ADVANCED AIRCRAFT FLIGHT PERFORMANCE

This book deals with aircraft flight performance. It focuses on commercial aircraft but also considers examples of high-performance military aircraft. The framework is a multi-disciplinary engineering analysis, fully supported by flight simulation, with software validation at several levels. The book covers topics such as geometrical configurations, configuration aerodynamics and determination of aerodynamic derivatives, weight engineering, propulsion systems (gas turbine engines and propellers), aircraft trim, flight envelopes, mission analysis, trajectory optimisation, aircraft noise, noise trajectories and analysis of environmental performance. A unique feature of this book is the discussion and analysis of the environmental performance of the aircraft, focusing on topics such as aircraft noise and carbon dioxide emissions.

Dr. Antonio Filippone’s expertise is in the fields of computational and experimental aerodynamics, flight mechanics, energy conversion systems, propulsion systems, rotating machines (helicopter rotors, propellers, wind turbines), systems engineering, and design and optimisation. He has published more than eighty technical papers, ten book chapters, and two books, including Flight Performance of Fixed and Rotary Wing Aircraft (2006).
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Ignorantia quem portum petat nullus suus ventus est.

No wind is favourable to a sailor who does not know at which port to land.

[Lucius A. Seneca (4 BC–AD 65), *Moral Letters to Lucilius* (letter 71)]
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Preface

This book is a derivative of an earlier textbook on flight performance. This new work reflects my increased wisdom on the subject and represents an almost complete departure from closed-form solutions that are traditionally taught in under-graduate and post-graduate programs. Over the past several years, I have benefited from the experience of teaching a flight performance course to senior engineers from industry, government departments and academia. In the process, I learned a few new things that now find a place somewhere in the book.

There is an increase in numerical methods in all fields of engineering; nevertheless, flight performance has remarkably resisted change. Some closed-form solutions have been retained for those engineers who need a quick answer. The modern airplane is a complex engineering machine governed by systems, software and avionics. Primitive methods are still widely used, which are then applied to aircraft design and produce results of dubious accuracy that cannot be assessed. Worryingly, these methods are used in most “conceptual design” and “multi-disciplinary optimisation” methods. Now assume, more realistically, that you have been hired to provide flight prediction tools to an airline operator or a manufacturer of engines or airframes, a national or international aviation authority, an air traffic control organisation. Why should they trust your performance software? What is the risk of under-predicting the mission fuel for an intercontinental flight?

As we worried about conceptual design, the world has moved on. There is increased emphasis on airplane evolution and upgrading, which is now reflected in my thinking. At the same time, the environmental performance of the aircraft has become very prominent. Therefore, part of this book is devoted to a wide spectrum of environmental aspects of flight. My initial concerns have slowly shifted from noise to engine emissions. Noise disappears as the aircraft moves away from the receiver, although not many would like to agree. Exhaust gases remain with us for the next few generations. In particular, aircraft condensation trails are there to remind us that aviation is having a measurable impact on our skies. The lack of flexibility in aircraft levels, stepped cruise and descent, and the use of holding patterns in congested air space are all problems that need a solution in the coming years.

The book contains considerable advanced material across several disciplines, including aircraft noise, environmental performance, airframe-propulsion integration, thermo-structural performance and flight mechanics. I am conscious of the
Preface

I am aware of the audacity of the task I have undertaken, but I am confident that this work meets the expectations of the aviation industry and the academic world.

I have developed some fully comprehensive flight codes. One code in particular, FLIGHT, to simulate aircraft performance and mission analysis of transport aircraft, contains most of the cross-disciplinary aspects of performance discussed in this book.

In its present form it consists of about 160 KLOCS (thousand lines of code). Other codes discussed in the book include the propeller code, that is fully integrated with FLIGHT, as well as a supersonic flight performance code (SFLIGHT). Several block flowcharts have been included to help with the understanding of computer programs, numerical models, system analysis and flight performance. The following material is made available to readers:

- Computer code FLIGHT (demo version)
- Computer code Prop/FLIGHT (demo version)
- Computer code SFLIGHT (demo version)
- All charts and figures in any suitable graphical format

Separate technical documents will be issued to the readers wishing to work with these computer models.

Dr. Z. Mohammed-Kassim, my long-time associate, has actively contributed to the work on aircraft noise and to considerable code debugging. My doctoral student Nicholas Bojdo took great care in reading some chapters. I am indebted to my editor, Peter Gordon, who has been enthusiastic about my work from the beginning of the project to the end. The editorial and production work was efficiently managed by Peggy Rote at Aptara, Inc.

Finally, I thank my wife, Susan, for having the patience to tolerate my late nights at the desk, especially when I reached the tunnel phase of my work, that is, when I thought the book was finished but in fact there was no end in sight. A sabbatical leave from the University has allowed me to step up my efforts. I am grateful to the University, and the School, for the opportunity they have given me.
Nomenclature

Organisations

Below is a list of organisations that publish regularly documents (technical reports, papers, journals, regulations) as well as more general information of aviation.

AAIB Air Accidents Investigation Branch, United Kingdom (www.aaib.gov.uk)
AIAA American Institute of Aeronautics & Astronautics (www.aiaa.org)
ANSI American National Standards Institute (www.ansi.org)
ASTM American Society for Testing and Materials (www.astm.org)
BTS Bureau of Transportation Statistics, USA (www.bts.gov)
CAA Civil Aviation Authority (www.caa.co.uk)
EASA European Aviation Safety Agency (www.easa.eu.int)
ESDU Engineering Data Unit (www.esdu.com)
FAA Federal Aviation Administration (www.faa.gov)
FSF Flight Safety Foundation (www.flightsafety.org)
IATA International Air Transport Association (www.iata.org)
ICAO International Civil Aviation Organisation (www.icao.int)
IPCC Inter-governmental Panel for Climate Change (www.ipcc.ch)
Jane’s Jane’s Information Systems (www.janes.com)
MIL Military Standards (www.mil-standards.com)
NASA National Administration for Space and Aeronautics (www.nasa.gov)
NATO Advisory Group, Aerospace Research & Development (www.rta.nato.int)
NATS National Air Traffic System, United Kingdom (www.nats.co.uk)
NTSB National Transportation Safety Board, United States (www.ntsb.gov)
RAeS The Royal Aeronautical Society (www.aerosociety.org)
SAE Society of Automotive Engineers (www.sae.org)
SAWE Society of Allied Weight Engineers (www.sawe.org)

Acronyms Used in This Book

ACT Additional Centre Tank
AEO All Engines Operating
AF Activity Factor
### Nomenclature

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<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>APU</td>
<td>Auxiliary Power Unit</td>
</tr>
<tr>
<td>ASDA</td>
<td>Accelerate-Stop Distance Available</td>
</tr>
<tr>
<td>ASI</td>
<td>Air Speed Indicator</td>
</tr>
<tr>
<td>ASK</td>
<td>Available Seat per Kilometre</td>
</tr>
<tr>
<td>ATC</td>
<td>Air Traffic Control</td>
</tr>
<tr>
<td>AUW</td>
<td>All-Up Weight</td>
</tr>
<tr>
<td>BFL</td>
<td>Balanced Field Length</td>
</tr>
<tr>
<td>BPR</td>
<td>By-pass Ratio</td>
</tr>
<tr>
<td>BRGW</td>
<td>Brake-Release Gross Weight</td>
</tr>
<tr>
<td>CAS</td>
<td>Calibrated Air Speed</td>
</tr>
<tr>
<td>CASK</td>
<td>Cost per Available Seat per Kilometre</td>
</tr>
<tr>
<td>CDA</td>
<td>Continuous Descent Approach</td>
</tr>
<tr>
<td>CG</td>
<td>Centre of Gravity</td>
</tr>
<tr>
<td>CTOL</td>
<td>Conventional Take-off and Landing</td>
</tr>
<tr>
<td>DOC</td>
<td>Direct Operating Costs</td>
</tr>
<tr>
<td>DOCG</td>
<td>Dry Operating Centre of Gravity</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
</tr>
<tr>
<td>DOW</td>
<td>Dry Operating Weight</td>
</tr>
<tr>
<td>EAS</td>
<td>Equivalent Air Speed</td>
</tr>
<tr>
<td>EBF</td>
<td>Externally Blown Flap</td>
</tr>
<tr>
<td>ECS</td>
<td>Environmental Conditioning System</td>
</tr>
<tr>
<td>EGT</td>
<td>Exhaust Gas Temperature</td>
</tr>
<tr>
<td>EPNdB</td>
<td>Effective Perceived Noise, in dB</td>
</tr>
<tr>
<td>EPNL</td>
<td>Effective Perceived Noise Level</td>
</tr>
<tr>
<td>ETOPS</td>
<td>Extended Twin-Engine OPerationS</td>
</tr>
<tr>
<td>FADEC</td>
<td>Full Authority Digital Engine Control</td>
</tr>
<tr>
<td>FCA</td>
<td>Final Cruise Altitude</td>
</tr>
<tr>
<td>FCOM</td>
<td>Flight Crew Operating Manual</td>
</tr>
<tr>
<td>FDR</td>
<td>Flight Data Recorder</td>
</tr>
<tr>
<td>FL</td>
<td>Fuselage Line; Flight Level</td>
</tr>
<tr>
<td>FLS</td>
<td>Flight Level Separation</td>
</tr>
<tr>
<td>FMS</td>
<td>Flight Management System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>GPU</td>
<td>Ground Power Unit</td>
</tr>
<tr>
<td>GRW</td>
<td>Gross Ramp Weight</td>
</tr>
<tr>
<td>GTOW</td>
<td>Gross Take-off Weight</td>
</tr>
<tr>
<td>IAS</td>
<td>Indicated Air Speed</td>
</tr>
<tr>
<td>ICA</td>
<td>Initial Cruise Altitude</td>
</tr>
<tr>
<td>ICW</td>
<td>Initial Cruise Weight</td>
</tr>
<tr>
<td>IDA</td>
<td>Initial Descent Altitude</td>
</tr>
<tr>
<td>IGE</td>
<td>In Ground Effect</td>
</tr>
<tr>
<td>ILS</td>
<td>Instrument Landing System</td>
</tr>
<tr>
<td>ISA</td>
<td>International Standard Atmosphere</td>
</tr>
<tr>
<td>KCAS</td>
<td>Calibrated Air Speed in knots</td>
</tr>
<tr>
<td>KEAS</td>
<td>Equivalent Air Speed in knots</td>
</tr>
<tr>
<td>KIAS</td>
<td>Indicated Air Speed in knots</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>-------------</td>
<td>-----------------------------------------------</td>
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<tr>
<td>KTAS</td>
<td>True Air Speed in knots</td>
</tr>
<tr>
<td>LRM</td>
<td>Long-Range Mach number</td>
</tr>
<tr>
<td>MAC</td>
<td>Mean Aerodynamic Chord</td>
</tr>
<tr>
<td>MBGW</td>
<td>Maximum Brake-Release Weight</td>
</tr>
<tr>
<td>MCP</td>
<td>Maximum Continuous Power</td>
</tr>
<tr>
<td>MEW</td>
<td>Manufacturer's Empty Weight</td>
</tr>
<tr>
<td>MIL</td>
<td>Military Standards (USA)</td>
</tr>
<tr>
<td>MLW</td>
<td>Maximum Landing Weight</td>
</tr>
<tr>
<td>MRM</td>
<td>Maximum-Range Mach number</td>
</tr>
<tr>
<td>MRW</td>
<td>Maximum Ramp Weight</td>
</tr>
<tr>
<td>MSP</td>
<td>Maximum Structural Payload</td>
</tr>
<tr>
<td>MTOP</td>
<td>Maximum Take-off Power</td>
</tr>
<tr>
<td>MTOW</td>
<td>Maximum Take-off Weight</td>
</tr>
<tr>
<td>MZFW</td>
<td>Maximum Zero-Fuel Weight</td>
</tr>
<tr>
<td>NADP</td>
<td>Noise Abatement Departure Procedure</td>
</tr>
<tr>
<td>OASPL</td>
<td>Overall Sound Pressure Level</td>
</tr>
<tr>
<td>OAT</td>
<td>Outside Air Temperature</td>
</tr>
<tr>
<td>ODE</td>
<td>Ordinary Differential Equation</td>
</tr>
<tr>
<td>OEI</td>
<td>One Engine Inoperative</td>
</tr>
<tr>
<td>OEW</td>
<td>Operating Empty Weight</td>
</tr>
<tr>
<td>OGE</td>
<td>Out of Ground Effect</td>
</tr>
<tr>
<td>OPR</td>
<td>Overall Pressure Ratio</td>
</tr>
<tr>
<td>PAX</td>
<td>Passengers</td>
</tr>
<tr>
<td>PNL</td>
<td>Perceived Noise Level</td>
</tr>
<tr>
<td>PNLT</td>
<td>Perceived Noise Level, Tone Corrected</td>
</tr>
<tr>
<td>PWL</td>
<td>One-third octave band Power Level</td>
</tr>
<tr>
<td>SAR</td>
<td>Specific Air Range</td>
</tr>
<tr>
<td>SAT</td>
<td>Static Air Temperature</td>
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<tr>
<td>SEL</td>
<td>Sound Exposure Level</td>
</tr>
<tr>
<td>SEP</td>
<td>Specific Excess Power</td>
</tr>
<tr>
<td>SFC</td>
<td>Specific Fuel Consumption</td>
</tr>
<tr>
<td>SHP</td>
<td>Shaft Horse Power</td>
</tr>
<tr>
<td>SI</td>
<td>International Units System</td>
</tr>
<tr>
<td>S/L</td>
<td>Sea Level</td>
</tr>
<tr>
<td>SPL</td>
<td>Sound Pressure Level</td>
</tr>
<tr>
<td>STOL</td>
<td>Short Take-off and Landing</td>
</tr>
<tr>
<td>TAS</td>
<td>True Air Speed</td>
</tr>
<tr>
<td>TAT</td>
<td>Total Air Temperature</td>
</tr>
<tr>
<td>TMA</td>
<td>Terminal Manoeuvre Area</td>
</tr>
<tr>
<td>TOCG</td>
<td>Take-off Centre of Gravity</td>
</tr>
<tr>
<td>TOD</td>
<td>Top Of Descent</td>
</tr>
<tr>
<td>TODA</td>
<td>Take-off Distance Available</td>
</tr>
<tr>
<td>TODR</td>
<td>Take-Off Distance Required</td>
</tr>
<tr>
<td>TOGA</td>
<td>Take-off and Go-Around</td>
</tr>
<tr>
<td>TORA</td>
<td>Take-off Distance Required</td>
</tr>
<tr>
<td>TORR</td>
<td>Take-Off Run Required</td>
</tr>
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# Nomenclature

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>TOW</td>
<td>Take-off Weight</td>
</tr>
<tr>
<td>TSFC</td>
<td>Thrust-Specific Fuel Consumption</td>
</tr>
<tr>
<td>ULD</td>
<td>Unit Load Device</td>
</tr>
<tr>
<td>VMC</td>
<td>Minimum Control Speed</td>
</tr>
<tr>
<td>VMCA</td>
<td>Minimum Control Speed in Air</td>
</tr>
<tr>
<td>VMGC</td>
<td>Minimum Control Speed on the Ground</td>
</tr>
<tr>
<td>VMO</td>
<td>Maximum Operating Speed</td>
</tr>
<tr>
<td>VNE</td>
<td>Velocity Not to Exceed</td>
</tr>
<tr>
<td>WAT</td>
<td>Weight-Altitude-Temperature</td>
</tr>
<tr>
<td>WBM</td>
<td>Weight and Balance Manual</td>
</tr>
<tr>
<td>ZFCG</td>
<td>Zero-Fuel Centre of Gravity</td>
</tr>
<tr>
<td>ZFW</td>
<td>Zero-Fuel Weight</td>
</tr>
</tbody>
</table>

The U.S. Department of Defense and NATO publish a dictionary of acronyms and aviation jargon. A detailed list of symbols follows each chapter.
Technology Warning

This book makes reference to real flight vehicles in realistic flight conditions. The data used to model these vehicles have been extracted, elaborated, interpolated or otherwise inferred from documents available in the public domain. These documents are either published by the manufacturer or the operators, or both. They are supplemented with official data published by several aviation authorities at the national and international level. Many of these documents are freely available to the public in electronic format from the manufacturers, through their websites, or the websites of their customers, or by third parties. No commercial, sensitive or restricted data have been disclosed anywhere. All sources have been cited when appropriate. There is no implication that the data refer to any particular aircraft owned or operated by any organisation. The flight performance shown is often validated, but sometimes it is not. Whenever figures or tables report the term “simulated” or “validated”, they refer to simulations carried out with the comprehensive performance code FLIGHT and its related software technology (available from the author).

Readers should be made aware that the statements made in this book are the author’s own. Readers should use judgement before making technical, commercial, military, marketing or business decisions. The author cannot take responsibility for any action resulting in damage, accident or loss, as a consequence of statements made in this book. None of the graphs, figures and tables shown in this book can be used to make a final judgement on any airplane, any manufacturer, any flight, any service or any design. Use of the graphs for flight planning is prohibited. If you are in doubt, please consult the author, or use the performance codes from the aircraft manufacturers.