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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Ignoranti 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)]

Advanced Aircraft Flight Performance

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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 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

APU	Auxiliary Power Unit
ASDA	Accelerate-Stop Distance Available
ASI	Air Speed Indicator
ASK	Available Seat per Kilometre
ATC	Air Traffic Control
AUW	All-Up Weight
BFL	Balanced Field Length
BPR	By-pass Ratio
BRGW	Brake-Release Gross Weight
CAS	Calibrated Air Speed
CASK	Cost per Available Seat per Kilometre
CDA	Continuous Descent Approach
CG	Centre of Gravity
CTOL	Conventional Take-off and Landing
DOC	Direct Operating Costs
DOCG	Dry Operating Centre of Gravity
DOF	Degree of Freedom
DOW	Dry Operating Weight
EAS	Equivalent Air Speed
EBF	Externally Blown Flap
ECS	Environmental Conditioning System
EGT	Exhaust Gas Temperature
EPNdB	Effective Perceived Noise, in dB
EPNL	Effective Perceived Noise Level
ETOPS	**E**xtended **T**win-Engine **OP**eration**S**
FADEC	Full Authority Digital Engine Control
FCA	Final Cruise Altitude
FCOM	Flight Crew Operating Manual
FDR	Flight Data Recorder
FL	Fuselage Line; Flight Level
FLS	Flight Level Separation
FMS	Flight Management System
GPS	Global Positioning System
GPU	Ground Power Unit
GRW	Gross Ramp Weight
GTOW	Gross Take-off Weight
IAS	Indicated Air Speed
ICA	Initial Cruise Altitude
ICW	Initial Cruise Weight
IDA	Initial Descent Altitude
IGE	In Ground Effect
ILS	Instrument Landing System
ISA	International Standard Atmosphere
KCAS	Calibrated Air Speed in knots
KEAS	Equivalent Air Speed in knots
KIAS	Indicated Air Speed in knots

KTAS	True Air Speed in knots
LRM	Long-Range Mach number
MAC	Mean Aerodynamic Chord
MBGW	Maximum Brake-Release Weight
MCP	Maximum Continuous Power
MEW	Manufacturer's Empty Weight
MIL	Military Standards (USA)
MLW	Maximum Landing Weight
MRM	Maximum-Range Mach number
MRW	Maximum Ramp Weight
MSP	Maximum Structural Payload
MTOP	Maximum Take-off Power
MTOW	Maximum Take-off Weight
MZFW	Maximum Zero-Fuel Weight
NADP	Noise Abatement Departure Procedure
OASPL	Overall Sound Pressure Level
OAT	Outside Air Temperature
ODE	Ordinary Differential Equation
OEI	One Engine Inoperative
OEW	Operating Empty Weight
OGE	Out of Ground Effect
OPR	Overall Pressure Ratio
PAX	Passengers
PNL	Perceived Noise Level
PNLT	Perceived Noise Level, Tone Corrected
PWL	One-third octave band Power Level
SAR	Specific Air Range
SAT	Static Air Temperature
SEL	Sound Exposure Level
SEP	Specific Excess Power
SFC	Specific Fuel Consumption
SHP	Shaft Horse Power
SI	International Units System
S/L	Sea Level
SPL	Sound Pressure Level
STOL	Short Take-off and Landing
TAS	True Air Speed
TAT	Total Air Temperature
TMA	Terminal Manoeuvre Area
TOCG	Take-off Centre of Gravity
TOD	Top Of Descent
TODA	Take-off Distance Available
TODR	Take-Off Distance Required
TOGA	Take-off and Go-Around
TORA	Take-off Distance Required
TORR	Take-Off Run Required

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

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.