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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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# Preface

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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 [kundu@qub.ac.uk](mailto:kundu@qub.ac.uk) or [M.Price@qub.ac.uk](mailto: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

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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

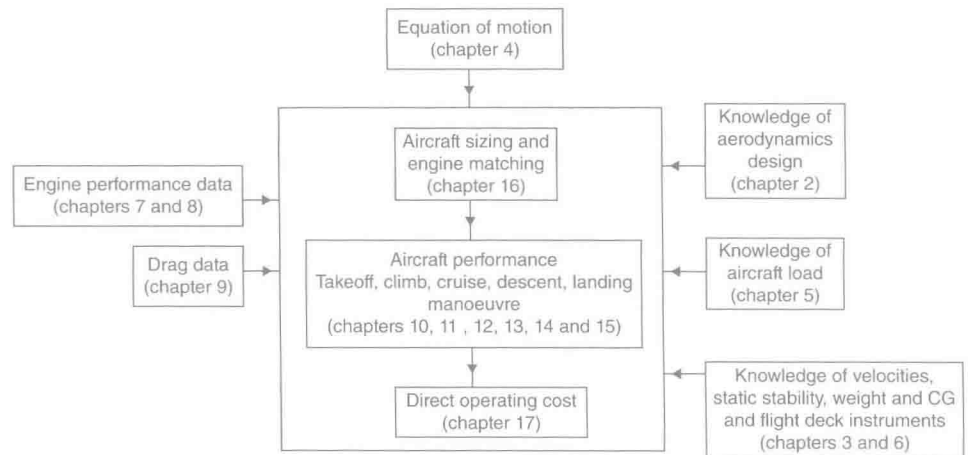
# Road Map of the Book

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## Organization

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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<br>(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<br>(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

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**By A.K. Kundu**

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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

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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

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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.

## A

|                    |   |
|--------------------|---|
| CG                 | centre of gravity                                       |
| c                  | chord   |
| $c_{\text{root}}$  | root chord  |
| $c_{\text{tip}}$   | tip chord   |
| cp                 | centre of pressure                                      |
| D                  | drag, diameter  |
| $D_{\text{skin}}$  | skin friction drag                                      |
| $D_{\text{press}}$ | 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)         |
| $F_{\text{ca}}$    | aft fuselage closure angle                              |
| $F_{\text{cf}}$    | front fuselage closure angle                            |
| $F_B$              | body axis   |
| $F_I$              | inertial axis   |
| $F_W$              | wind axis   |
| $F_{\text{xxx}}$   | component mass fraction, subscript identifies the item  |
| $F/m_n$            | 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  |
| $M_T$              | fuel mass   |
| $M_i$              | component group mass, subscript identifies the item     |
| $M_{\text{xxx}}$   | 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                              |
| $p_{\infty}$       | 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)                              |
| $T_{SL,S}$   | sea-level static thrust at takeoff rating                       |
| $T/W$        | thrust loading  |
| $t/c$        | thickness to chord ratio  |
| tf           | turbofan  |
| $U_g$        | vertical gust velocity  |
| $U_{\infty}$ | 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

|            |  |
|------------|--|
| $\alpha$   | angle of attack  |
| $\beta$    | CG angle with vertical at main wheel, blade pitch angle, side-slip angle |
| $\Gamma$   | dihedral angle, circulation  |
| $\gamma$   | ratio of specific heat, fuselage clearance angle                         |
| $\Delta$   | increment measure  |
| $\delta$   | boundary layer thickness   |
| $\epsilon$ | downwash angle   |



|           |  |
|-----------|--|
| $\eta_t$  | thermal efficiency   |
| $\eta_p$  | propulsive efficiency                                      |
| $\eta_o$  | overall efficiency   |
| $\Lambda$ | wing sweep, subscript indicates at the chord line          |
| $\lambda$ | taper ratio  |
| $\mu$     | friction coefficient, wing mass                            |
| $\rho$    | density  |
| $\theta$  | elevation angle, flight path angle, fuselage upsweep angle |
| $\pi$     | constant=3.14  |
| $\sigma$  | atmospheric density ratio                                  |
| $\tau$    | thickness parameter  |
| $v$       | velocity   |
| $\phi$    | roll angle, bank angle                                     |
| $\psi$    | azimuth angle, yaw angle                                   |
| $\omega$  | 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   |
| $\infty$ | 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                                     |