Fundamentals of Jet Propulsion with Applications

This introductory text on air-breathing jet propulsion focuses on the basic operating principles of jet engines and gas turbines. Previous coursework in fluid mechanics and thermodynamics is elucidated and applied to help the student understand and predict the characteristics of engine components and various types of engines and power gas turbines. Numerous examples help the reader appreciate the methods and differing, representative physical parameters. A capstone chapter integrates the text material in a portion of the book devoted to system matching and analysis so that engine performance can be predicted for both on- and off-design conditions. The book is designed for advanced undergraduate and first-year graduate students in aerospace and mechanical engineering. A basic understanding of fluid dynamics and thermodynamics is presumed. Although aircraft propulsion is the focus, the material can also be used to study ground- and marine-based gas turbines and turbomachinery and some advanced topics in compressors and turbines.

Ronald D. Flack is a Professor, former Chair of Mechanical and Aerospace Engineering, and former Director of the Rotating Machinery and Controls (ROMAC) Industrial Research Program at the University of Virginia. Professor Flack began his career as an analytical compressor design engineer at Pratt & Whitney Aircraft. He is an ASME Fellow and is actively involved in research on experimental internal flows in turbomachines and fluid film bearings.

Fundamentals of Jet Propulsion with Applications

RONALD D. FLACK
University of Virginia

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
40 West 20th Street, New York, NY 10011-4211, USA

www.cambridge.org
Information on this title: www.cambridge.org/9780521819831

First published 2005

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication Data

Flack, Ronald D., 1947–
Fundamentals of jet propulsion with applications / Ronald D. Flack, Jr.
p. cm. – (Cambridge aerospace series ; 17)
Includes bibliographical references and index.
ISBN 0-521-81983-0 (hardback)
1. Jet engines. I. Title. II. Series.
TL709.F5953 2005
621.43′52 – dc22 2004020358

On the cover is the PW 4000 Series – 112-inch fan (courtesy of Pratt & Whitney)

ISBN-13 978-0-521-81983-1 hardback
ISBN-10 0-521-81983-0 hardback

Dedicated to Harry K. Herr, Jr.

(Uncle Pete)

who quietly helped me find the right career direction

Contents

Preface

My goal with this project is to repay the gas turbine industry for the rewarding profession it has provided for me over the course of more than three decades. At this point in my career, student education is a real passion for me and this book is one way I can archive and share experiences with students. I have written this text thinking back to what I would have liked as an undergraduate student nearly 40 years ago. Thus, this work has been tailored to be a very student friendly text.

This book is intended to serve primarily as an introductory text in air-breathing jet propulsion. It is directed at upper-level undergraduate students in mechanical and aerospace engineering. A basic understanding of fluid mechanics, gas dynamics, and thermodynamics is presumed; however, thermodynamics is reviewed, and an appendix on gas dynamics is included for reference. Although the work is entitled *Jet Propulsion*, it can well be used to understand the fundamentals of "aeroderivative" ground- or marine-based gas turbines such as those used for marine propulsion, ground transportation, or power generation. Although turbomachinery is not the primary target of the text, it is the book's secondary focus, and thus the fundamentals of, and some advanced topics in, compressors and turbines are also covered.

This text covers the basic operating principles of jet engines and gas turbines. Both the fundamental mathematics and hardware are addressed. Numerous examples based on modern engines are included so that students can grasp the methods and acquire an appreciation of different representative physical parameters. For this reason, development of "plug-and-chug" equations or "formulas" is de-emphasized, and the solutions of all examples are logically and methodically presented. The examples are an integral part of the presentation and are not intended to be side issues or optional reading. A student is expected to understand the individual steps of analyzing an entire engine or an individual component. By the use of examples and homework problems a student is also expected to develop an appreciation of trend analysis; that is, if one component is changed by a known amount, how will the overall engine performance change? Both British and SI units are used in the examples. A strong and unique feature of the book is a capstone chapter (Chapter 11) that integrates the previous 10 chapters into a section on component matching. From this integrated analysis, engine performance can be predicted for both on- and off-design conditions.

Subjects are treated with equal emphasis, and the parts of the book are interdependent in such a way that each step builds on the previous one. The presentation is organized into three basic areas as follows:

1. Cycle Analysis (Chapters 1 through 3) – In these chapters, different engines are defined, the fundamental thermodynamic and gas dynamic behavior of the various components are covered, and ideal and nonideal analyses are performed on each type of engine considered as a whole. Fundamental applicable thermodynamic principles are reviewed in detail. The performance of each individual component is assumed to be known at this point in the text. Trend studies and quantitative analysis methodologies are presented. The effects of nonideal characteristics are

demonstrated by comparing performance results with those that would occur if the characteristics were ideal.

2. Component Analysis (Chapters 4 through 10) – In these chapters the components are studied and analyzed individually using thermodynamic, fluid mechanical, and gas dynamic analyses. Diffusers, nozzles, axial flow compressors, centrifugal compressors, axial flow turbines, combustors and afterburners, ducts, and mixers are covered. Individual component performance can be predicted and analyzed, including on- and off-design performance and "maps," thus expanding on the fundamentals covered in cycle analyses. The effects on component performance of different geometries for the various components are covered. Some advanced topics are included in these sections.
3. System Analysis and Matching (Chapter 11) – This chapter serves as a capstone chapter and integrates the component analyses and characteristic "maps" into generalized cycle analyses. Individual component performance and overall engine performance are predicted and analyzed simultaneously. Both on- and off-design analyses are included, and prediction of engine parameters such as the engine operating line and compressor surge margin is possible.

Every chapter begins with an introduction providing an historical overview and outlining the objectives of the chapter. At the end of every chapter, a summary reviews the important points and specifies which analyses a student should be able to perform. In addition, appendixes are included that review or introduce compressible flow fundamentals, general concepts of turbomachinery, and general concepts of iteration methods – all of which are a common thread throughout the text.

The text is well suited to independent study by students or practicing engineers. Several topics are beyond what a one-semester undergraduate course in gas turbines can include. For this reason, the book should also be a valuable reference text.

A suite of user-friendly computer programs is available to instructors through the Cambridge Web site. The programs complement the text, but it can stand alone without the programs. I have used the programs in a variety of ways. I have found the programs (especially the cycle analysis, turbomachinery, and matching programs) to be most useful for design problems, and this approach reduces the need for repetitious calculations. In general, I provide the programs to students once they have demonstrated proficiency at making the fundamental calculations. The programs are as follows:

Atmosphere – Table for standard atmosphere.
Simple1D – Compressible one-dimensional calculations or tables for Fanno line, Rayleigh line, isentropic, normal shock flow, or constant static temperature flows.
General1D – Computations for combined Fanno line, Rayleigh line, drag object, mixing flow, and area change.
Shock – Calculations for normal, planar oblique, or conical oblique shocks.
Nozzle – Calculations for shockless nozzle flow.
JetEngineCycle – Cycle analysis of ideal and real ramjets, turbojets, turbofans, and turboprops.
PowerGTCycle – Cycle analysis of power-generation gas turbines with regenerators.
Turbomachinery – Mean-line turbomachinery calculations for axial and radial compressors and axial and radial turbines.
SLA – Three-dimensional streamline analysis of axial flow compressors or turbines with radial equilibrium with several specifyable boundary condition types.

CompressorPerf – Fundamental prediction of compressor stage efficiency due to lift and drag characteristics and incidence flow.

Kerosene – Adiabatic flame temperature of *n*-decane for different fuel-to-air mix ratios.

JetEngineMatch – Given diffuser, compressor, burner, turbine, and nozzle maps are matched to find overall turbojet engine performance and airframe drag maps are used to match engines with an aircraft.

PowerGTMatch – Given inlet, compressor, burner, turbine, regenerator, and exhaust maps are matched to find overall power-generation gas turbine performance.

A solutions manual (PDF) to the more than 325 end-of-chapter problems is also available to instructors. Please email Cambridge University Press at: solutions@cambridge.org.

This book was primarily written in two stages: first from 1988 to 1993 and then from 2000 to 2004 – the void being while I was Chair of our department. The bulk of the writing was done at the University of Virginia, although a portion of the book was written at Universität Karlsruhe while I was on sabbatical (twice). Some chapters were used in my jet propulsion class starting in 1989, and I began to use full draft versions of the text starting in 1992. In the course of this extended use, students have suggested many changes, which I have included; more than 300 students have been very important to the development of the text. I have also used portions of draft versions of the text in a graduate-level turbomachinery course, and graduate students have also made very useful suggestions. Over the past 15 years, I have incorporated many comments from students, and I took such suggestions very seriously. I am indebted to the numerous students who contributed in this way.

This project has been most fulfilling and it has been a culminating point in my own life. Through the writing and the resulting input from students, I have become a better and more patient teacher in all aspects of my life. Acknowledgments and thanks are in order starting with Mac Mellor and Sigmar Wittig, back in 1968, and then Doyle Thompson, in 1971, who triggered my interest in gas dynamics and gas turbines with projects at Purdue – the concepts have been central to my professional life since then. Certainly, thanks are due to my colleagues at both the University of Virginia and Universität Karlsruhe for their collegiality. Special appreciation is due to all of my graduate students at the University of Virginia, Universität Karlsruhe, and Ruhr Universität Bochum, who helped keep me young through the years. Portions of the proceeds of this text are going back to the University of Virginia, Universität Karlsruhe, and Purdue to help further undergraduate gas turbine education.

My family has been a timeless inspiration to me. Missy and Todd are both great kids who allowed me to forget work when needed, and now my granddaughters Mya and Maddie enable me again to see how much fun little ones can be. And then there are Zell and Dieter – one could not want better companions.

I cannot say enough about Nancy, my soul mate and best friend since 1966. This book would never have come to fruition without her positive influence. She helped me to realize the true value of life and to keep the proper perspectives.

Ron Flack
2004

Foreword

The book entitled *Fundamentals of Jet Propulsion with Applications*, by Ronald D. Flack, will satisfy the strong need for a comprehensive, modern book on the principles of propulsion – both as a textbook for propulsion courses and as a reference for the practicing engineer.

Professor Flack has written an exciting book for students of aerospace engineering and design. His book offers a combination of theory, practical examples, and analysis utilizing information from actual aerospace databases to motivate students; illustrate, and demonstrate physical phenomena such as the principles behind propulsion cycles, the fundamental thermofluids governing the performance of – and flow mechanisms in – propulsion components, and insight into propulsion-system matching.

The text is directed at upper-level undergraduate students in mechanical and aerospace engineering, although some topics could be taught at the graduate level. A basic understanding of fluid mechanics, gas dynamics, and thermodynamics is presumed, although most principles are thoroughly reviewed early in the book and in the appendixes. Propulsion is the primary thrust, but the material can also be used for the fundamentals of ground- and marine-based gas turbines. Turbomachinery is a secondary target, and the fundamentals and some advanced topics in compressors and turbines are covered.

The specific and unique contributions of this book and its strengths are that fundamental mathematics and modern hardware are both covered; moreover, subjects are treated with equal emphasis. Furthermore, the author uses an integrated approach to the text in which each step builds on the previous one (cycle analyses and engine design are treated first, component analysis and design are treated next, and finally and uniquely, component matching and its influence on cycle analysis are addressed to bring all of the previous subjects together). The latter feature is a very great strength of the text. In contrast to most other texts, the author incorporates many numerical examples representing current engines and components to demonstrate the main points. The examples are a major component of the text, and the author uses them to stress important points. In working through these examples, the author de-emphasizes the use of “ready-made formulas.” Numerous trend analyses are performed and presented to give students a “feel” of what can be expected if engine or component parameters are varied. The book can be used as a text for a university course or as a self-learning reference text.

At the beginning of every chapter the author presents an introduction outlining some history as well as the objectives of the chapter. At the end of every chapter he provides a summary recalling the key points of the chapter and places the chapter in the context of other chapters. The text is well suited for independent study by students or practicing engineers. Several topics are covered that are beyond those typically included in a one-semester undergraduate gas turbine course. As a result, the book should also be a valuable reference text.

As a teacher of an aerospace engineering course, I strongly recommend the book to college engineering students and teachers, practicing engineers, and members of the general public who want to think and be challenged to solve problems and learn the technical fundamentals of propulsion.

Abraham Engeda
Professor of Mechanical Engineering and
Director of Turbomachinery Laboratory
Michigan State University
2004