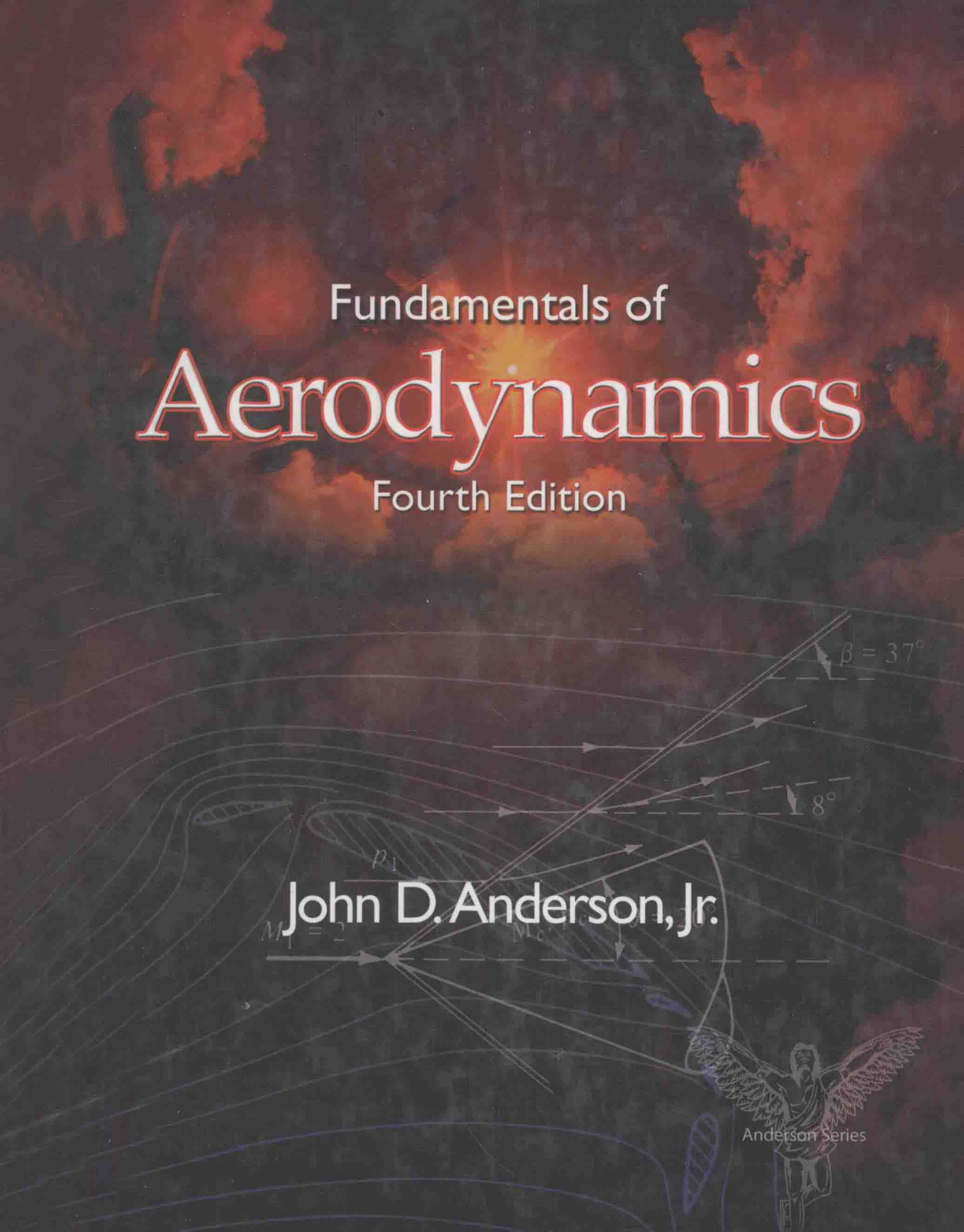
Fundamentals of Aerodynamics

Fourth Edition



John D. Anderson, Jr.

Anderson Series

Fundamentals of Aerodynamics

Fourth Edition

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National Air and Space Museum
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University of Maryland

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FUNDAMENTALS OF AERODYNAMICS, FOURTH EDITION

This book is printed on acid-free paper.

2 3 4 5 6 7 8 9 0 DOC/DOC 0 9 8 7 6

ISBN-13 978-0-07-295046-5
ISBN-10 0-07-295046-3

Publisher: *Suzanne Jeans*
Senior Sponsoring Editor: *Michael S. Hackett*
Developmental Editor: *Kathleen L. White*
Executive Marketing Manager: *Michael Weitz*
Project Manager: *April R. Southwood*
Senior Production Supervisor: *Laura Fuller*
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Designer: *Rick D. Noel*
Cover Designer: *John Rokusek*
Lead Photo Research Coordinator: *Carrie K. Burger*
Supplement Producer: *Tracy L. Konrardy*
Compositor: *Interactive Composition Corporation*
Typeface: *10.5/12 Times Roman*
Printer: *R. R. Donnelley Crawfordsville, IN*

(USE) Cover Images: Front: © *PhotoLink/Getty Images, PhotoDisc Volume: Science, Technology and Medicine, Aeroplane flying through a cloudy sky*
Rear: © *NASA, Courtesy NASA Dryden Flight Research Center Photo Collection, NASA Photo ED99-45243-01, X43A Hypersonic Experimental Vehicle*

Library of Congress Cataloging-in-Publication Data

Anderson, John David.
Fundamentals of aerodynamics / John D. Anderson, Jr. — 4th ed.
p. cm. (McGraw-Hill series in aeronautical and aerospace engineering)
Includes index.
ISBN 978-0-07-295046-5 — ISBN 0-07-295046-3 (hard copy : alk. paper)
1. Aerodynamics. I. Title. II. Series.

TL570.A677 2007
629.132′3—dc22 2005015910
CIP

www.mhhe.com

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Fourth Edition

John D. Anderson, Jr.

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John D. Anderson, Jr., University of Maryland, *Consulting Editor*

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McGRAW-HILL SERIES IN AERONAUTICAL AND AEROSPACE ENGINEERING

The Wright brothers invented the first practical airplane in the first decade of the twentieth century. Along with this came the rise of aeronautical engineering as an exciting, new, distinct discipline. College courses in aeronautical engineering were offered as early as 1914 at the University of Michigan and at MIT. Michigan was the first university to establish an aeronautics department with a four-year degree-granting program in 1916; by 1926 it had graduated over one hundred students. The need for substantive textbooks in various areas of aeronautical engineering became critical. Rising to this demand, McGraw-Hill became one of the first publishers of aeronautical engineering textbooks, starting with *Airplane Design and Construction* by Ottorino Pomilio in 1919, and the classic and definitive text *Airplane Design: Aerodynamics* by the iconic Edward P. Warner in 1927. Warner's book was a watershed in aeronautical engineering textbooks.

Since then, McGraw-Hill has become the time-honored publisher of books in aeronautical engineering. With the advent of high-speed flight after World War II and the space program in 1957, aeronautical and aerospace engineering grew to new heights. There was, however, a hiatus that occurred in the 1970s when aerospace engineering went through a transition, and virtually no new books in the field were published for almost a decade by anybody. McGraw-Hill broke this hiatus with the foresight of its Chief Engineering Editor, B.J. Clark, who was instrumental in the publication of *Introduction to Flight* by John Anderson. First published in 1978, *Introduction to Flight* is now in its 5th Edition. Clark's bold decision was followed by McGraw-Hill riding the crest of a new wave of students and activity in aerospace engineering, and it opened the flood-gates for new textbooks in the field.

In 1988, McGraw-Hill initiated its formal series in Aeronautical and Aerospace Engineering, gathering together under one roof all its existing texts in the field, and soliciting new manuscripts. This author is proud to have been made the Consulting Editor for this Series, and to have contributed some of the titles. Starting with eight books in 1988, the Series now embraces 24 books covering a broad range of discipline in the field. With this, McGraw-Hill continues its tradition, started in 1919, as the premier publisher of important textbooks in aeronautical and aerospace engineering.

John D. Anderson, Jr.
July, 2005

Editor's Note: John D. Anderson's textbooks in aeronautical and aerospace engineering have been a cornerstone of McGraw-Hill's success in the engineering discipline for over two decades. With the publication of *Fundamentals of Aerodynamics,* fourth edition, McGraw-Hill has officially named the Anderson Series, celebrating the impact this collection has had on the discipline and on students past and present. We hope you enjoy the newest revision to this collection.

ABOUT THE AUTHOR

John D. Anderson, Jr., was born in Lancaster, Pennsylvania, on October 1, 1937. He attended the University of Florida, graduating in 1959 with high honors and a bachelor of aeronautical engineering degree. From 1959 to 1962, he was a lieutenant and task scientist at the Aerospace Research Laboratory at Wright-Patterson Air Force Base. From 1962 to 1966, he attended the Ohio State University under the National Science Foundation and NASA Fellowships, graduating with a Ph.D. in aeronautical and astronautical engineering. In 1966, he joined the U.S. Naval Ordnance Laboratory as Chief of the Hypersonics Group. In 1973, he became Chairman of the Department of Aerospace Engineering at the University of Maryland, and since 1980 has been professor of Aerospace Engineering at the University of Maryland. In 1982, he was designated a Distinguished Scholar/Teacher by the University. During 1986–1987, while on sabbatical from the University, Dr. Anderson occupied the Charles Lindbergh Chair at the National Air and Space Museum of the Smithsonian Institution. He continued with the Air and Space Museum one day each week as their Special Assistant for Aerodynamics, doing research and writing on the history of aerodynamics. In addition to his position as professor of aerospace engineering, in 1993, he was made a full faculty member of the Committee for the History and Philosophy of Science and in 1996 an affiliate member of the History Department at the University of Maryland. In 1996, he became the Glenn L. Martin Distinguished Professor for Education in Aerospace Engineering. In 1999, he retired from the University of Maryland and was appointed Professor Emeritus. He is currently the Curator for Aerodynamics at the National Air and Space Museum, Smithsonian Institution.

Dr. Anderson has published ten books: *Gasdynamic Lasers: An Introduction,* Academic Press (1976), and under McGraw-Hill, *Introduction to Flight* (1978, 1984, 1989, 2000, 2005), *Modern Compressible Flow* (1982, 1990, 2003), *Fundamentals of Aerodynamics* (1984, 1991, 2001), *Hypersonic and High Temperature Gas Dynamics* (1989), *Computational Fluid Dynamics: The Basics with Applications* (1995), *Aircraft Performance and Design* (1999), *A History of Aerodynamics and Its Impact on Flying Machines,* Cambridge University Press (1997 hardback, 1998 paperback), *The Airplane: A History of Its Technology,* American Institute of Aeronautics and Astronautics (2003), and *Inventing Flight,* Johns Hopkins University Press (2004). He is the author of over 120 papers on radiative gasdynamics, reentry aerothermodynamics, gasdynamic and chemical lasers, computational fluid dynamics, applied aerodynamics, hypersonic flow, and the history of aeronautics. Dr. Anderson is in *Who's Who in America.* He is an Honorary Fellow of the American Institute of Aeronautics and Astronautics (AIAA). He is also a fellow of the Royal Aeronautical Society, London. He is a member of Tau Beta Pi, Sigma Tau, Phi Kappa Phi, Phi Eta Sigma, The American

Society for Engineering Education, the History of Science Society, and the Society for the History of Technology. In 1988, he was elected as Vice President of the AIAA for Education. In 1989, he was awarded the John Leland Atwood Award jointly by the American Society for Engineering Education and the American Institute of Aeronautics and Astronautics "for the lasting influence of his recent contributions to aerospace engineering education." In 1995, he was awarded the AIAA Pendray Aerospace Literature Award "for writing undergraduate and graduate textbooks in aerospace engineering which have received worldwide acclaim for their readability and clarity of presentation, including historical content." In 1996, he was elected Vice President of the AIAA for Publications. He has recently been honored by the AIAA with its 2000 von Karman Lectureship in Astronautics.

From 1987 to the present, Dr. Anderson has been the senior consulting editor on the McGraw-Hill Series in Aeronautical and Astronautical Engineering.

Dedicated to My Family

Sarah-Allen, Katherine, and Elizabeth

PREFACE TO THE FIRST EDITION

This book is for students—to be read, understood, and enjoyed. It is consciously written in a clear, informal, and direct style designed to *talk* to the reader and to gain his or her immediate interest in the challenging and yet beautiful discipline of aerodynamics. The explanation of each topic is carefully constructed to make sense to the reader. Moreover, the structure of each chapter is highly organized in order to keep the reader aware of where we are, where we were, and where we are going. Too frequently the student of aerodynamics loses sight of what is trying to be accomplished; to avoid this, we attempt to keep the reader informed of our intent at all times. For example, virtually each chapter contains a road map—a block diagram designed to keep the reader well aware of the proper flow of ideas and concepts. The use of such chapter road maps is one of the unique features of this book. Also, to help organize the reader's thoughts, there are special summary sections at the end of most chapters.

The material in this book is at the level of college juniors and seniors in aerospace or mechanical engineering. It assumes no prior knowledge of fluid dynamics in general, or aerodynamics in particular. It does assume a familiarity with differential and integral calculus, as well as the usual physics background common to most students of science and engineering. Also, the language of vector analysis is used liberally; a compact review of the necessary elements of vector algebra and vector calculus is given in Chapter 2 in such a fashion that it can either educate or refresh the reader, whichever may be the case for each individual.

This book is designed for a 1-year course in aerodynamics. Chapters 1 to 6 constitute a solid semester emphasizing inviscid, incompressible flow. Chapters 7 to 14 occupy a second semester dealing with inviscid, compressible flow. Finally, Chapters 15 to 18 introduce some basic elements of viscous flow, mainly to serve as a contrast to and comparison with the inviscid flows treated throughout the bulk of the text.

This book contains several unique features:

1. The use of chapter road maps to help organize the material in the mind of the reader, as discussed earlier.
2. An introduction to computational fluid dynamics as an integral part of the beginning study of aerodynamics. Computational fluid dynamics (CFD) has recently become a third dimension in aerodynamics, complementing the previously existing dimensions of pure experiment and pure theory. It is absolutely necessary that the modern student of aerodynamics be introduced to some of the basic ideas of CFD—he or she will most certainly come face to face with either its "machinery" or its results after entering the professional ranks of practicing aerodynamicists. Hence, such subjects as

the source and vortex panel techniques, the method of characteristics, and explicit finite-difference solutions are introduced and discussed as they naturally arise during the course of our discussions. In particular, Chapter 13 is devoted exclusively to numerical techniques, couched at a level suitable to an introductory aerodynamics text.

3. A short chapter is devoted entirely to hypersonic flow. Although hypersonics is at one extreme end of the flight spectrum, it has current important applications to the design of the space shuttle, hypervelocity missiles, and planetary entry vehicles. Therefore, hypersonic flow deserves some attention in any modern presentation of aerodynamics. This is the purpose of Chapter 14.
4. Historical notes are placed at the end of many of the chapters. This follows in the tradition of the author's previous books, *Introduction to Flight: Its Engineering and History* (McGraw-Hill, 1978), and *Modern Compressible Flow: With Historical Perspective* (McGraw-Hill, 1982). Although aerodynamics is a rapidly evolving subject, its foundations are deeply rooted in the history of science and technology. It is important for the modern student of aerodynamics to have an appreciation for the historical origin of the tools of the trade. Therefore, this book addresses such questions as who were Bernoulli, Euler, d'Alembert, Kutta, Joukowski, and Prandtl; how was the circulation theory of lift developed; and what excitement surrounded the early development of high-speed aerodynamics? The author wishes to thank various members of the staff of the National Air and Space Museum of the Smithsonian Institution for opening their extensive files for some of the historical research behind these history sections. Also, a constant biographical reference was the *Dictionary of Scientific Biography,* edited by C. C. Gillespie, Charles Schribner's Sons, New York, 1980. This is a 16-volume set of books which is a valuable source of biographic information on the leading scientists in history.

This book has developed from the author's experience in teaching both incompressible and compressible flow to undergraduate students at the University of Maryland. Such courses require careful attention to the structure and sequence of the presentation of basic material, and to the manner in which sophisticated subjects are described to the uninitiated reader. This book meets the author's needs at Maryland; it is hoped that it will also meet the needs of others, both in the formal atmosphere of the classroom and in the informal pleasure of self-study.

Readers who are already familiar with the author's *Introduction to Flight* will find the present book to be a logical sequel. Many of the aerodynamic concepts first introduced in the most elementary sense in *Introduction to Flight* are revisited and greatly expanded in the present book. For example, at Maryland, *Introduction to Flight* is used in a sophomore-level introductory course, followed by the material of the present book in junior- and senior-level courses in incompressible and compressible flow. On the other hand, the present book is entirely self-contained;

no prior familiarity with aerodynamics on the part of the reader is assumed. All basic principles and concepts are introduced and developed from their beginnings.

The author wishes to thank his students for many stimulating discussions on the subject of aerodynamics—discussions which ultimately resulted in the present book. Special thanks go to two of the author's graduate students, Tae-Hwan Cho and Kevin Bowcutt, who provided illustrative results from the source and vortex panel techniques. Of course, all of the author's efforts would have gone for nought if it had not been for the excellent preparation of the typed manuscript by Ms. Sue Osborn.

Finally, special thanks go to two institutions: (1) the University of Maryland for providing a challenging intellectual atmosphere in which the author has basked for the past 9 years and (2) the Anderson household—Sarah-Allen, Katherine, and Elizabeth—who have been patient and understanding while their husband and father was in his ivory tower.

John D. Anderson, Jr.

PREFACE TO THE FOURTH EDITION

The purpose of this fourth edition is the same as the first three—to be read, understood, and enjoyed. Due to the extremely favorable comments from readers and users of the first three editions, virtually all of the earlier editions have been carried over intact to the fourth edition. Therefore, all the basic philosophy, approach, and content discussed and itemized by the author in the Preface to the First Edition is equally applicable now. Since that preface was repeated earlier, no further elaboration will be given.

The fourth edition carries over the special educational tools introduced in the Second and Third Editions, namely: (1) the use of roadmaps at the beginning of each chapter to guide the reader safely and securely through the material of each chapter, and to highlight the important flow of ideas, and (2) the design boxes that are scattered throughout the book. These design boxes are special sections for the purpose of discussing design aspects associated with the fundamental material covered throughout the book. These sections are literally placed in boxes to set them apart from the mainline text. Modern engineering education is placing more emphasis on design, and the design boxes in this book are in this spirit. They are a means of making the fundamental material more relevant, and making the whole process of learning aerodynamics more fun.

Question: What distinguishes the fourth edition from the first three? *Answer:* Much new material has been added in order to enhance, update, and expand that covered in the earlier editions. There are 51 new figures, and 50 inserts of new material. In particular, the fourth edition has two important new features:

1. The classic organization has been preserved, namely, the presentation of the fundamental principles of aerodynamics in Part 1, inviscid incompressible flow in Part 2, inviscid compressible flow in Part 3, and viscous flow in Part 4. Specific sections on viscous flow, however, have been added much earlier in the book in order to give the reader some idea of how the inviscid results are tempered by the influence of friction. This is done by adding self-contained viscous flow sections at the end of various chapters, written and placed in such a way that they do not interfere with the flow of the inviscid flow discussion, but are there to complement the discussion. For example, at the end of Chapter 4 on incompressible, inviscid flow over airfoils, there is a viscous flow section that deals with the prediction of skin-friction drag on such airfoils. A similar viscous flow section at the end of Chapter 12 deals with friction drag on high-speed airfoils. At the end of the chapters on shock waves and nozzle flows, there are viscous flow sections on shock-wave/boundary-layer interactions. And so forth.

2. Preview boxes have been introduced at the beginning of each chapter. These short sections, literally set in boxes, are to inform the reader in plain language what to expect from each chapter, and why the material is important and exciting. They are primarily motivational; they help to encourage the reader to actually enjoy reading the chapter, therefore enhancing the educational process.

The fourth edition also has many additional new worked examples. When learning new technical material, especially material of a fundamental nature as emphasized in this book, one can never have too many examples of how the fundamentals can be applied to the solution of problems.

In the same spirit, at the end of most chapters, new homework problems have been added to those carried over from the third edition.

Finally, as an aid with the worked examples and the new homework problems, tables of the Standard Atmosphere in both the SI and English Engineering units have been included as new Appendices.

All the new additional material not withstanding, the main thrust of this book remains the presentation of the fundamentals of aerodynamics; the new material is simply intended to enhance and support this thrust. We repeat that the book is organized along classical lines, dealing with inviscid incompressible flow, inviscid compressible flow, and viscous flow in sequence (and now with the new self-contained viscous flow sections presented earlier in the book). My experience in teaching this material to undergraduates finds that it nicely divides into a two-semester course with Parts 1 and 2 in the first semester, and Parts 3 and 4 in the second semester. Also, I have taught the entire book in a fast-paced, first-semester graduate course intended to introduce the fundamentals of aerodynamics to new graduate students who have not had this material as part of their undergraduate education. The book works well in such a mode.

I would like to thank the McGraw-Hill editorial and production staff for the excellent help in producing this book, especially Katie White in Boston, and April Southwood in Dubuque. Also, special thanks go to my long-time friend and associate, Sue Cunningham, whose expertise as a scientific typist is beyond comparison, and who has typed all my book manuscripts for me, including this one, with great care and precision.

I also thank the following reviewers for their valuable feedback: Roger L. Simpson, Virginia Polytechnic Institute and State University; Narayanan Komerath, Georgia Institute of Technology; Ramkumar N. Parthasarathy, University of Oklahoma; and Anastasios S. Lyrintzis, Purdue University.

As a final comment, aerodynamics is a subject of intellectual beauty, composed and drawn by many great minds over the centuries. *Fundamentals of Aerodynamics* is intended to portray and convey this beauty. Do you feel challenged and interested by these thoughts? If so, then read on, and enjoy!

John D. Anderson, Jr.

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