JET PROPULSION

This book is a self-contained introduction to the aerodynamic and thermodynamic design of modern civil and military jet engines. Through two engine design projects, for a large passenger aircraft and a new fighter aircraft, the text explains modern engine design. Individual sections cover aircraft requirements, aerodynamics, principles of gas turbines and jet engines, elementary compressible fluid mechanics, bypass pressure ratio selection, scaling and dimensional analysis, turbine and compressor design and characteristics, design optimization and off-design performance.

The civil aircraft, which was the core of Part 1 of earlier editions, has now been in service for several years as the Airbus A380. Attention in the aircraft industry has now shifted to two-engine aircraft with a greater emphasis on reduction of fuel burn. The model created for Part 1 is therefore a hypothetical new two-engine aircraft aimed at high efficiency.

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A Simple Guide to the Aerodynamics and Thermodynamic Design and Performance of Jet Engines

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PREFACE

PREFACE TO THE THIRD EDITION

The civil aircraft, the Airbus A380, which resembles the New Large Aircraft of Part 1 of earlier editions, has been in service for several years. Attention in the aircraft industry has now shifted to two-engine aircraft with a greater emphasis on reduction of fuel burn, so the model created for Part 1 is the New Efficient Aircraft, a twin aimed at high efficiency. There is another change to highlight, which is the switch to using fan pressure ratio as the independent design variable rather than bypass ratio. In the time since the first edition, the typical fan pressure ratios have been reduced, and this has necessarily led to a considerable increase in complexity. The changes relating to military combat engines are relatively small.

Another major change is the inclusion of a co-author. Andy Heyes had used the second edition in teaching a course in Imperial College and was well placed in terms of knowledge and experience to work on the third edition.

For the third edition, we would like to acknowledge additional help from friends and colleagues. From Rolls-Royce, we would mention Conrad Banks, John Bolger, Simon Gallimore, Peter Hopkins, Glen Knight, Paul Madden, Alan Newby, Ian Rainbow and Joe Walsh; from Pratt and Whitney, Yuan Dong, Alan Epstein and Jayant Sabnis; from Stanford University, Juan Alonso and Anil Variyar; from the University of Cambridge, Chez Hall and John Young; from Imperial College, Aaron Costall, Ricardo Martinez-Botas and Peter Newton; from Ohio State, Mike Dunn, retired from NASA, Tony Strazisar; retired from General Electric, Meyer Benzakein; and retired from Airbus, Jeff Jupp.

PREFACE TO THE FIRST EDITION

This book arose from an elementary course taught to undergraduates, which forms the first ten chapters, concerned with the design of the engines for a new 600-seat long-range airliner. Introductory undergraduate courses in thermodynamics and fluid mechanics would provide the reader with the required background, but the material is also presented in a way to be accessible to any graduate in engineering or physical sciences with a little background reading. The coverage is deliberately restricted almost entirely to the thermodynamic and aerodynamic aspects of jet propulsion, a large topic in itself. The still larger area associated with mechanical aspects of engines is not covered, except that empirical information for such quantities as maximum tip speed are used, based on experience. To cover the mechanical design of engines would have required a much bigger book than this and would have required a mass of knowledge which I do not possess.

In preparing the course, it was necessary for me to learn new material, and for this, I obtained help from many friends and colleagues in industry, in particular at Rolls-Royce. This brought me to realise how specialised the knowledge has become, with relatively few people having a firm grasp outside their own speciality. Furthermore, a high proportion of those with the wide grasp are nearing retirement age, and a body of knowledge and experience is being lost. The idea therefore took hold that there is scope for a book which will have wider appeal than a book for students – it is intended to appeal to people in the aircraft engine industry who would like to understand more about the overall design of engines than they might normally have had the opportunity to master. My ambition is that many people in the industry will find it useful to have this book for reference, even if not displayed on bookshelves.

The original course, Chapters 1–10, was closely focused on an elementary design of an engine for a possible (even likely) new large civil aircraft. Because the intention was to get the important ideas across with the least complication, a number of simplifications were adopted, such as taking equal and constant specific heat capacity for air and for the gas leaving the combustor, as well as neglecting the effect of cooling air to the turbines.

Having decided that a book could be produced, the scope was widened to cover component performance in Chapter 11 and off-design matching of the civil engine in Chapter 12. Chapters 13–18 look at various aspects of military engines; this is modelled on the treatment in Chapters 1–10 of the civil engine, postulating the design requirement for a possible new fighter aircraft. In dealing with the military engine, some of the simplifications deliberately adopted in the early chapters are removed; Chapter 19 therefore takes some of these improvements from Chapters 13–18 to look again at the civil engine.

Throughout the book, the emphasis is on being as simple as possible, consistent with a realistic description of what is going on. This allows the treatment to move quickly and the book to be brief. But more important, it means that someone who has mastered the simple formulation can make reasonably accurate estimates for performance of an engine and can estimate changes in performance with alteration in operating conditions or component behaviour. Earlier books become complicated because of the use of algebra; furthermore, to make the algebra tractable frequently forces approximations which are unsatisfactory. The present book uses arithmetic much more – by taking advantage of the computer and the calculator, the numerical operations are almost trivial. The book contains a substantial number of exercises which are directed towards the design of the civil engine in the early chapters and the military engine in the later chapters. The exercises form an integral part of the book and follow, as far as possible, logical steps in the design of first the civil engine and then the military combat engine. Many of the insights are drawn from the exercises.

Because Chapters 1–10 were directed at undergraduates, there are elementary treatments of some topics (most conspicuously, the thermodynamics of gas turbines, compressible fluid mechanics and turbomachinery), but only that amount needed for understanding the remainder of the treatment. I decided to leave this elementary material in, having in mind that some readers might be specialists in areas sufficiently far from aerodynamics and thermodynamics that a brief but relevant treatment would be helpful.

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It is my pleasure to acknowledge the help I have had with this book from my friends and colleagues. The largest number are employed by Rolls-Royce (or were until their retirement) and include Alec Collins, Derek Cook, Chris Freeman, Simon Gallimore, Keith Garwood, John Hawkins, Geoffery Hodges, Dave Hope, Tony Jackson, Brian Lowrie, Sandy Mitchell, James Place, Paul Simkin, Terry Thake and Darrell Williams. Amongst this group I would like to record my special gratitude to Tim Camp, who worked through all the exercises and made many suggestions for improving the text. I would also like to acknowledge the late Mike Paramour of the Ministry of Defence. In the Whittle Laboratory, I would like to record my particular debt to John Young and also to my students Peter Seitz and Rajesh Khan. I am also grateful for the help from other students in checking late drafts of the text. In North America, I would like to mention Ed Greitzer and Jack Kerrebrock (of the Gas Turbine Laboratory of MIT), Bill Heiser (of the Air Force Academy), Phil Hill (of the University of British Columbia), Bill Steenken and Dave Wisler (of GE Aircraft Engines) and Robert Shaw. Above all, I would like to express my gratitude to Ian Waitz of the Gas Turbine Laboratory of MIT, who did a very thorough job of assessing and weighing the ideas and presentation – the book would have been very much the worse without him. In addition to all these people, I must acknowledge the help and stimulus from the students who took the course and the people who have added to my knowledge and interest in the field over many years.

THE EXERCISES

An important part of the book are exercises related to engine design. To make these possible, it is necessary to assume numerical values for many of the parameters, and appropriate values are therefore assumed to make the exercises realistic. These values are necessarily approximate, and in some cases so, too, is the model in which they are used. The answers to the exercises, however, are given to a higher level of precision than the approximations deserve. This is done to assist the reader in checking solutions to the exercises and to ensure some measure of consistency. The wise reader will keep in mind that the solutions are in reality less accurate than the number of significant figures seems to imply.

The usefulness of the book will be greatly increased if the exercises are undertaken. In some cases, one exercise leads to another, and a few simple calculations on a handheld calculator suffice. In others, it is desirable to carry out several calculations with altered parameters, and such cases call out for a computer and spreadsheet. Those exercises marked with an asterisk provide results to be entered onto the design sheets for the New Efficient Aircraft and the New Fighter Aircraft.

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SOLUTIONS TO THE EXERCISES

Solutions to all the exercises may be obtained from the publisher by e-mailing solutions@cambridge.org.

GLOSSARY

afterburner	a device common in military engines where fuel is burned downstream of the turbine and upstream of the final propulsive nozzle. Also known as an augmentor or as reheat.
aspect ratio	the ratio of one length to another to define shape, usually the ratio of span to chord.
blades	the name normally given to the aerofoils in a turbomachine (compressor or turbine). Sometimes stationary blades are called stator vanes (or just vanes) and rotor blades are called buckets.
booster	a name given to compressor stages on the LP shaft in two-shaft engines. The booster stages only affect the core flow.
bypass engine	an engine in which some of the air (the bypass stream) passes around the core of the engine. The bypass stream is compressed by the fan and then accelerated in the bypass stream nozzle. These are sometimes called turbofan engines or fan engines.
bypass ratio	the ratio of the mass flow rate in the bypass stream to the mass flow rate through the core of the engine.
chord	the length of a wing or a turbomachine blade in the direction of flow.
combustor	also known as a combustion chamber. The component where the fuel is mixed with the air and burned.
compressor	the part of the engine which compresses the air, a turbomachine consisting of stages, each with a stator and rotor row.
core	the compressor, combustion chamber and turbine at the centre of the engine. The core turbine drives only the core compressor. A given core can be put to many different applications, with only minor modifications, so it could form part of a high-bypass ratio engine, a turbojet (with zero bypass ratio) or part of a land-based power generation system. The core is sometimes called the gas generator.
drag	the force D created by the wings, fuselage, etc. in the direction opposite to the direction of travel.
fan	the compressor operating on the bypass stream; normally the pressure ratio of the fan is small, not more than about 1.8 for a modern high-bypass civil engine (in one stage with no inlet guide vanes) and not more than about 4.5 in a military engine in two or more stages.
gross thrust	the thrust F_G created by the exhaust stream without allowing for the drag created by the engine inlet flow; for a stationary engine, the gross thrust is equal to the net thrust.
HP	the high-pressure compressor and turbine are part of the engine core. They are mounted on either end of the HP shaft. In a two-shaft engine, they form the core spool.
incidence	sometimes called angle of attack, the angle at which the wing is inclined to the direction of travel or the angle at which the incoming flow direction is inclined to a wing or to a compressor or turbine blade.

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IP	the intermediate-pressure compressor or turbine, mounted on the IP shaft. There is only an IP shaft in a three-shaft engine.
jetpipe	the duct or pipe downstream of the LP turbine and upstream of the final propulsive nozzle.
LCV	the lower calorific value of the fuel; the energy released per unit mass of fuel in complete combustion when the products are cooled down to the inlet temperature but none of the water vapour is allowed to condense.
lift	the force L created, mainly by the wings, perpendicular to the direction of travel.
LP	the low-pressure compressor and turbine are mounted on either end of the LP shaft. Combined, they form the LP spool.
nacelle	the surfaces enclosing the engine, including the intake and the nozzle.
net thrust	the thrust F_N created by the engine available to propel the aircraft after allowing for the drag created by the inlet flow to the engine. (Net thrust is equal to gross thrust minus the ram drag.)
ngv	the nozzle guide vane, another name for the stator row in a turbine.
nozzle	a contracting duct used to accelerate the stream to produce a jet. In some cases, for high-performance military engines, a convergent-divergent nozzle may be used.
payload	the part of the aircraft weight which is capable of earning revenue to the operator (can be freight or passengers).
pylon	the strut which connects the engine to the wing.
ram drag	the momentum of the relative flow entering an engine.
sfc	specific fuel consumption (actually the *thrust* specific fuel consumption) equal to the mass flow rate of fuel divided by net thrust. The units should be in the form (kg/s)/kN but the units are often given as $\text{lb}\,\text{h}^{-1}\text{lb}^{-1}$ or $\text{kg}\,\text{h}^{-1}\text{kg}^{-1}$.
specific thrust	the net thrust per unit mass flow through the engine, units m/s.
spool	used to refer to the compressor and turbine mounted on a single shaft, so a two-spool engine is synonymous with a two-shaft engine.
stagnation	stagnation temperature is the temperature which a fluid would have if brought to rest adiabatically. The stagnation pressure is the pressure if the fluid were brought *isentropically* to rest. Stagnation quantities depend on the frame of reference and are discussed in Chapter 6.
static	static temperature and pressure are the actual temperature and pressure of the fluid, in contrast to the stagnation quantities defined earlier.
turbine	a component which extracts work from a flow. It consists of rotating and stationary blades. The rotating blades are called rotor blades, and the stationary blades are called stator blades or nozzle guide vanes.
turbofan	a jet engine with a bypass stream.
turbojet	a jet engine with no bypass stream – these were the earliest types of jet engines and are still used for very-high-speed propulsion.

NOMENCLATURE

a	speed of sound $\sqrt{\gamma RT}$
A	area
A_R	Aspect ratio
bpr	bypass ratio
c	chord of wing or blade
c_p	specific heat at constant pressure
C_D	drag coefficient
C_L	lift coefficient
D	drag (force opposing motion)
d_r, D	diameter
E	energy state $m(gh + V^2/2)$
E_s	specific energy state $gh + V^2/2$
F_G	gross thrust
F_N	net thrust
g	acceleration due to gravity
h	static enthalpy
h_0	stagnation enthalpy
h, H	altitude
h	blade height (i.e. span)
H	range factor
i	incidence
L	lift (force perpendicular to direction of motion)
LCV	lower calorific value of fuel
m	mass
$\dot{m}$	mass flow rate
$\overline{m}$	non-dimensional mass flow rate, $\dot{m}\sqrt{c_p T_0}/Ap_0$
M	Mach number
n	load factor
N	shaft rotational speed
opr	overall pressure ratio
p	static pressure
p_0	stagnation pressure
q	dynamic pressure $\frac{1}{2}\rho V^2$
Q	heat transfer
$\dot{Q}$	heat transfer rate
r	radius (Chapters 9 and 18)
r	pressure ratio
R	gas constant
s	entropy
SAR	specific air range
SEP	specific excess power
sfc	specific fuel consumption
T	static temperature
T_0	stagnation temperature
U	blade speed
V	velocity
V_j	jet velocity
V^{rel}	velocity relative to moving blade
w	weight
W	work
$\dot{W}$	work rate, power
α	flow direction (measured from axial)
α^{rel}	flow direction relative to moving blades
β	blade direction measured from axial
γ	ratio of specific heats c_p/c_v
δ	flow deviation (Chapters 9 and 18)
δ	p_0/p_{0ref}
η	efficiency
θ	$\sqrt{T_0/T_{0ref}}$
ρ	density
ε	cooling effectiveness (Chapter 5)
Ω	angular velocity

Subscripts

a	ambient
ab	afterburner
air	air
b	bypass
c	core
dry	no afterburner in use
e	combustion products (c_p and γ)
f	fuel
$isen$	isentropic (efficiency)
m	mean
p	polytropic (efficiency)
sl	sea level
$therm$	thermal (efficiency)

A NOTE ON NOMENCLATURE

The various stations or positions throughout an engine are given numbers, and different companies have different conventions for the many positions along the flow path of a multi-spool engine. An internationally recommended numbering scheme applies to some of the major stations, and of these the most important station numbers to remember are the following:

2	engine inlet face
3	compressor exit and combustion chamber inlet
4	combustion chamber exit and turbine inlet

The preceding brief list shows the one superficial snag: the inlet face of the engine is station 2, whereas most teaching courses call it station 1. The reason for this discrepancy is that for some engine installations, particularly in high-speed aircraft, there can be a substantial reduction in stagnation pressure along the inlet; station 2 is after this loss has taken place. In this book, the international standard will be used, where appropriate, with 2 at the inlet to the engine, and a simplified guide is shown in Figure 7.1. For more detailed treatment of the engine, the scheme in Figure 12.7 or Figure 15.1 should be consulted.

Subscript zero is used to denote stagnation conditions, for example stagnation pressure, p_0, and stagnation temperature, T_0. (See Chapter 6 for an explanation of the terms *stagnation pressure* and *stagnation temperature.* Some people use the word *total* in place of *stagnation*.) The stagnation pressure at engine inlet is therefore written p_{02} and temperature at turbine entry as T_{04}.

TERMINOLOGY

There are differences between British and American usage, but usually these are small – *aeroplane* and *airplane*, for example. It may be noted that in Britain, it is normal to use the word *civil* when referring to aviation, aircraft and air transport, where in the United States the word *commercial* would normally be used. In the book, the British usage *civil* is adopted. However, although it is still quite common in Britain to refer to *reheat*, the corresponding American term *afterburner* is used throughout the book.