Newton's, among others, calculations) may have discouraged attempts of the best German engine-makers of the time to build aircraft engines because they would have been too heavy. Sadly, Lilienthal's aerial developments ended abruptly and his experience was lost when he died in a crash in 1896.

1.2.3 From 1900 to World War I (1914)

The question of who was first in flight is an important event to remember. The Wright Brothers (United States) are recognized as the first to achieve sustained, controlled flight in a heavier-than-air manned flying machine (Wright Flyer, Figure 1.3). Before discussing their achievement, some "also-rans" deserve mention. John Stringfellow accomplished the first powered flight of an unmanned heavier-than-air machine in 1848 in England. In France, Clement Ader also made a successful flight in his "Eole". Gustav Weisskopf (Whitehead), a Bavarian who migrated to the US, claimed to have made a sustained, powered flight [3] on 14 August 1901, in Bridgeport, Connecticut. Karl Jatho of Germany made a 200-foot hop (longer than the Wright Brothers first flight) powered (10-HP Buchet engine) flight on 18 August 1903. At what distance a "hop" becomes a "flight" could be debated. Perhaps most significant are the efforts of



■ **FIGURE 1.2** **Early heavier-than-air unpowered aircraft: Cayley's kite plane, and one of Lilienthal's gliders (reproduced with permission of NASA)**



■ **FIGURE 1.3** **Early heavier-than-air powered aircraft: the Wright Flyer, and Langley's Aerodrome (reproduced with permission of NASA)**

Samuel P. Langley, who made three attempts to get his designs (Aerodrome) airborne with a pilot at the controls (Figure 1.3). His designs were aerodynamically superior to the Wright flyer, but the strategy to ensure pilot safety resulted in structural failure while catapulting from a ramp toward water. His model aircraft were flying successfully in 1902. (To prove the capability, subsequently in 1914 Curtiss made a short flight with a modified Aerodrome.) The failure of his aircraft also broke Professor Langley; a short time afterwards, he died of a heart attack. Professor Langley, a highly qualified scientist, had substantial government funding, whereas the Wright brothers were mere bicycle mechanics without any external funding.

The Wright Brothers' aircraft was inherently unstable, but good bicycle mechanics that they were, they understood that stability could be sacrificed if sufficient control authority was maintained. They employed a foreplane (canard) for pitch control, which also served as a stall-prevention device. Modern designs have reprised this solution as seen in the Burt Rutan-designed aircraft. Exactly a century later, a flying replica model of the Wright Flyer failed to lift off on its first flight. A full-scale non-flying replica of the Wright Flyer is on display at the Smithsonian Museum in Washington, DC. This exhibit and other similar museums are well worth a trip. Strangely, the Wright Brothers did not exploit their invention; however, having been shown that sustained and controlled flight was possible, a new generation of aerial entrepreneurs quickly arose. Newer inventions followed in rapid succession, from pioneers such as Alberto Santos Dumas, Louis Bleriot, and Glenn Curtiss to name but a few. The list grew rapidly. Each inventor presented a new contraption, some of which demonstrated genuine design improvements. Fame, adventure, and "*Gefühl*" (feelings) were the drivers, since the early years saw little financial gain from selling "joy rides" and air shows – spectacles never seen before then and still appealing to the public today.

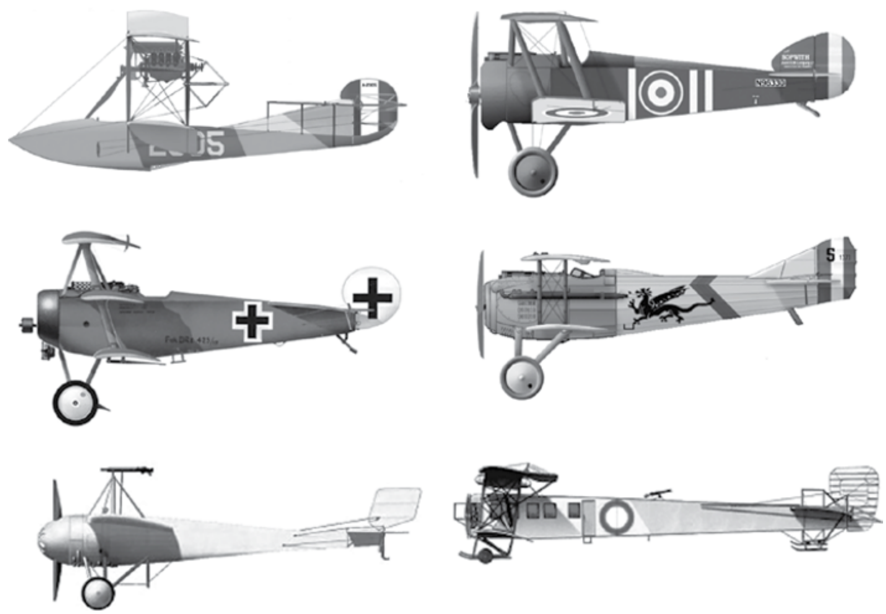
It did not take long to demonstrate the advantages of aircraft for mail delivery and military applications. At approximately 100 miles per hour (mph), on average, aircraft were travelling three times faster than any surface vehicle – and in straight lines. Mail was delivered in less than half the time. The potential for military applications was dramatic and well demonstrated during World War I. About a decade after the first flight in 1903, aircraft manufacturing had become a lucrative business. The Short Brothers and Harland (now part of the Bombardier Aerospace group) was a company that started aircraft manufacturing by contracting to fabricate the Wright designs. The company is now the oldest surviving aircraft manufacturer still in operation. In 2008, it celebrated its centenary, the first aircraft company to do so.

1.2.4 World War I (1914–1918)

Balloons were the earliest (second half of nineteenth century) airborne military vehicle, but controlled aircraft replaced their role as soon their effectiveness were demonstrated just before World War I. Their initial role was as an observation platform, and soon their military offensive capabilities (bombing, dogfights, etc.) were established. Their combat effectiveness became a decisive factor for military strategy. This rapidly attracted entrepreneurs in both private and public sectors. On both sides of the Atlantic the number of aircraft and engine designs and manufacturing establishments exceeded more than 100 organizations. With the growing recognition of the potential of military aircraft applications, the actual demand was in Europe. Serious military aircraft design activities began after war broke out. German aeronautical science and technologies made rapid advances.

This section shows how quickly the aircraft industry grew within a decade of the first flight, initially driven by military application. This is the period that lay the foundations of what was to come subsequently. The section is kept brief by giving only a few aircraft examples here.

***In the US*:** In 1908, the US Army accepted tender for military aircraft, and after extensive tests the Signal Corps accepted Wright Model A, powered by a 35 HP engine (Figure 1.4) in 1909. In 1912 the Wright Model B was used for the first time to demonstrate the firing of a machine gun from a airplane. Soon after, Glenn Curtiss became the dominant US aircraft designer. Curtiss aircraft introduced naval carrier-based flying during 1910–11. The company became early pioneers of producing military flying boats: planes that could take off and land in water. One of the earlier designs was the Curtiss F4 (Figure 1.4). The Boeing Company was started around this time. Among the famous names of early aviation are Martin, Packard,



■ **FIGURE 1.4 Very early powered aircraft (World War I). Left panel: top, Curtiss F4 (US) (reproduced with permission of www.wp.scn.ru/); middle, Fokker Dr1 (Germany) (reproduced with permission of www.fokkerdr1.com/); bottom, Caproni Ca.20 (Italy) (reproduced with permission of www.airlinepicture.blogspot.com). Right panel: top, Sopwith Camel (UK) (reproduced with permission of www.worldac.de/); middle, SPAD S VII (France) (reproduced with permission of www.greatwarflyingmuseum.com); bottom, Sikorsky Ilya Muromets Bomber (reproduced with permission of www.aviastar.org/air/russia). See Table 1.1 for their performance summary**

■ **TABLE 1.1**
Performance summary of the aircraft in Figure 1.4

	Curtiss F4 flying boat	Sopwith Camel	Fokker Dr1	SPAD S VII	Caprioni Ca.20	Ilya Mouromets
Engine, HP	2×275	130	110	150	110	4×148
Wing area, ft^2	1216	231	201	192	144	1350
MTOM, lb	10,650	1455	1292	1632	≈1290	12,000
Max. speed, knots	85	115	185	119	100	110

Vaught, and so on; possibly in excess of two dozen aircraft and engine design and manufacturing companies emerged in the US during this period. Despite this, America introduced arguably superior European-designed military aircraft into their armed forces.

***In the UK*:** Upon the recommendation of the British Defence Ministry in 1911, the Royal Flying Corps (RFC) was formed in 1912. In 1918 it merged with the Royal Naval Air Service to form the Royal Air Force (RAF). The Royal Aircraft Factory B.E.2 was a single-engined two-seat biplane, in service with the RFC in 1912. They were used as fighters, interceptors, light bombers, trainers and reconnaissance aircraft. A more successful design with better capabilities was the single-seat Sopwith Pup. It entered service in the autumn of 1916. The Avro 504 (100–130 HP) and Sopwith Camel (1913, 110 HP – Figure 1.4) are some of the well-known aircraft of the time. Some of the other famous UK aircraft of the time bore the names of Armstrong-Whitworth, A.V. Roe, Blackburn, Bristol, Boulton/Paul, De Havilland, Fairey, Handley Page, Short Brothers, Supermarine, Vickers, and Westland.

***In Germany*:** *Die Fliegertruppen des Deutschen Kaiserreiches* (the Flier Troops of the German Kaiser Empire) of the Imperial German Army Air Service was formed in 1910, and changed its name to the Luftstretkräfte in 1916 (this became the Luftwaffe in the mid-1930s). Advances made by German aeronautical science and technologies produced many types of relatively high performance aircraft at the time. These saw action during World War I. The triplane Fokker Dr1 (Figure 1.4) was perhaps the most famous fighter of the period. The triplane was flown by the famous "Red Baron", Rittmeister Manfred Freiherr von Richthofen, the top-scoring ace of World War 1 with 80 confirmed kills. Another successful German military airplane, the Albatross III, served on the Western Front until the end of 1917. The Junkers D.I was the first ever cantilever monoplane design to enter production. It utilized corrugated metal wings and front fuselage, with a fabric covering being used only on the rear fuselage. The Friedrichshafen FF.33 was one of the earliest German single-engine amphibious reconnaissance biplanes (1914). Some of the other famous German aircraft of the time bore the names of A.E.G., Aviatik, D.F.W., Fokker, Gotha (Gothaer Waggonfabrik), Halberstadt, Hannoversche, Junkers, Kondor, Roland, L.V.G., and Zeppelin.

***In France*:** The French Air Force (*Armée de l'Air*, ALA) is the air force of the French Armed Forces. It was formed in 1909 as the *Service Aéronautique*, as part of the French Army, and was made an independent military branch in 1933. The first Bleriot XIs entered military service in France in 1910. Other famous French military aircraft are Nieuport 10 (1914, 80 HP) and their subsequent designs. The SPAD S VII (Figure 1.4) was a successful French fighter aircraft of World War I used by many countries. The Caudron G.4 series was the first French-built twin-engine bomber biplane platform introduced in the early years of World War I. Some of the other famous French aircraft of the time bore the names of Hanriot, Maurice Farman, Moraine-Saulnier, and Salmson. Many countries, such as the UK, the US, Italy and Russia, bought French military aircraft for their Air Force.

***Other European Countries*:** Aircraft design and manufacturing activities in other European countries, such as Italy, Russia, the Scandinavian countries, Spain and Portugal, were also vigorously pursued. Only Italian and Russian designs are briefly given below.

Italy could claim to be amongst the earliest to experiment with military aviation. As early as 1884, before powered heavier-than-air vehicles, the *Regio Esercito* (Italian Royal Army) operated balloons as observation platforms. During the early World War I period, Caproni developed a series of successful heavy bombers. The Caproni Ca.20 (1914) was one of the first real fighter planes (Figure 1.4). It is a monoplane that integrated a movable, forward-firing drum-fed Lewis machine gun two feet above the pilot's head, firing over the propeller arc. Some of the other famous Italian aircraft of the time bore the names of Società Italiana Aviazione and Ansaldo.

The Russian Empire under the Czar had the Imperial Russian Air Force possibly before 1910. Russian aeronautical sciences had advanced research of the time through famous names like Tsiolkovsky and Zhukovsky. The history of military aircraft in Imperial Russia is closely associated with the name of Igor Sikorsky. He emigrated to the US in 1919; aircraft bearing his name are still produced. In 1913–14 Sikorsky built the first four-engine biplane, the Russky Vityaz. His famous bomber aircraft, the Ilya Muromets, is shown in Figure 1.4. Other famous aircraft of Russian origin of the time had the names Anade, Antara, Anadwa, and Grigorvich.

1.2.5 The Inter-War Period: the Golden Age (1918–1939)

The urgent necessity for military activities during World War I advanced aeronautical science and technology to the point where it presented an attractive proposition for business growth. The aeronautical activities in the peace period were deployed to increase industrial and national growth. The enhanced understanding of aerodynamics, aircraft control laws, thermodynamics, metallurgy, structural and system analyses ensured that aircraft and engine size and performance grew in rapid strides. A wide variety of innovative new designs emerged to cover wide applications in both military and civil operations. Records for speed, altitude and payload capabilities were updated at frequent intervals. This period is seen as the Golden Age of aeronautics.

With enhanced aeronautical knowledge to increase aircraft capabilities, availability of experienced pilots and public awareness offered the ideal environment to make commercial aviation a reality. Surplus post-war experienced pilots were available who could easily adapt to newer designs. They kept them engaged with performing air-shows and offering joy rides. In this period, aircraft industries geared up in defence applications and in civil aviation, with financial gain as the clear driver. The free market economy of the West contributed much to aviation progress; its downside, possibly reflecting greed, was under-regulation. The proliferation showed signs of compromise with safety issues, and national regulatory agencies quickly stepped in, legislating for mandatory compliance with airworthiness requirements (US, 1926). Today, every nation has its own regulatory agency.

One of the earliest applications of commercial operation with passenger flying was done on the modified Sikorsky Ilya Muromets (Figure 1.4). It had an insulated cabin with heating and lighting, comfortable seats, lounge and toilet. Fokker was a Dutch aircraft manufacturer named after its founder, Anthony Fokker. The company operated under several different names, starting out in 1912 in Schwerin, Germany, moving to the Netherlands in 1919. In the 1920s, Fokker entered its glory years, becoming the world's largest aircraft manufacturer. Its greatest success was the F.VIIa/3 m trimotor passenger aircraft, which was used by 54 airline companies worldwide. It shared the European market with the Junkers all-metal aircraft, but dominated the American market until the arrival of the Ford Trimotor, which copied the aerodynamic features of the Fokker F.VII, and Junkers structural concepts. In May 1927, Charles Lindberg won the Ortega Prize for the first individual non-stop transatlantic flight.

Early aircraft design was centred on available engines, and the size of the aircraft depended on the use of multiple engines. The combination of engines, materials, and aerodynamic technology enabled aircraft speeds of approximately 200 mph; altitude was limited by human physiology. In the 1930s, Durener Metallwerke of Germany introduced *duralumin*, with higher strength-to-weight ratios of isotropic material properties, and dramatic increases in speed and altitude resulted.

1.2.6 World War II (1939–1945)

The introduction of duralumin brought a new dimension to manufacturing technology. Structure, aerodynamics, and engine development paved the way for substantial gains in speed, altitude, and manoeuvring capabilities. These improvements were seen predominantly in World War II designs such as the Supermarine Spitfire, the North American P-51, the Focke-Wolfe 190, and the Mitsubishi Jeero-Sen. Multi-engine aircraft also grew to sizes never before seen.

The invention of the jet engine (independently by Whittle in the UK and von Ohain in Germany) realised the potential for unheard-of leaps in speed and altitude, resulting in parallel improvements in aerodynamics, materials, structures, and systems engineering. Heinkel He 178 was the first jet-powered aircraft (27 August 1939), followed by the Gloster E.28 on 15 May 1941.

1.2.7 Post World War II

A better understanding of supersonic flow and a suitable rocket engine made it possible for Chuck Yeager to break the sound barrier in a Bell X1 in 1949 (the aircraft is on show at the Smithsonian Air and Space Museum in Washington, DC). Tens of thousands of the Douglas C-47 Dakota and Boeing B17 Flying Fortress were produced. Post-war, the De Havilland Comet was the first commercial jet aircraft in service; however, plagued by several tragic crashes, it failed to become the financial success it promised.

The 1960s and 1970s saw rapid progress, with many new commercial and military aircraft designs boasting ever-increasing speed, altitude and payload capabilities. Scientists made considerable gains in understanding the relevant branches of science: in aerodynamics [4], concerning high lift and transonic drag; in materials and metallurgy, improving the structural integrity; and in solid-state physics. Some of the outstanding designs of those decades emerged from the Lockheed Company, including the F104 Starfighter, the U2 high-altitude reconnaissance aircraft, and the SR71 Blackbird. These three aircraft, each holding a world record of some type, were designed in Lockheed's Skunk Works, under the supervision of Clarence (Kelly) Johnson. I recommend that readers study the design of the nearly half-century-old SR71, which still holds the speed-altitude record for aircraft powered by air-breathing engines.

During the late 1960s, the modular approach to gas-turbine technology gave aircraft designers the opportunity to match aircraft requirements (i.e. mission specifications and economic considerations) with "rubberized" engines (see Section 7.2). This was an important departure from the 1920s and 1930s, when aircraft sizing was based around multiples of fixed-size engines. Chapter 7 describes the benefits of modular engine design. This advancement resulted in the development of families of aircraft design. Plugging the fuselage and, if necessary, allowing wing growth accessed a wider market area at a lower development cost because considerable component commonality could be retained in a family: a significant cost-reduction design strategy. Capitalistic objectives render designers quite conservative, forcing them to devote considerably more time to analysis. Military designs emerge from more extensive analysis – for example, the strange-looking Lockheed F117 is configured using stealth features to minimize radar signatures. Now, more mature stealth designs look conventional (e.g. the Lockheed F22).

1.3 Current Aircraft Design Status

A major concern that emerged in the commercial aircraft industry from the market trend and forecast analysis of the early 1990s was the effect of inflation on aircraft manufacturing costs. Since then, all major manufacturers and the subcontracting industries have implemented cost-cutting measures. It became clear that a customer-driven design strategy is the best approach for survival in a fiercely competitive marketplace. The paradigm of "better, farther, and cheaper to market" replaced, in a way, the old mantra of "higher, faster, and farther" [5]. Manufacturing considerations came to the forefront of design, and new methodologies were developed, such as DFM/A and Six Sigma.

With rising airfares, air travellers have become cost-sensitive. In commercial aircraft operations, the direct operating cost (DOC) depends more on the acquisition cost (i.e. unit price) than on the fuel cost (year 2000 prices) consumed for the mission profile. Today, for the majority of mission profiles, fuel consumption constitutes between 15% and 30% of the DOC, whereas the aircraft unit price contributes between three and four times as much, depending on the payload range [6]. For this reason, manufacturing considerations that can lower the cost of aircraft production should receive as much attention as the aerodynamic saving of drag counts. The situation would change if the cost of fuel exceeds the current airfare sustainability limit (see Chapter 17), when drag-reduction efforts regain ground.

The conceptual phase of aircraft design is now conducted using a multidisciplinary approach (i.e. concurrent engineering), which must include manufacturing engineering and an appreciation for the cost implications of early decisions; the "buzzword" is *integrated product and process development* (*IPPD*). Section 1.8 briefly describes typical project phases as they are practised currently. Margins of error have shrunk to the so-called zero tolerance so that tasks are done correctly the first time; the Six Sigma approach is one management tool used to achieve this end. The importance of environmental issues has emerged, forcing regulatory authorities to impose limits on noise and engine emission levels. Recent terrorist activities are forcing the industry and operators to consider preventative design features.

1.3.1 Current Civil Aircraft Trends

Current commercial transport aircraft in the 100 to 300 passenger classes all have a single slender fuselage, backward-swept low-mounted wings, two under-slung wing-mounted engines, and a conventional *empennage* (i.e. a horizontal and a vertical tail); this conservative approach is revealed in the similarity of configuration. The similarity in larger aircraft is the two additional engines; there have been three-engine designs, but only on a few aircraft, because the configuration was rendered redundant by variant engine sizes that cover the in-between sizes and extended twin operations (ETOPS). The largest commercial jet transport aircraft, the Airbus 380 (Figure 1.5), made its first flight on 27 April 2005, and is currently in service. The Boeing 787 Dreamliner (Figure 1.5) is the replacement for its successful Boeing 767 and 777 series, aiming at competitive economic performance.

The last three decades witnessed a 5–6% average annual growth in air travel, exceeding 2×109 revenue passenger miles (RPM) per year. Publications by the International Civil Aviation Organization (ICAO), the National Business Aviation Association (NBAA), and other journals provide overviews of civil aviation economics and management. The potential market for commercial aircraft sales is of the order of billions of dollars per year. However, the demand for air travel is cyclical and – given that it takes about four years from the introduction of a new aircraft design to market – operators must be cautious in their approach to new acquisitions. They do not

■ **FIGURE 1.5 Current wide-body large commercial transport aircraft: the Airbus 380 (reproduced with permission of Airbus), and the Boeing 787 Dreamliner (reproduced with permission of Boeing)** want new aircraft to join their fleet during a downturn in the air-travel market. Needless to say, market analysis is important in planning new purchases.

Deregulation of airfares has made airlines compete more fiercely in their quest for survival. The growth of budget airlines compared with the decline of established airlines is another challenge for operators. Boeing introduced its 737 twin-jet aircraft (derived from the three-engine B727, the bestseller at the time), and after nearly four decades of production to this day, has become the bestseller in the history of the commercial aircraft market. Of course, in that time, considerable technological advancements have been incorporated, improving the B737's economic performance by about 50%.

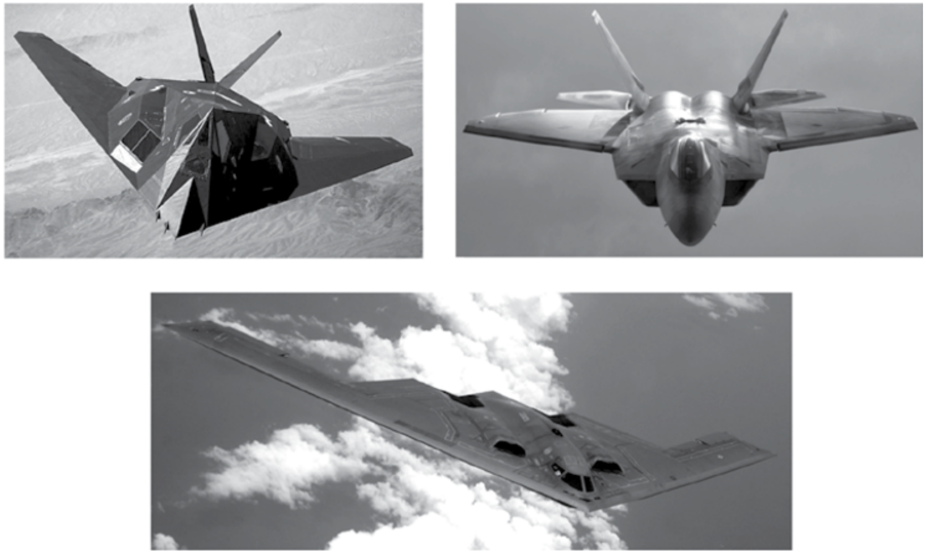
The gas-turbine turboprop offers better fuel economy than current turbofan engines. However, because of propeller limitations, the turboprop-powered aircraft's cruising speed is limited to about two-thirds of the high-speed subsonic turbofan-powered aircraft. For lower operational ranges (e.g., less than 1000 nautical miles (nm), the difference in sortie time would be of the order of less than half an hour, yet there is a saving in fuel costs of approximately 20%. If a long-range time delay can be tolerated (e.g. for cargo or military heavy-lift logistics), then large turboprop aircraft operating over longer ranges become meaningful. Advances in propeller technology are pushing turboprop powered aircraft cruising speeds close to the turbofan-powered aircraft high subsonic cruise speeds.

1.3.2 Current Military Aircraft Trends

Military aircraft designs have the national interest as a priority over commercial considerations. While commercial aircraft can earn self-sustaining revenue, military operations depend totally on taxpayers' money with no cash flow back, other than export sales that carry the risk of disclosure of tactical advantages. The cost frame of a new design has risen sufficiently to strain the economy of single nations. Not surprisingly, the number of new designs has drastically reduced, and military designs are moving towards multinational collaborations among allied nations, where the retention of confidentiality in defence matters is possible.

There are differences between civil and military design requirements (see Section 1.14.1). However, there are some similarities in their design processes up to the point when a new break-through is introduced – one thinks instinctively of how the jet engine changed in design in the 1940s. Consider the F117 Nighthawk (Figure 1.6); the incorporation of stealth technology appeared to be an aerodynamicist's nightmare, but it now conforms to something familiar in the shape of the F35 Lightning II (its prototype X35 is shown in Figure 1.6). We must not forget that military roles are more than just combat; they extend to transportation and surveillance (reconnaissance, intelligence gathering and electronic warfare). F35, Eurofighter, Rafale, Gripen, and Sukhoi 30 are the current frontline fighter aircraft. In strategic bombin, the B52 served for four decades and is to continue for another two decades – some design! The latest B2 bomber (Figure 1.6) looks like an advanced flying wing without the vertical tail.

Combat roles are classified as interdiction, air superiority, air defence and, when missions overlap, multi-role (see Section 10.4 for details). Action in hostile environments calls for special attention to: design for survivability; systems integration for target acquisition and weapons management; and design considerations for reliable navigation and communication. All told, it is a complex system, mostly operated by a single pilot – an inhuman task if the workload was not relieved by microprocessor-based decision-making. Fighter pilots are a special breed of aircraft operators with the best emotional and physical conditioning to cope with the stresses involved. Aircraft designers have a deep obligation to ensure combat pilot survivability. Unmanned aerial vehicle (UAV) technology is in the offing – the Middle-Eastern conflicts saw successful use of the Global Hawk for surveillance. Of late, UAVs are used as a weapon delivery system.



■ **FIGURE 1.6 Current combat aircraft. Top left: F117 Nighthawk (reproduced with permission of the US Airforce/ Sgt Aaron Allmon; top right: X-35 (F35 experimental) (reproduced with permission of the US Airforce/Dana Russo); bottom, B2 Bomber (reproduced with permission of the US Airforce/Sgt Jeremy Wilson)**

1.4 Future Trends

It is clear that in the near future, vehicle capabilities will be pushed to the extent permitted by economic and defence factors and infrastructure requirements (e.g. navigation, ground handling, support, etc.). It is no exception from past trends that speed, altitude and payload will be expanded in both civilian and military capabilities. Coverage of the aircraft design process in the next few decades is given in [7]. In technology, smart materials (e.g. adaptive structure) will gain ground, microprocessor-based systems will advance to reduce weight and improve functionality, and manufacturing methodology will become digital. However, unless the price of fuel increases beyond affordability, investment in aerodynamic improvement will be next in priority.

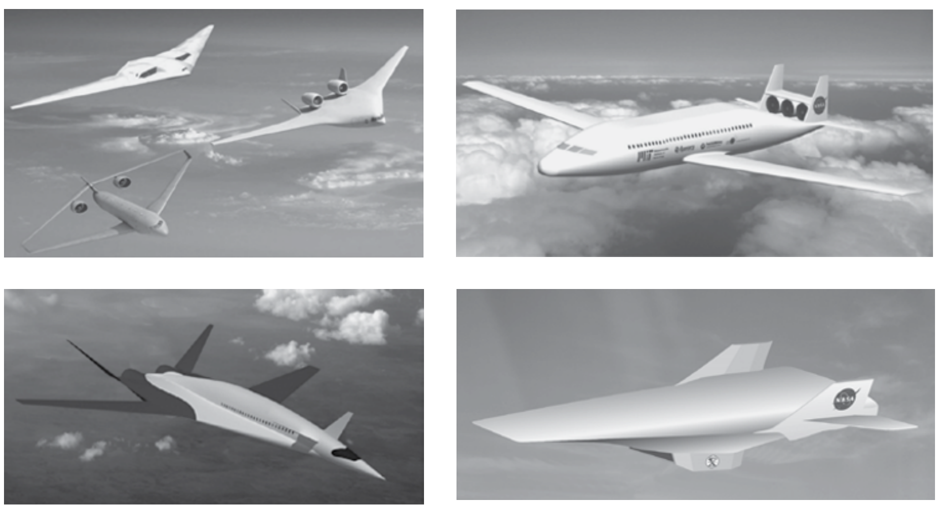
1.4.1 Trends in Civil Aircraft

Any extension of payload capability will remain subsonic for the foreseeable future, and will lie in the wake of gains made by higher-speed operational success. High-capacity operations will remain around the size of the Airbus 380. Some well-studied futuristic designs (Figure 1.7) have the possibility of further size increases. A blended-wing body (BWB) can use the benefits of the wing-root thickness being sufficiently large to permit merging (Figure 1.7, top) with the fuselage, thereby benefiting from the fuselage’s contribution to lift and additional cabin volume. Another alternative would be that of the joined-wing concept (Figure 1.7, bottom). Studies of twin-fuselage, large transport aircraft also indicate potential. A joined fuselage (Figure 1.7) is also a well studied concept.

The speed–altitude extension will progress initially through supersonic transports (SSTs) and then hypersonic transport (HST) vehicles. SST technology is well proven by three decades of the Anglo-French-designed Concorde, which operated above Mach 2 at altitudes of 50,000 feet carrying 128 passengers.

The next-generation SST will have about the same speed-altitude capability (possibly less in speed capability, around Mach 1.8), but the size will vary from as few as ten business passengers to approximately 300 passengers (Figure 1.7) to cover at least transatlantic and transcontinental operations. Transcontinental operations would demand sonic-shock strength reduction through aerodynamic gains rather than speed reduction; anything less than Mach 1.6 has less to offer in terms of time savings. The real challenge would be to have HST (Figure 1.7) operating at approximately Mach 6 that would require operational altitudes above 100,000 ft. Speeds above Mach 6 offer diminishing returns in time saved because the longest distance necessary is only about 12,000 nm (i.e. about 3 hours of flight time). Military applications for HST vehicles are likely to precede civilian applications, and small-scale HSTs have been flown recently.

The concept of rocket propulsion in modern application came from Von Braun's V2 rocket, an idea taken from Tippu's success in using rockets against the British-led Indian army at the Battle of Srirangapatna in 1792 [8]. The experience of Tippu Sultan's rockets led the British to develop missiles at the Royal Laboratory of Woolwich Arsenal, under the supervision of Sir William Congreve, in the late eighteenth century. A new type of speed-altitude capability will come from suborbital space flight (tourism) using rocket powered aircraft, as demonstrated by Rutan's Space Ship Two that hitchhikes with the White Knight to altitude (Figure 1.8), from where it makes the ascent. Interest in this aircraft has continued to grow; the prize of $10 million offered could be compared with that of a transatlantic prize followed by commercial success.



■ **FIGURE 1.7** **Current combat aircraft. Top left: blended wing aircraft; top right: joined twin fuselage; bottom left, supersonic transport aircraft; bottom right, hypersonic aircraft (all photos reproduced with permission of NASA)**

■ **FIGURE 1.8** **White Knight carrying Space Ship Two**

Both operators and manufacturers will be alarmed if the price of fuel continues to rise to a point where the air-transportation business finds it difficult to sustain operations. The industry would demand that power plants use alternative fuels such as biofuel, liquid hydrogen (LOH), and possibly nuclear power for large transport aircraft covering long ranges. Aircraft fuelled by LOH have been used in experimental flying for some time, and fossil fuel mixed with biofuel is currently being flight-tested.

A new type of vehicle known as a ground-effect vehicle is a strong candidate for carrying a large payload (e.g. can be bigger than Airbus 380 aircraft) and flying close to the surface, almost exclusively over water. (A ground-effect vehicle is not really new: the Russians built a similar vehicle called the *Ekranoplan*, but it did not appear in the free-market economy.)

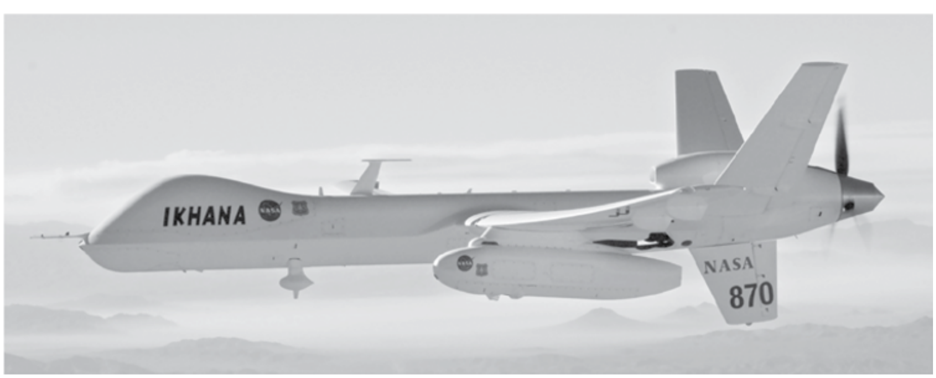
Smaller Bizjets and regional jets will morph, and unfamiliar shapes may appear on the horizon, but small aircraft in personal ownership used for utility and pleasure flying are likely to revolutionize the concept of flying through their popularity, similar to how the automobile sector grew. The revolution will occur in short-field capabilities, with vertical takeoffs, and safety issues in both design and operation. Smaller aircraft used for business purposes will see more private ownership to stay independent of the more cumbersome airline operations. There is a good potential for airparks to grow. Various “roadable” aircraft (flying cars) have been designed. The major changes would be in system architecture through miniaturization, automation, and safety issues for all types of aircraft.

1.4.2 Trends in Military Aircraft

Progress in military aircraft would defy all imaginations. Size and shape would be as small as insects (micro-aircraft – dragonfly drones) for surveillance, to larger than any existing kind [9]. Vehicles as small as 15 cm and 1 kg mass have been successfully built for operation. Prototypes much smaller have been successfully flown.

As system-processing power grows, the capability to make weapon delivery decisions advances to an accuracy that could eliminate an onboard human interface, and thereby at one stroke the question of pilot survivability is taken out of the design process, which in turn permits the aircraft to operate at higher load, improving combat capability. Reliance on in-built intelligence would certainly make more remotely piloted vehicles (RPVs) come into in operation. Other terminologies are *unmanned*, *unoccupied*, and *pilotless*. However, unmanned aerial vehicle (UAV) is the prevalent terminology. Nations who can afford it have already entered the race to develop UAVs. Figure 1.9 shows an operational UAV, Ikhana, used for imaging. Futuristic concepts are the Boeing X45A and US Navy X47B (Northrop), as JUCAS (Joint Unmanned Combat Air System).

Once again it is the electronics that would play the main role, although aerodynamic challenges on stealth, manoeuvre and improved capability/efficiency would be as important as structural/material considerations. Engine development would also be a parallel development with all of these discoveries/inventions.



■ FIGURE 1.9 Ikhana (General Atomics) (reproduced with permission of General Atomics Aeronautical Systems, Inc.)

1.4.3 Forces and Drivers

This section discusses the current status of forces and drivers that control design activities. The current aircraft design strategy is linked to industrial growth, which in turn depends on national infrastructure, governmental policies, workforce capabilities, and natural resources; these are generally related to global economic-political circumstances. More than any other industry, the aerospace sector is linked to global trends. A survey of any newspaper provides examples of how civil aviation is affected by recession, fuel price increases, spread of infectious diseases and international terrorism. In addition to its importance for national security, the military aircraft sector is a key element in several of the world's largest economies. Indeed, aerospace activities must consider the national infrastructure as an entire system. A skilled labour force is an insufficient condition for success if there is no harmonization of activity with national policies; the elements of the system must progress in tandem. Because large companies affect regional health, they must share socioeconomic responsibility for the region in which they are located.

The current status stems from the 1980s when returns on investment in classical aeronautical technologies such as aerodynamics, propulsion, and structures began to diminish. Around this time, however, advances in microprocessors enabled the miniaturization of control systems and the development of microprocessor-based automatic controls, which gave additional weight-saving benefits. Dramatic but less ostensible changes in aircraft management began to be embedded in design. At the same time, global political issues raised new concerns as economic inflation drove man-hour rates to a point at which cost-cutting measures became paramount. In the last three decades of the twentieth century, man-hour rates in the West rose four to six times (depending on the country), resulting in aircraft price hikes (typically by about six times for the Boeing 737 – of course, accompanied by improvements in design and operational capabilities.) Lack of economic viability resulted in the collapse or merger/takeover of many well-known aircraft manufacturers. The number of aircraft companies in Europe and North America shrank by nearly three-quarters; currently, only two aircraft companies (Boeing and Airbus) in the West are producing large commercial-transport aircraft. Bombardier Aerospace and Embraer of Brazil have recently entered the large-aircraft market, joining the Russians, the Chinese and the Japanese. Over time, aircraft operating cost terminologies have evolved, and currently, the following standardized definitions are used in this book:

IOC (indirect operating cost):	Comprises costs not directly involved with the sortie (trip).
COC (cash operating cost):	Comprises the trip (sortie) cost elements.
FOC (fixed operating cost):	Comprises cost elements even when not flying but related to trip cost.
DOC (direct operating cost):	= COC + FOC.
TOC (total operating cost):	= IOC + DOC.

1.5 Airworthiness Requirements

From the days of barnstorming and stunt flying in the 1910s, it became obvious that commercial interest had the potential to short-circuit safety considerations. Government agencies quickly stepped in to safeguard people's security and safety without deliberately harming commercial interest. Western countries developed and published thorough systematic rules – these are in the public domain (see relevant websites). In civil applications, they are the Federal Aviation

Regulations or FAR and Certification Standards published by the European Aviation Safety Agency, EASA (formerly Joint Aviation Requirements (JARs) defined by the Joint Aviation Authorities, JAA); both are quite close. The author prefers to work with the established FAR at this point. In military applications, the standards are Milspecs (US) and Defense Standard 970 (earlier AvP 970 – UK); they do differ in places.

The US Government have 50 titles of Code of Federal Regulations (CFRs) published in the Federal Register, covering wide areas subject to federal regulations. The Federal Aviation Regulations (or FARs), are rules prescribed by the Federal Aviation Administration (FAA) governing all aviation activities in the US under title 14 of the CFRs, which covers wide varieties of aircraft-related activities in many parts, of which this book deals mainly with Parts 23, 25, 33 and 35. However, another set of regulations in Title 48 of CFRs is the Federal Acquisitions Regulations, and this has led to confusion with the use of the acronym "FAR". Therefore, the FAA began to refer to aerospace-specific regulations by the term "14 CFR part XX" instead of FAR. There is a growing tendency in the industry to adapt to using 14 CFR part XX. However, to retain the use of FAR meaning Federal Aviation Regulation is still acceptable, and in this book the authors continue with the use of the older practice of the term FAR.

Safety standards were developed through multilateral discussions between manufacturers, operators and government agencies, which continue even today. These minimum standards come as regulations and are mandatory. The regulatory aspects have two kinds of standards, as follows.

- **Airworthiness Standards**: These concern aircraft design by the manufacturers complying with regulatory requirements to ensure design integrity for the limiting performance. These are outlined in FAR 25/JAR 25 in extensive detail in a formal manner, and are revised when required. After substantiating the requirements through extensive testing, an Aircraft Flight Manual (AFM) is issued by the manufacturers for each type of aircraft designed.
- **Operating Standards**: These concern the technical operating rules to be adhered to by the operators, are outlined in FAR 121/JAR-OPS-1 in extensive detail in a formal manner, and are revised when required. The aircraft operational capabilities are substantiated by the manufacturer through extensive flight tests and are certified by the government certification agencies (e.g. FAA/JAA). The contents of the AFM are recast in a Flight Crew Operating Manual (FCOM) that outlines the aircraft limitations and procedures, along with the full envelope of aircraft performance data. Today, with the integration of computers in aircraft operation, it is possible to monitor aircraft performance (APM) for optimum operations. Today, the operational aspects require full understanding of operating microprocessor-based aircraft design.

In civil aviation, every country requires safety standards to integrate with their national infrastructure and climatic conditions for aircraft operation, as well as to relate to their indigenous aircraft designs. Therefore, each country started with their own design and operations regulations. As aircraft started to cross international borders, the standards for foreign-designed aircraft had to be re-examined and possibly re-certified to allow safe operation within their country. To harmonize the diverse nature of the various demands, the International Civil Aviation Organization (ICAO) was formed in 1948, to recommend the international minimum recommended standards. It has now become legal for international practice. However, within each country their own operational regulations might still apply; while countries in North America and some European countries adopt FAR 121, some other European countries follow JAR-OPS-1.

Aircraft operation is prone to litigation, as mishaps do occur. To avoid ambiguity as well to ensure clarity to design, FAA documentations are written in a very elaborate and articulated manner, demanding in-depth study in order to understand and apply them. It is for this reason this book does not exactly copy the FAR lines, but instead quotes the relevant Part number, outlining the requirements with explanations and supported by worked examples. The authors recommend that readers access the latest FAA publication; their web site at http://www.faa.gov/regulations_policies/faa_regulations/should prove useful. Most academic/aeronautical institute libraries necessarily keep FAR documents. For those in industry, these documents will be available there. Aeronautical engineering does not progress without these documents to guarantee a minimum safety in design and operation.

The FAR (14CFT) Part 25 has the most stringent airworthy compliance requirements. The FAR 23 (general aviation aircraft) and the FAR Part 103 (ultra-light aircraft) have considerably lower levels of requirements and use the same performance equations for analyses. This book deals only with the FAR (14CFR) Part 25.

1.6 Current Aircraft Performance Analyses Levels

Aircraft performance analysis is needed at the very early stages of the conceptual design phase and continues in every phase of the programme, updating capabilities as more accurate data are available until it is substantiated through flight tests. At the conceptual stage the performance prediction has to be sufficiently accurate to obtain management "go-ahead" for a programme that bears promise of eventual success. In the next phase the performance figures are fine-tuned to give a guarantee to potential operators. Industry must be able to perform aircraft performance analysis to a high degree of accuracy.

The analyses of aircraft performance cascade down from the preliminary study to final refinement by design engineers, followed by flight test substantiation, and eventually the engineers preparing the aircraft flight manuals (AFM) and the flight crew operating manual (FCOM) for operational usage. The various levels where aircraft performances are evaluated are briefly given below.

By the designers

(i) *At research level (feasibility study)*: In this stage, engineers examine new technologies and their capabilities to advance new aircraft designs, and examine possible modifications to improve existing designs. At this level, researchers explore newer aircraft performance capabilities, and optimize operational procedures using close-form equations that yield quick results for comparison and selection.

(ii) *Conceptual design level (Phase I of a project)*: This is the outcome of the feasibility study showing potential to progress the design towards market launch. In this phase, the study needs to be done in a specific manner to fix configurations in a family framework by sizing the aircraft with matched engines. In this phase, full aircraft analysis is not required. It only covers what is required to speak with potential customers with promising performance specifications sufficient to make comparisons with the competition. If successful, go-ahead for the programme is given at the end of the study.

(iii) *Detailed design level (Phases II and III)*: This is the post go-ahead phase analysis to give guarantees to potential customers. By now, more aerodynamic information is available through wind tunnel testing and CFD analyses. More detailed and accurate aircraft performance estimations are now possible.

(iv) *Final level (Phase IV)*: This is the final design phase, and aircraft performance tests are carried out to obtain certification of airworthiness. All technical/engineering and ground/flight-tested substantiation data are then passed to a dedicated group to prepare the aircraft flight manual (AFM) and the flight crew operating manual

(FCOM) for operational usage. The format of presenting aircraft performance in the AFM and the FCOM is different from the format of aircraft performance documents used by the designers; the former are derived from the latter. The performance documents prepared during Phases I, II and III, and used by engineers, contain predictive data that are substantiated through ground/flight tests. The full set of engineering data is given to experienced performance engineers at the dedicated customer support group who prepare the AFM and FCOM manuals for the airline operators. Typically, the design office uses the prevailing terminologies, but the AFM and the FCOM must incorporate standard formal terminologies specified by the airworthiness agencies to avoid any ambiguity. While preparing the operational manuals does not involve extensive computation, it requires articulated presentation since errors or lack of clarity are not acceptable. This book follows the typical terminologies used by engineers, along with introducing the synonymous formal terminologies to keep the readers informed.

By the operators

Using the manufacturer-supplied AFMs and FCOMs, the operators have their own performance engineers conduct analyses; the extent depends on the operators' strategic plans. Typically, these analyses are not as extensive as what the designers do, as it is not required. They cover: (i) market comparison to make selection of aircraft type; (ii) city-pair route planning (new or old routes); (iii) performance revisions on account of repairs; (iv) design modifications to improvement performance; and (v) accident/incidence analyses. Operating cost analyses form one of the core aspects of the study.

1.7 Market Survey

In a free market economy, industry cannot survive unless it grows; governmental subsistence can only be seen as a temporary relief. The starting point to initiate a new aircraft design project is to establish the key drivers – the requirements and objectives based on market, technical, certification and organizational requirements. These drivers are systematically analysed and then documented by the aircraft manufacturers (Table 1.2). Documents, in several volumes, describing details of the next layer of design specifications (requirements), are issued to those organizations involved with the project. Market surveys determine customer requirements, and user feedback guides the product. In parallel, the manufacturers incorporate the latest, but proven, technologies to improve design and stay ahead of the competition, always constrained

■ **TABLE 1.2**
The drivers leading to the final design

Market drivers from operators	Regulatory drivers from government	Technology drivers from industry
Payload-range, speed	Airworthiness regulations	Aerodynamics
Field performance	Policies (e.g. fare deregulation)	Propulsion
Comfort level	Route permission	Structures
Functionality	Airport fees	Materials
Maintenance	Interest rates	Avionics/electrical
Support	Environmental issues	Systems, fly-by-wire
Aircraft family	Safety issues	Manufacturing philosophy

by the financial viability of what the market can afford. Dialogue between manufacturers and operators continues all the time to bring out the best in the design.

Military product development has a similar approach, but would require some modifications to Table 1.2. Here, government is both the single customer and the regulatory body. Therefore, competition is only between the bidding manufacturers. The market is replaced by the operational requirements arising from perceived threats from potential adversaries. Column 1 of Table 1.2 then becomes “Operational Drivers”, which includes weapons management and counter intelligence. Hence, this section on market survey is divided into civil and military customers as shown in Table 1.3. “Customer” is a broad-based term and is defined in this book in the manner given in Table 1.3.

In the UK military, the Ministry of Defence (MoD), as the single customer, searches for a product and floats a Request for Proposal (RFP) to the national infrastructure, where most manufacturers are run privately. It is nearly the same in the US under different terminologies. Product search is a complex process – the MoD must know the potential adversary’s existing and future capabilities, and administrate national RD&D infrastructures to be ready with discoveries/innovations to supersede the adversary’s capabilities. The Air Staff Target (AST) is an elaborate aircraft specification as customer requirement. A military project is of national interest and in today’s practice the capable companies are invited first to produce a ‘Technology Demonstrator’ as proof of concept. The loser in the competition gets paid by the government for the demonstrator and learns a lot about very advanced technology for the next RFP or civilian design (so that, in a true sense, there is no loser) and the nation hones its technical manpower.

Although used, the authors do not think that RFP is an appropriate terminology in civil applications – here, who is making the request? It is important for the aircraft manufacturers to know the requirements of many operators and supply a product that meets the market’s demands in performance, cost and time frames. Airline, cargo and private operators are the direct customers of the aircraft manufacturers, who do not have direct contact with the next level of customers (i.e. passengers and cargo handlers). Airlines do their market surveys of passenger and freight requirements and pass the information to the manufacturer. These are often established by extensive studies of target city pairs, current market coverage and growth trends, and passenger input. Their feedback comes with diverse requirements that need to be coalesced to a marketable product. A large order from a single operator could start a project, but manufacturers must cater for many operators to enlarge and stabilize their market share. The civil market is searched through a multitude of queries to various operators (airlines), nationally and internationally. In civil aviation, the development of national infrastructure must be run in coordination with the aircraft manufacturers and operators to ensure national growth. Airlines generate revenue by carrying passengers and freight; these provide the cash flow that supports the maintenance and development of the civil aviation infrastructure. Cargo generates important revenues for airlines and airports, and its market should not be underestimated, even if it means modifying older airplanes. Manufacturers and operators remain constantly in touch with each other in order to develop product lines with new and/or modified aircraft. The aircraft manufacturers need to

■ **TABLE 1.3**
Customers of aircraft manufacturers

	Civil customers	Military customers
Top level	Airline/cargo/private operators	MoD (single)
Next level	Passengers and cargo handlers	Foreign MoD
Revenue	Cash flows back through revenue earned	No operational revenue, possible export revenue

harmonize diversity in requirements in order to arrive at a point where the management decides to undertake a conceptual study to obtain "go ahead". This is nothing close to the route taken by the MoD to initiate a RFP with a single customer demand.

The private or executive aircraft market is driven by operators who are closely connected to business interests and cover a wide spectrum of types, varying from four passengers to specially modified mid-sized jets.

Military aircraft utilization in peacetime is approximately 7500 hours, about a tenth that of commercial transport aircraft (≈75,000 hours), in its life-span. Peacetime military aircraft yearly utilization is very low (around 600 hours) compared with civil aircraft yearly utilization, which can exceed 3000 hours.

1.8 Typical Design Process

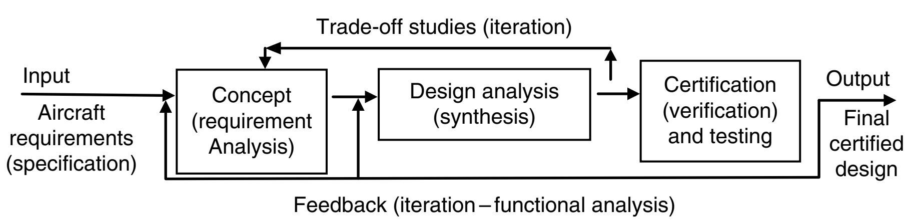
The typical aircraft design process follows the classical pattern of a systems approach. The official definition of a system adopted by the International Council of Systems Engineering (INCOSE – [10]) is that "a 'system' is an interacting combination of elements, viewed in relation to function". The design "system" has an input (a specification/requirement), which undergoes a process (phases of design) to obtain an output (certified design through substantiated aircraft performance), as shown in Figure 1.10.

1.8.1 Four Phases of Aircraft Design

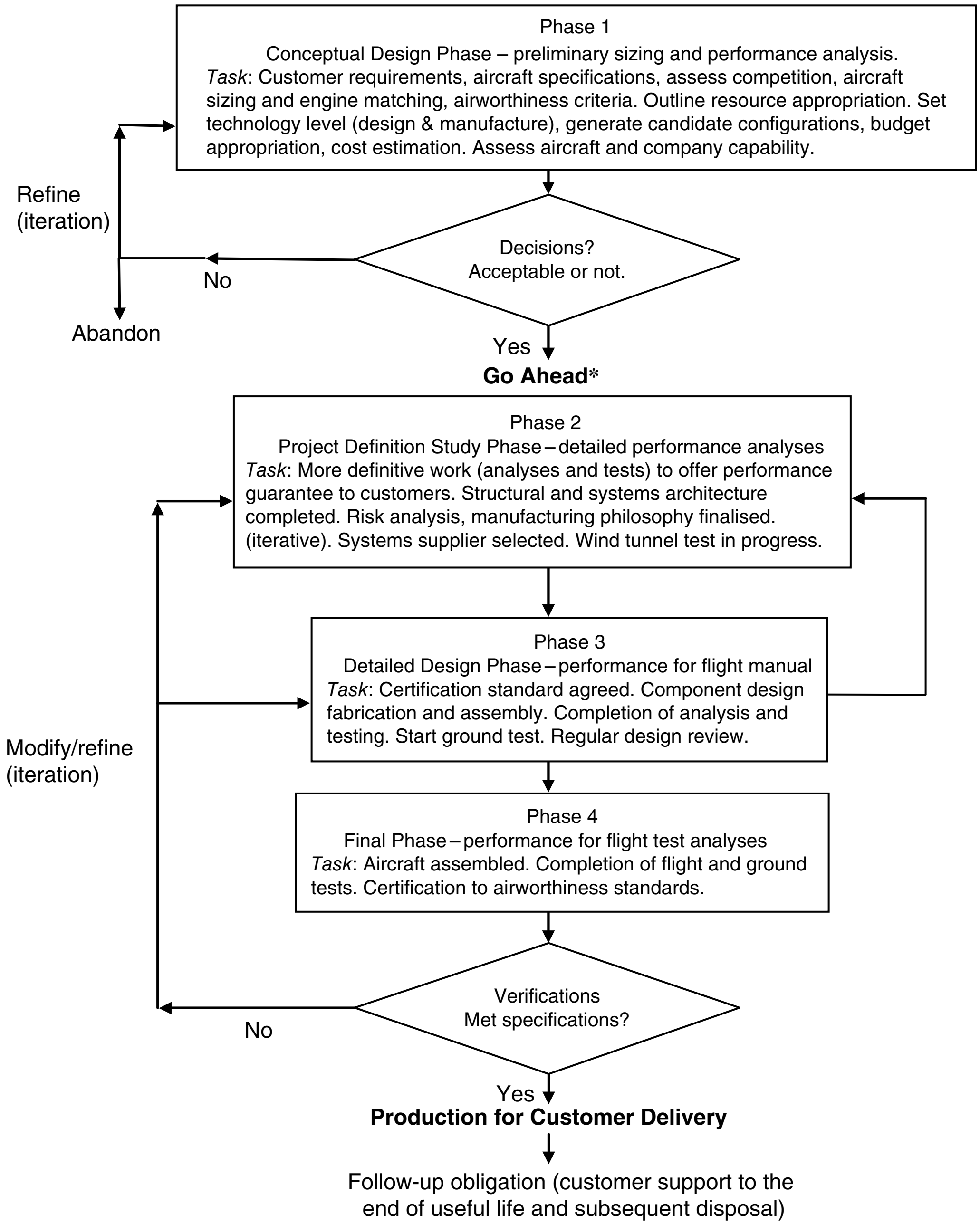
Aircraft manufacturing organizations conduct round-the-year exploratory work on research, design and technology development, as well as market analysis to search for a product, and when it is found, the project gets formally initiated in the four phases as shown in Figure 1.11, which is valid for both civil and military projects.

From organization to organization, the terminologies of the phases vary. The difference between the terminologies is trivial, as the task breakdown covered in various phases is about the same. For example, some may see Market Study and Specification Requirements as Phase 1, making Conceptual Study as Phase 2; some may define the Project Definition Phase (Phase 2) and Detailed Design Phase (Phase 3) as the Preliminary Design Phase and Full Scale Development Phase, respectively. Some would prefer to invest early on risk analysis in Phase 1, but it could be done at Phase 2 when the design is better defined, saving Phase 1 budgetary provision in case the project fails to get a "go-ahead". Military programmes may require early risk analysis as they would be incorporating technologies yet to be proven in operation. Some may see disposal of aircraft at the end as part of the design phase of a project. Figure 1.11 offers a typical/generic pattern prevailing in industry.

Aircraft performance analyses are carried out in all four phases at various levels, as given below. The formulation of physics is the same for all; the difference lies in the extent of coverage and rigour for the performance evaluation required.



■ **FIGURE 1.10**
The aircraft design process



* Some companies may delay "go ahead" until more information is available. Some Phase 2 tasks (e.g. risk analysis) may be carried out as a Phase 1 task to obtain "go ahead".

■ **FIGURE 1.11** **Introduction to the four phases of aircraft design and development**

Phase 1 ***Conceptual Design Phase***: In this phase, preliminary performance studies are conducted to size aircraft for a family of variants and find matched engines to meet market specifications: takeoff and landing, speeds at initial climb and cruise, and meeting the payload-range. These evaluations are primarily used by management to arrive at the "go-ahead" decision and also by potential customers. Expected accuracy of the results should be within less than ±5%.

Phase 2 ***Project Definition Study Phase***: After "go-ahead" is obtained, more definitive work (analyses and tests) are carried out in this phase to offer aircraft performance guarantees to customers. This also offers an opportunity to refine sizing and engine matching before metal cutting starts. Expected accuracy should be within less than ±3%.

Phase 3 ***Detailed Design Phase***: This is the time when accurate aircraft performances for the flight manual are carried out to some agreed certification standards. The equations of performance analyses are the same, but evaluated in detail for the full flight envelope for the allowable climatic conditions. Expected accuracy should be within less than ±2%.

Phase 4 ***Final Phase***: Aircraft performance for flight test analyses to calibrate with estimation. This is to ensure that aircraft performance does not fall short of the guaranteed values.

The methodologies presented in this book should cater for aircraft performance analyses for all the four stages. Details of activities of the various phases are described in the next sections.

Table 1.4 suggests a generalized functional envelope of aircraft design architecture, which is in line with the index given for commercial transport aircraft by the Aircraft Transport Association (ATA) [11], which recently changed name to A4A, Airlines for America. Further breakdowns of subsystems are given in the respective chapters.

The components of the aircraft as subsystems exist interdependently in a multidisciplinary environment, even if they have the ability to function on their own. For example, wing flap deployment on the ground is inert, while in flight it affects the vehicle motion. Individual components, such as the wing, nacelle, undercarriage, fuel system, air-conditioning, and so on, can also be seen as subsystems. Components are supplied for structural and system testing in conformance with airworthiness requirements in practice. Close contact is maintained with

■ **TABLE 1.4**
Aircraft systems

Design	Operation
Aerodynamics	Training
Structure	Product support
Power Plant	Facilities
Electrical/avionics	Ground/office
Hydraulic/pneumatic	Flight operations
Environmental control	
Cockpit/interior design	
Auxiliary systems	
Production engineering feedback	
Testing and certification	

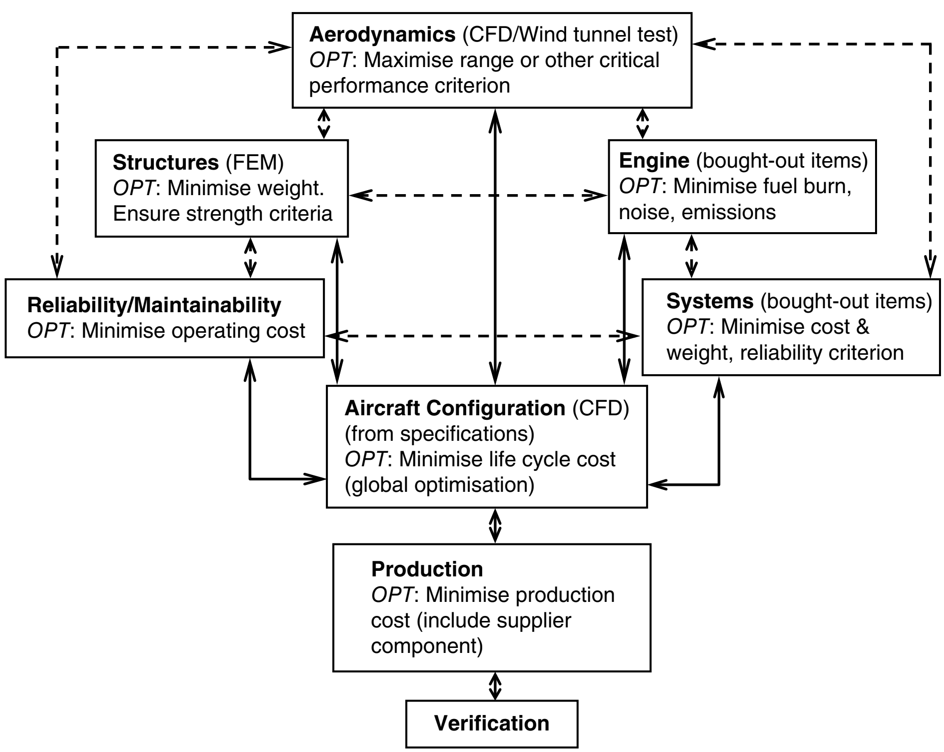
planning engineers to ensure that production costs are minimized and to ensure that build tolerances are consistent with design requirements.

Extensive wind tunnel, structure and systems testing will be required early in the design cycle to ensure safe flight tests, leading to airworthiness certification approval. The multidisciplinary "systems" approach to aircraft design is carried out within the context of IPPD. The generic methodology has four phases (see next section) to get a new aircraft conceived, designed, built and certified. Civil projects usually proceed to pre-production build aircraft, which will be flight-tested and sold subsequently.

Military projects proceed with technology demonstrators as prototypes before "go-ahead" is given. Military technology demonstrators are normally scaled-down aircraft meant to substantiate untried cutting-edge technology. These are not sold for operational usages.

Company management sets up a "design built team" (DBT) to meet at regular intervals to conduct design reviews and make decisions on the best compromises through multidisciplinary analysis (MDA) and multidisciplinary optimization (MDO) as shown in Figure 1.12 – this is what is meant by IPPD (concurrent engineering) environment.

Specialist areas may optimize their design goals, but in the IPPD environment, compromise has to be sought. *Optimization of individual goals through separate design considerations may prove counterproductive and usually prevent the overall (global) optimization of ownership cost.* MDO offers good potential, but to obtain global optimization is not easy; it is still evolving. In a way, a global MDO, involving large numbers of variables, is still an academic pursuit. Industries are in a position to use sophisticated algorithms in some proven areas. One such situation is to reduce manufacturing cost by reshaping component geometry as a compromise to lower cost (i.e. to minimize complex component curvature). To offer a family of



■ **FIGURE 1.12**
Multidisciplinary analysis (MDA) and optimization (MDO) flowchart (IPPD)

variant aircraft the compromises are evident, as none of the individuals in the family are optimized, but together they offer the best value for money.

Once the aircraft has been delivered to the operators (customers), a manufacturer is not free from obligations. Manufacturers continue with support work on maintenance, design improvements and attention to operational queries, right up to the end of aircraft life. Modern designs are expected to achieve three to four decades of operation. Manufacturers may even face litigation if customers find cause to sue. Compensation payments have crippled some famous general aviation names. Fortunately, the 1990s saw a relaxation of the litigation laws in general aviation – after a certain period of time when a design is established, the manufacturer's liabilities are reduced – which resulted in a revitalization of the general aviation market. Military programmes involve support from "cradle to grave", that is, from delivery of the new aircraft to end of service life.

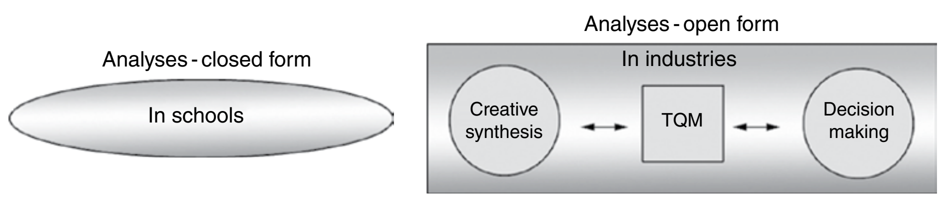
It is important to emphasize that the product must be "right-first-time". Mid-course changes add needless cost that could hurt the project – a big change may not even prove sustainable. Procedural methodologies such as the Six-Sigma approach have been devised to make sure changes are minimized.

1.9 Classroom Learning Process

To meet our objectives to offer close-to-industrial practice in this book, it would be appropriate here to harmonize some of the recognized gaps between academia and industry as discussed in [12] to [19]. Before we embark on dealing with the aircraft performance analyses, we will lay out our intended classroom learning process, as previously tested in industry and in academia.

It is clear that unless the engineer has sufficient analytical ability, it will be impossible for him/her to convert creative ideas into profitable product. Today's innovators who have no analytical and practical skills must depend on engineers to accomplish routine tasks under professional investigation, and to make necessary decisions to develop an idea into a marketable product.

Traditionally, universities develop analytical abilities by offering the fundamentals of engineering science. Courses are structured with all the material available in textbooks or notes; problem assignments are straightforward with unique answers. This may be termed a "closed-form" education. Closed-form problems are easy to grade and a teacher's knowledge is not challenged (relatively). Conversely, industry requires the tackling of "open-form" problems for which there is no single answer. The best solution is the result of interdisciplinary interaction of concurrent engineering within design built teams (DBTs), in which total quality management (TQM) is needed to introduce "customer-driven" products at the best value. Offering open-ended courses in design education that cover industrial requirements is more difficult and will challenge a teacher, especially when industrial experience is lacking. The associative features of closed- and open-form education are shown in Figure 1.13 [19].



■ **FIGURE 1.13 Associative features of "closed" and "open" form education (adapted from [19], American Institute of Aeronautics and Astronautics, Inc.)**

To meet industry's needs, newly graduated engineers need a brief transition time before they can become productive, in line with the specialized tasks assigned to them. They must have a good grasp of the mathematics and engineering sciences necessary for analysis and sufficient experience for decision-making. They must be capable of working under minimal supervision, with the creative synthesis that comes from experience that academia cannot offer. The industrial environment will require new recruits to work in a team, with an appreciation of time, cost, and quality under TQM, which is quite different from classroom experience. Today's conceptual aircraft designers must master many trades and specialize in at least one, not ignoring the state-of-the-art "rules of thumb" gained from past experiences; there is no substitute. They need to be good "number-crunchers" with excellent analytical ability. They also need assistance from an equally good support team to encompass wider areas. This is the purpose of the coursework in this book: to provide close-to-industry standard computations and engineering approaches necessary for analysis, and enough experience to work in a team.

For this reason, the authors emphasize that introductory class-work projects should be familiar to students so that they can relate to the examples and subsequently substantiate their work with an existing type. Working on an unfamiliar or non-existent design does not enhance the learning process at the introductory level. In industry, aircraft performance analyses are fully computerized for every phase of project work. However, in the classroom it is recommended to perform manual computation using spreadsheets.

Today, use of computer-aided design (CAD) is an integral part of engineering analyses. As an example, Figure 1.14 gives a 3D CAD drawing of an F16 fighter aircraft. 3D modelling provides fuller, more accurate shapes that are easy to modify, and facilitates maintenance of sequential configuration evolution. Accurate geometric details from CAD can be easily retrieved for drag estimation by the indispensable manual method.

There are considerably more benefits from CAD (3D) solid modelling; it can be uploaded directly into computational fluid dynamics (CFD) analysis to continue with aerodynamic estimations, as one of the first tasks is to estimate loading for structural analysis using the finite element method (FEM). The solid model offers accurate surface constraints for generating internal structural parts. CAD drawings can be uploaded directly to computer-aided manufacture (CAM) operations, ultimately leading to paperless design and manufacture offices. Vastly increased computer power has reached the desktop with parallel processing. Computer-aided engineering (CAE: e.g. CAD, CAM, CFD, FEM and systems analyses) is the accepted practice in the industry. Those who can afford supercomputers will

■ FIGURE 1.14 Typical 3D CAD drawing of F16 (reproduced with permission of Pablo Quispe Avellaneda, Naval Engineer, Peru)

have the capability to conduct research in areas hitherto unexplored or facing limitations (e.g. high-end CFD, FEM and multidisciplinary optimization (MDO)).

Finally, the authors recommend that performance engineers have some flying experience, which is most helpful in understanding the flying qualities of aircraft they are trying to analyze. Obtaining a licence requires effort and financial resources, but a few hours of planned flight experience would be instructive. One may discuss with the flight instructor what needs to be demonstrated, for example, aircraft characteristics in response to control input, stalling, "*g*" force in steep manoeuvres, stick forces, and so forth. Some universities offer a few hours of flight-tests as an integral part of aeronautical engineering courses; however, the authors suggest even more: hands-on experience under the supervision of a flight instructor. A driver with a good knowledge of the design features has more appreciation for the automobile.

1.10 Cost Implications

The authors emphasize here that there is a significant difference between civil and military programmes in predicting costs related to aircraft unit-price costing. The civil aircraft design has an international market with cash flowing back from revenues earned from fare-paying customers (i.e. passengers and freight) - a regenerative process that returns funds for growth and sustainability to enhance the national economy. Conversely, military aircraft design originates from a single customer demand for national defence and cannot depend on export potential – it does not have cash flowing back, and it strains the national economy out of necessity. Civil aircraft designs share common support equipment and facilities, which appear as indirect operational costs (IOCs) and do not significantly load aircraft pricing. The driving cost parameter for civilian aircraft design is the DOC, omitting the IOC component. Therefore, using a generic term of life cycle cost (LCC) = (DOC + IOC) in civil applications may be appropriate in context, but would prove to be off track for aircraft design engineers. Military design and operations incorporating discreet advances in technology necessarily have exclusive special support systems, equipment and facilities. The vehicles must be maintained for operation-readiness around the clock. Part of the supply costs and support costs for aircraft maintenance must be borne by manufacturers that know best and are in a position to maintain confidentiality on the high-tech defence equipment. The role of a manufacturer is defined in the contractual agreement to support its product for the entire life cycle of the aircraft "from cradle to grave" Here, LCC is meaningful for aircraft designers in minimizing costs for the support system integral to the specific aircraft design. Commercial transports would have nearly five times more operating hours than military vehicles in peacetime. Military aircraft have relatively high operating costs even when they sit idle on the ground. Academic literature has not been able to address clearly the LCC issues in order to arrive at an applicable standardized costing methodology. Aircraft design strategy is constantly changing. Initially driven by the classical subjects of aerodynamics, structures, and propulsion, the industry is now customer-driven and the design strategies consider the problems for manufacture/assembly that lead the way in reducing manufacturing costs. In summary, an aircraft engineer must be cost-conscious now, and even more so in future projects. Reference [20] addresses cost considerations in detail.

Aircraft design and manufacture are not driven by cost estimators and accountants; they are still driven by engineers. Unlike classical engineering sciences, costing is not based on natural laws; it is derived to some extent from manmade policies, which are rather volatile, being influenced by both national and international origins. The sooner the engineers include costing as an integral part of design, the better will be the competitive edge.

1.11 Units and Dimensions

The postwar dominance of British and American aeronautics has kept the use of the foot-pound-second system (FPS, also known as the Imperial System) current, despite the use of non-decimal fractions and the ambiguity of the word *pound* in referring to both mass and weight. The benefits of the Système International (SI) are undeniable: a decimal system and a distinction between mass and weight. However, there being "nowt so queer as folk," I am presented with an interesting situation in which both FPS and SI systems are used. Operational users prefer FPS (i.e. altitudes are measured in feet); however, scientists and engineers find SI more convenient. This is not a problem if one can become accustomed to the conversion factors. Appendix A provides an exhaustive conversion table that adequately covers the information in this book. However, readers will be relieved to know that in most cases, the text follows current international standards in notation units. Aircraft performance is conducted at the International Standard Atmosphere (ISA) (see Section 2.2). References are given when design considerations must cater to performance degradation in a non-standard day.

1.12 Use of Semi-empirical Relations and Graphs

DATCOM (US) and RAE DATA sheets (UK, recently replaced by ESDU) served many generations of engineers for more than a half century and are still in use. Over time, as technology advanced, new tools using computer-aided engineering (CAE) have somewhat replaced earlier methods. Inclusion of many of DATCOM/ESDU semi-empirical relations and graphs proves meaningless unless their use is shown in worked examples. It is important for instructors to compile as many test data as possible in their resources.

Semi-empirical relations and graphs cannot guarantee exact results; at best it is coincidental if they prove to be error-free. A user of semi-empirical relations and graphs must be aware of the extent of error that can incur. Even when providers of semi-empirical relations and graphs give the extent of the error range, it is difficult to substantiate any errors in a particular application.

If test results are available, they should be used in conjunction with the semi-empirical relations and graphs. Tests (e.g. aerodynamics, structures and systems) are expensive to conduct but they are indispensable to the process. Certifying agencies impose mandatory requirements on manufacturers to substantiate their designs with test results. These test results are archived as a databank to ensure that in-house semi-empirical relations are kept "commercial in confidence" as proprietary information. CFD and FEM are next in priority. The consistency of CFD in predicting drag has to be proven conclusively. At this stage, semi-empirical relations and graphs are used extensively in drag prediction as well as weight prediction.

Data reading from graphs is normal engineering practice, since graphs are readily available and data can be quickly obtained. But not all data are computerized (a good example is the general use of drag polar), and accuracy in reading data from graphs depends on their resolution. The graphs given in this book are small and do not have adequate resolution, therefore any readings are unlikely to be accurate. A good example will be shown in Section 9.9.1. It is recommended that the readers plot graphs with consistent accurate data in high resolution using high-end graph-plotting software.

1.13 How Do Aircraft Fly?

The mechanics of flight stems from the interaction between wind (air) and wing. A special property of air (gas) is the ability to generate lift through *wing–wind* interaction. Nature is conservative. Mass, momentum and energy in airflow is conserved unless there is an external intervention. Static pressure of the system is a form of energy (potential), and velocity is its kinetic energy. Together, the total energy is conserved – if one is changed, then the other is affected. For example, if velocity is increased, then its static pressure drops, and vice versa. This phenomenon is expressed as Bernoulli's Theorem.

A typical bread-slice-like wing section is known as an aerofoil, and its upper surface is more curved than the lower surface. Therefore, airspeed over the wing is faster (reducing its static pressure) than across the lower surface, resulting in a pressure difference directed upward. A sized wing area at a particular speed needs to generate requisite force (lift) to keep an aircraft in sustained flight. There is a minimum aircraft speed (stall speed) below which the wing will stall and will not develop sufficient lift. More details are given in Chapter 2. The entire subject matter comprises flight mechanics and its associated aerodynamic theories.

1.13.1 Classification of Flight Mechanics

The subject of flight mechanics may be divided into four subtopics:

1. **Performance:** The study of how an aircraft performs in terms of its kinematics, which is dependent on aerodynamic characteristics such as lift, drag and moments, and engine characteristics. It involves estimation of the extent of aircraft capability, which can be divided broadly as follows:
   a. Point performance: the aircraft capability at an instant, involving rate capabilities (e.g. speed, climb rate, descent rate, turn rate, etc.).
   b. Integrated performance: the aircraft capability integrated over a time period (e.g. takeoff and landing field length, climb to height, descent, mission range, etc.).
2. **Static stability:** The study of the tendency of the aircraft to remain in steady level flight when slightly perturbed. This leads to the prediction of the control movements and control forces required to change airspeed or load factor. This in turn leads to the idea of *handling qualities*. Longitudinal static stability is introduced in Chapter 6, as this affects aircraft performance.
3. **Dynamic stability:** The study of the motion of the aircraft after it has been disturbed in some fashion. The motions are classically divided into *modes of motion*, and the characteristics of the modes of motion are used to predict the flying qualities of the aircraft. Some modes are more important than others. The five classical modes are described in Chapter 6, but not treated in this book.
4. **Control:** The study of the effect of controls on the flying characteristics of the aircraft. Control is not dealt with in this course. It is treated as a separate subject.

The topic of this book is the first: the performance of aircraft. Aircraft design characteristics influence performance, and so their study is an integral part of understanding performance.

1.14 Anatomy of Aircraft

The study of aeronautics requires familiarity with aircraft configuration and the relevance of its components. The conventional aircraft configuration can be decomposed into the following eight sections.

1. **Fuselage:** This might crudely be regarded as the part of the aircraft that performs the function for which the aircraft was designed – carrying passengers, freight, electronic communications or munitions.

2. **The main wing:** The wing generates most of the lift required for flight. *Dihedral angle* or *sweep* on the wings provides *lateral (roll) stability*. *Flaps* on the trailing edge operate in sympathy and are used to enhance the lifting ability of the wing at low airspeeds. *Leading edge slats* and *wing spoilers* might be found on more complex wings.
3. **Ailerons:** These outboard flaps operate differentially and are used to control the roll rate of the aircraft. (See below for a little more detail.)
4. **Empennage:** The empennage comprises the horizontal (*tailplane*) and vertical (*fin*) surfaces at the rear of the aircraft.
5. **Tailplane:** The tail plane provides *longitudinal* (*pitch*) *stability*. The *elevator* is the flap on the tail plane and is used to control the aircraft in pitch. The *trim tab* is a small flap on the trailing edge of the elevator; it is used to balance the aerodynamic loads on the elevator in order to reduce the effort required of the pilot to maintain airspeed.
6. **Fin:** The fin provides *directional* (*yaw*) *stability*. The flap on the fin is called the *rudder* and is used to control the sideslip angle of the aircraft.
7. **Powerplant:** The power plant provides the thrust that balances the drag of the aircraft. Without the power plant, the aircraft is a glider. Power plants may be piston-props, turboprops or turbofans (see Chapter 4).
8. **Undercarriage:** The undercarriage or landing gear allow for safe operations on the ground (taxiing, takeoff, landing).

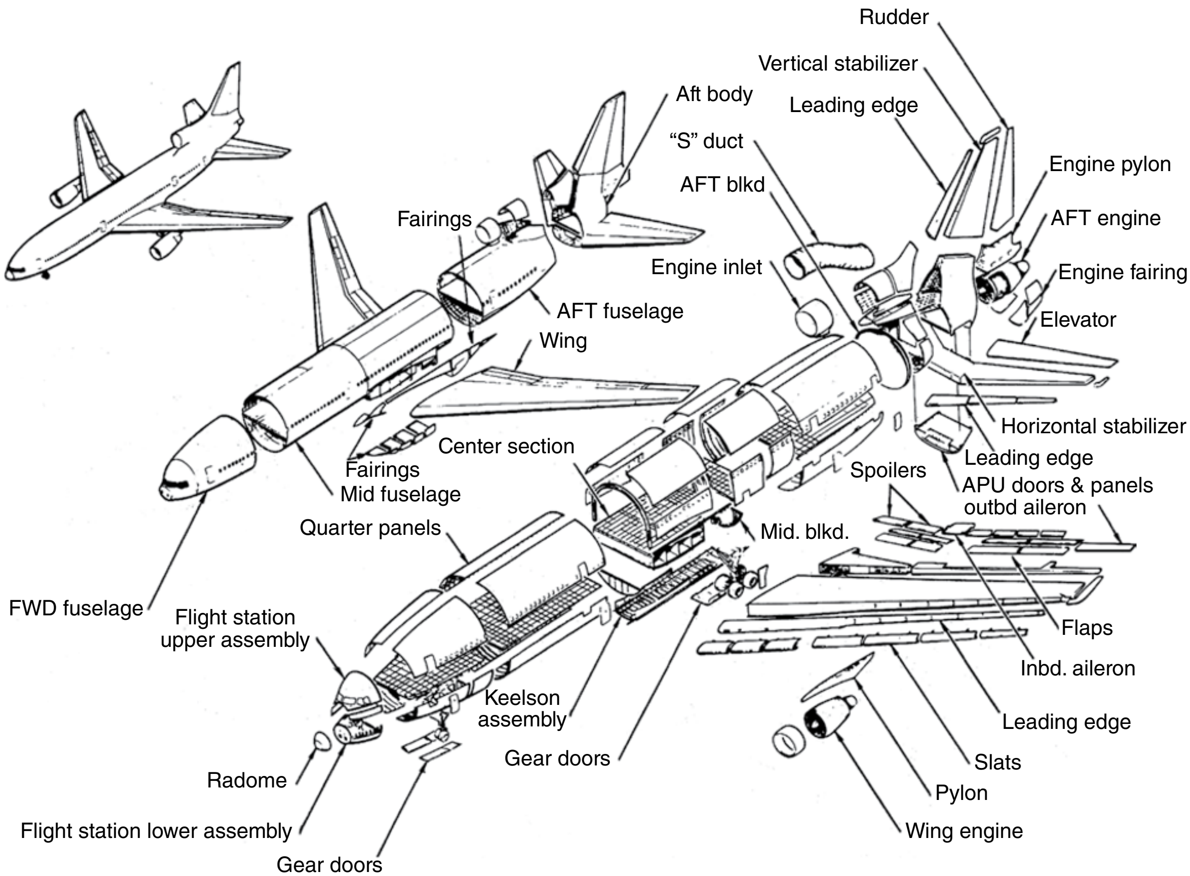
Both civil and military aircraft have different categories of design to cater for specific mission roles, and therefore aircraft performance capabilities will show wide variation. Section 10.4 describes in detail the various types of mission profiles for both civil and military aircraft.

The typical aircraft components of large aircraft are shown in Figure 1.15. The obvious components are generic (e.g. wing, fuselage, nacelle, empennage, control surfaces, etc.) for all types. Less obvious ones are typically winglets and strakes, but they play vital roles – otherwise they would not be there. There are many options. For convenience, components are associated in groups as described below. Not shown in the figure are the trimming surfaces used to reduce control forces experienced by the pilot.

Fuselage group: This starts with the nose cone, and then the constant mid-section fuselage, followed by the tapered aft fuselage, and at the end is the tail cone. The fuselage belly fairing (shown in Figure 1.15 as several sub-assembly components below the fuselage) may be used to house equipment at the wing–fuselage junction, such as the undercarriage wheels.

Wing group: This comprises the main wing, high lift devices, spoilers, control surfaces, tip devices and the structural wing box that passes through the fuselage. High lift devices include leading edge slats or trailing edge flaps; in Figure 1.15, the leading edge slats are shown attached with the main wing but the trailing edge flaps and spoilers are shown detached from the port wing. Spoilers are used to decelerate aircraft on descent and as the name suggests they spoil lift over the wing and are useful as “lift dumpers” on touchdown; thereby the undercarriage more rapidly absorbs the aircraft’s weight, allowing more effective application of brakes. In some aircraft, small differential deflections of spoilers with or without the use of ailerons are used to stabilize aircraft rolling tendencies in disturbances. The wing is shown with winglets at the tip: winglets are one of a set of tip treatments that can reduce the induced drag of the aircraft.

Empennage group: The empennage is the set of stability and control surfaces at the back of the aircraft. In Figure 1.15 it is shown as a vertical tail split into the fin in front and the rudder



■ **FIGURE 1.15** **Lockheed 1011 (courtesy of Michael Niu [20], reproduced with permission of Commlit Press)**

at the back, and an end cap on the top; the horizontal tail, shown as a T-tail set at the top of the vertical tail, comprises the stabilizer and the elevator.

Nacelle group: The podded nacelles are shown mounted on either side of the aft fuselage; pylons effect the attachment.

Undercarriage group: Undercarriage, or landing gear, usually comprises a nose wheel assembly and two sets of main wheels, forming a tricycle configuration. Tail dragging, bicycle and even quad configurations are possible, depending on the application of the aircraft. Wheels are usually retracted in flight, and the retraction mechanism and stowage bay all form part of the undercarriage group.

Military aircraft statistics and geometric details need to be looked at differently on account of the very different mission role. Combat aircraft do not have passengers and the payloads have wide variation in armament type to carry internally and/or externally. Military configurations are more diverse than civil designs. Figure 1.16 shows a blowout diagram for the General Dynamics (now Boeing) F16. The component groups are similar to what is described above, except modern fighters do not have nacelles as the engine is housed inside the fuselage.