Fifth Edition

Fundamentals of AERODYNAMICS

John D. Anderson, Jr.

Anderson Series

Fundamentals of Aerodynamics

Fifth Edition

John D. Anderson, Jr.
Curator of Aerodynamics
National Air and Space Museum
Smithsonian Institution
and
Professor Emeritus
University of Maryland

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The white cloud that you see in the flow over the top of the F-22 on the cover of this book is due to water vapor condensation occurring through the supersonic expansion waves on the top of the airplane. This white cloud is abruptly terminated when the flow subsequently passes through the trailing-edge shock waves behind the airplane. A detailed physical explanation of this flow can be found in Problem 9.21 at the end of Chapter 9.

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PREFACE TO THE FIFTH EDITION

This book is for students—to be read, understood, and enjoyed. It is consciously written in a clear, informal, and direct style to *talk* to the reader and 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 tightly 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, I attempt to keep the reader informed of my intent at all times. For example, preview boxes are 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. In addition, 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 preview boxes and chapter road maps are 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, whatever 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 20 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. 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.

Other features of this book are:

1. An introduction to computational fluid dynamics as an integral part of the study of aerodynamics. Computational fluid dynamics (CFD) has recently become a third dimension in aerodynamics, complementing the previously existing dimensional 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 discussion. In particular, Chapter 13 is devoted exclusively to numerical techniques, couched at a level suitable to an introductory aerodynamics text.
2. A 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, planetary entry vehicles, and modern hypersonic atmospheric cruise vehicles. Therefore, hypersonic flow deserves some attention in any modern presentation of aerodynamics. This is the purpose of Chapter 14.
3. Historical notes are placed at the end of many of the chapters. This follows in the tradition of some of my previous textbooks, *Introduction to Flight: Its Engineering and History,* sixth edition (McGraw-Hill, 2008). and *Modern Compressible Flow: With Historical Perspective,* third edition (McGraw-Hill, 2003). 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 the circulation theory of lift developed; and what excitement surrounded the early development of high-speed aerodynamics. I wish 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 16-volume set of books is a valuable source of biographic information on leading scientists in history.
4. Design boxes 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.

Because of the extremely favorable comments from readers and users of the first four editions, virtually all the content of the earlier editions has been carried over intact to the present fifth edition. In this edition much new material has been added in order to enhance, update, and expand that covered in the earlier editions. There are 41 new figures, 23 inserts of new material and new sections, many new worked examples, and additional homework problems. In particular, the fifth edition has the following **new features:**

1. A new section in Chapter 6 on airplane lift and drag. The flow over a complete airplane is an important three-dimensional flow. This section, in a chapter on three-dimensional flows, focuses on how to estimate the lift and drag of a complete airplane.
2. A new section in Chapter 9 on the flow field behind a curved shock wave explaining why this flow is rotational.
3. A new section in Chapter 9 that asks the question why does the X-15 hypersonic research vehicle have a wedge tail instead of a slender airfoil section? The answer involves an innovative application of shock-expansion theory, and serves as an interesting design example of the importance of shock waves and expansion waves.
4. A new section highlighting the blended-wing-body configuration. This is a very promising innovative design concept for high-speed subsonic transports and cargo carriers. This section emphasizes how the principles of subsonic compressible flow discussed in Chapter 11 are applied to the blended wing body.
5. A new historical note on the origin of the swept-wing concept. Who conceived the use of swept wings for high-speed airplanes? Why? This section covers the history of the swept-wing concept and incorporates some newly discovered German design data from World War II.
6. A new section on supersonic flow over cones. This is an important addition to Chapter 13 on numerical techniques for nonlinear supersonic flow, because supersonic flow over cones is a classic example of supersonic aerodynamics. Moreover, this section is an important precursor to a following section on hypersonic waveriders in Chapter 14.
7. A new section on Hypersonic Viscous flow in Chapter 14. Here, aspects of aerodynamic heating are discussed, and the role of aerodynamic heating in hypersonic vehicle design is explored. Aerodynamic heating of blunt and slender bodies in hypersonic flow is examined, showing why hypersonic vehicles have blunt noses and leading edges.

8. A new section on applied hypersonic aerodynamics: hypersonic waveriders, in Chapter 14. Hypersonic waveriders are a viable new configuration for hypersonic vehicles, and this is an extensive discussion of such vehicles – how they are designed and an examination of their aerodynamic advantage.
9. A small part of the existing Part 4 on viscous flow has been shortened and streamlined. Part 4 was never designed to represent a total course on viscous flow, but rather is included for balance and completeness of the fundamentals of aerodynamics.
10. 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.
11. New homework problems at the end of each chapter, added to those carried over from the fourth edition

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. I repeat that the book is organized along classical lines, dealing with inviscid incompressible flow, inviscid compressible flow, and viscous flow in sequence. 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 their excellent help in producing this book, especially Lorraine Buczek and Jane Mohr 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.

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I want to thank my students over the years for many stimulating discussions on the subject of aerodynamics, discussions which have influenced the development of this book. Special thanks go to three institutions (1) The University of Maryland for providing a challenging intellectual atmosphere in which I have basked for the past 37 years; (2) The National Air and Space Museum of the Smithsonian

Institution for opening the world of the history of the technology of flight for me, and (3) the Anderson household—Sarah-Allen, Katherine and Elizabeth—who have been patient and understanding over the years while their husband and father was in his ivory tower. Also, I pay respect to the new generation, which includes my two beautiful granddaughters, Keegan and Tierney Glabus, who represent the future.

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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PART 1

Fundamental Principles

In Part 1, we cover some of the basic principles that apply to aerodynamics in general. These are the pillars on which all of aerodynamics is based. ■