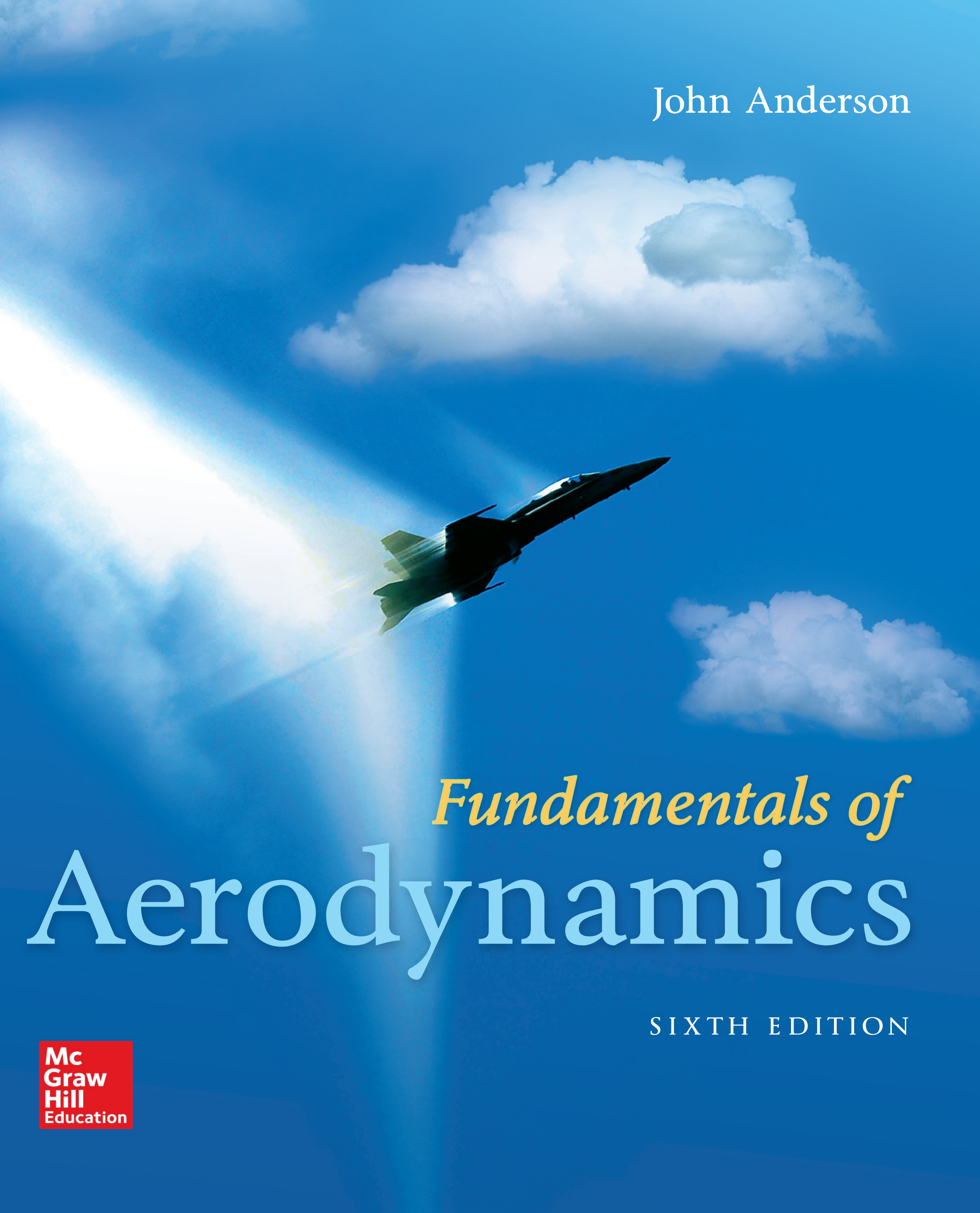

John Anderson

Fundamentals of Aerodynamics

SIXTH EDITION

Mc Graw Hill Education

Fundamentals of Aerodynamics

Sixth Edition

John D. Anderson, Jr.

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John D. Anderson, Jr.

Fundamentals of Aerodynamics

Sixth Edition

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

Mc Graw Hill Education

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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 11 books: *Gasdynamic Lasers: An Introduction,* Academic Press (1976), and under McGraw-Hill, *Introduction to Flight* (1978, 1984, 1989, 2000, 2005, 2008, 2012, 2016), *Modern Compressible Flow* (1982, 1990, 2003), *Fundamentals of Aerodynamics* (1984, 1991, 2001, 2007, 2011), *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), *Inventing Flight,* Johns Hopkins University Press (2004), and X-15, The World's Fastest Rocket Plane and the Pilots Who Ushered in the Space Age, with co-author Richard Passman, Zenith Press in conjunction with the Smithsonian Institution (2014). 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 a member of the National Academy of Engineering, and 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.

CONTENTS

PREFACE TO THE SIXTH EDITION

This book follows in the same tradition as the previous editions: it 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 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, 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, 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 one-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 dimension 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 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*, 8th Edition (McGraw-Hill, 2016) and *Modern Compressible Flow: With Historical Perspecive*, 3rd 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 Bernoulli, Euler, d'Alembert, Kutta, Joukowski, and Prandtl were; 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 is a 16-volume set of books that is a valuable source of biographic information on the 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.

Due to the extremely favorable comments from readers and users of the first five editions, virtually all the content of the earlier editions has been carried over intact to the present sixth edition. In this edition, however, a completely new educational tool has been introduced in some of the chapters in order to enhance and expand the reader's learning process. Throughout the previous editions, numerous worked examples have been included at the end of many of the sections to illustrate and reinforce the ideas and methods discussed in *that particular section*. These are still included in the present sixth edition. However, added at the end of a number of the chapters in this sixth edition, a major challenge is given to the reader that integrates and uses thoughts and equations *drawn from the chapter as a whole*. These new sections are called END OF CHAPTER INTEGRATED WORK CHALLENGES. They are listed next:

1. **Chapter 1:** A forward-facing axial aerodynamic force on an airfoil sounds not possible, but it can actually happen. What are the conditions under which it can happen?
   Also, the history of when such a forward-facing force was first observed is discussed.
2. **Chapter 2:** Using the momentum equation, develop the relation between drag on an aerodynamic body and the loss of total pressure in the flow field.
3. **Chapter 3:** Perform a conceptual design of a low-speed subsonic wind tunnel.
4. **Chapter 4:** Find a way to account for the effects of wind tunnel walls on the measurements made on an aerodynamic body in a low-speed wind tunnel.
5. **Chapter 7:** Obtain and discuss a relation between supersonic wave drag on a body and the entropy increase in the flow.
6. **Chapter 9:** Consider the sonic boom generated from a body in supersonic flight. What is it? How is it created? How can its strength be reduced?
7. **Chapter 10:** Perform a conceptual design of a supersonic wind tunnel.
8. **Chapter 11:** At the end of World War II, in the face of the lack of reliable transonic wind tunnels and the extreme theoretical difficulty solving the nonlinear mathematical equations that govern transonic flow, the NACA developed an innovative experimental method for obtaining transonic aerodynamic data. Called the "wing-flow technique," it involved mounting a small airfoil wing model vertically on the surface of the wing of a P-51

fighter airplane at a location inside the bubble of locally supersonic flow formed on the P-51 wing when the airplane exceeded its critical Mach number. Design this apparatus, taking into account the size of the test model, the flow conditions over the test model, the optimum locations on the P-51 wing, etc. Also, the history of the wing-flow techniques will be given.

The answers to these Integrated Work Challenges are given right there in the text so that the reader can gain instant gratification after working them out, just like the other worked examples; the answers are just more complex with a more widespread educational value.

New homework problems have been added to McGraw-Hill's online learning environment, Connect®. These question banks will include all end-of-chapter problems from the textbook and additional problems unique to Connect.

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 Jolynn Kilburg and Thomas Scaife, PhD, in Dubuque. Our photo researcher, David Tietz, was invaluable in searching out new and replacement photographs for the new edition to satisfy new McGraw-Hill guidelines; I don't know what I would have done without him. 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 want to thank my students over the years for many stimulating discussions on the subject of aerodynamics, discussions that 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 42 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. **To them, I dedicate this book**.

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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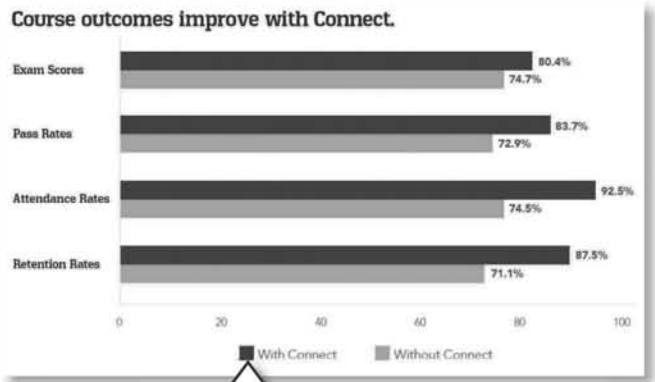

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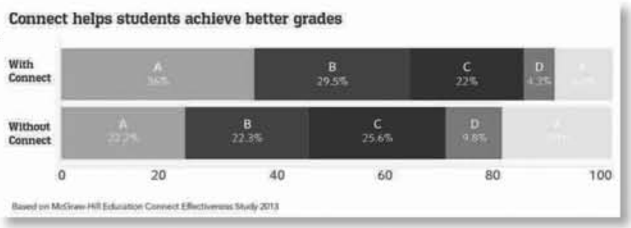

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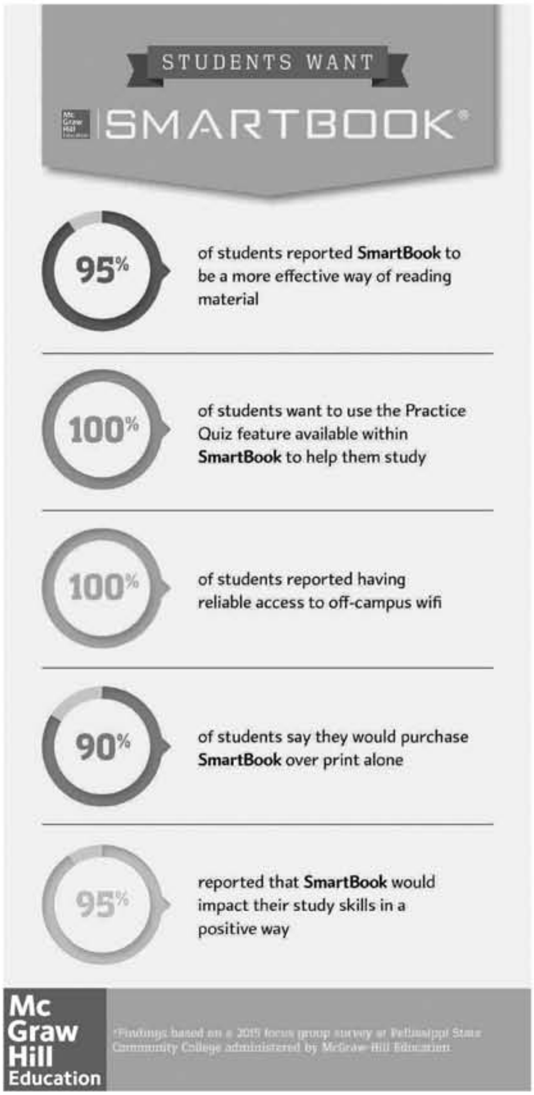


PART 1

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.

CHAPTER 1

Aerodynamics: Some Introductory Thoughts

The term "aerodynamics" is generally used for problems arising from flight and other topics involving the flow of air.

Ludwig Prandtl, 1949

Aerodynamics: The dynamics of gases, especially atmospheric interactions with moving objects.

The American Heritage Dictionary of the English Language, 1969

PREVIEW BOX

Why learn about aerodynamics? For an answer, just take a look at the following five photographs showing a progression of airplanes over the past 70 years. The Douglas DC-3 (Figure 1.1), one of the most famous aircraft of all time, is a low-speed subsonic transport designed during the 1930s. Without a knowledge of low-speed aerodynamics, this aircraft would have never existed. The Boeing 707 (Figure 1.2) opened high-speed subsonic flight to millions of passengers beginning in the late 1950s. Without a knowledge of high-speed subsonic aerodynamics, most of us would still be relegated to ground transportation.

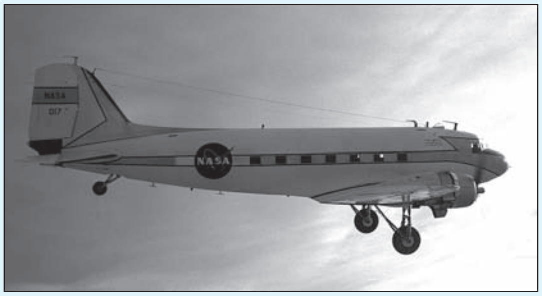


Figure 1.1 Douglas DC-3 (*NASA*).

Figure 1.2 Boeing 707 (© *Everett Collection Historical/Alamy*).

Figure 1.5 Lockheed-Martin F-22 (*U.S. Air Force Photo/Staff Sgt. Vernon Young Jr.*).

Figure 1.3 Bell X-1 (*Library of Congress [LC-USZ6-1658]*).

Figure 1.6 Blended wing body (*NASA*).

Figure 1.4 Lockheed F-104 (*Library of Congress [LC-USZ62-94416]*).

The Bell X-1 (Figure 1.3) became the first piloted airplane to fly faster than sound, a feat accomplished with Captain Chuck Yeager at the controls on October 14, 1947. Without a knowledge of transonic aerodynamics (near, at, and just above the speed of sound), neither the X-1, nor any other airplane, would have ever broken the sound barrier. The Lockheed F-104 (Figure 1.4) was the first supersonic airplane point-designed to fly at twice the speed of sound, accomplished in the 1950s. The Lockheed-Martin F-22 (Figure 1.5) is a modern fighter aircraft designed for sustained supersonic flight. Without a knowledge of supersonic aerodynamics, these supersonic airplanes would not exist. Finally, an example of an innovative new vehicle concept for high-speed subsonic flight is the blended wing body shown in Figure 1.6. At the time of writing, the blended-wing-body promises to carry from 400 to 800 passengers over long distances with almost 30 percent less fuel per seat-mile than a conventional jet transport. This would be a "renaissance" in long-haul transport. The salient design aspects of this exciting new concept are discussed in Section 11.10. The airplanes in Figures 1.1–1.6 are six good reasons to learn about aerodynamics. The major purpose of this book is to help you do this. As you continue to read this and subsequent chapters, you will progressively learn about low-speed aerodynamics, high-speed subsonic aerodynamics, transonic aerodynamics, supersonic aerodynamics, and more.

Airplanes are by no means the only application of aerodynamics. The air flow over an automobile, the gas flow through the internal combustion engine powering an automobile, weather and storm prediction, the flow through a windmill, the production of thrust by gas turbine jet engines and rocket engines, and the movement of air through building heater and air-conditioning systems are just a few other examples of the application of aerodynamics. The material in this book is powerful stuff—important stuff. Have fun reading and learning about aerodynamics.

To learn a new subject, you simply have to start at the beginning. This chapter is the beginning of our study of aerodynamics; it weaves together a series of introductory thoughts, definitions, and concepts essential to our discussions in subsequent chapters. For example, how does nature reach out and grab hold of an airplane in flight—or any other object emmersed in a flowing fluid—and exert an aerodynamic force on the object? We will find out here. The resultant aerodynamic force is frequently resolved into two components defined as lift and drag; but rather than dealing with the lift and drag forces themselves, aerodynamicists deal instead with lift and drag *coefficients*. What is so magic about lift and drag coefficients? We will see. What is a Reynolds number? Mach number? Inviscid flow? Viscous flow? These rather mysterious sounding terms will be demystified in the present chapter. They and others constitute the language of aerodynamics, and as we all know, to do anything useful you have to know the language. Visualize this chapter as a beginning language lesson, necessary to go on to the exciting aerodynamic applications in later chapters. There is a certain enjoyment and satisfaction in learning a new language. Take this chapter in that spirit, and move on.

1.1 IMPORTANCE OF AERODYNAMICS: HISTORICAL EXAMPLES

On August 8, 1588, the waters of the English Channel churned with the gyrations of hundreds of warships. The great Spanish Armada had arrived to carry out an invasion of Elizabethan England and was met head-on by the English fleet under the command of Sir Francis Drake. The Spanish ships were large and heavy; they were packed with soldiers and carried formidable cannons that fired 50 lb round shot that could devastate any ship of that era. In contrast, the English ships were smaller and lighter; they carried no soldiers and were armed with lighter, shorter-range cannons. The balance of power in Europe hinged on the outcome of this naval encounter. King Philip II of Catholic Spain was attempting to squash Protestant England's rising influence in the political and religious affairs of Europe; in turn, Queen Elizabeth I was attempting to defend the very existence of England as a sovereign state. In fact, on that crucial day in 1588, when the English floated six fire ships into the Spanish formation and then drove headlong into the ensuing confusion, the future history of Europe was in the balance. In the final outcome, the heavier, sluggish, Spanish ships were no match for the faster, more maneuverable, English craft, and by that evening the Spanish Armada lay in disarray, no longer a threat to England. This naval battle is of particular importance because it was the first in history to be fought by ships on both sides powered completely by sail (in contrast to earlier combinations of oars and sail), and it taught the world that political power was going to be synonymous with naval power. In turn, naval power was going to depend greatly on the speed and

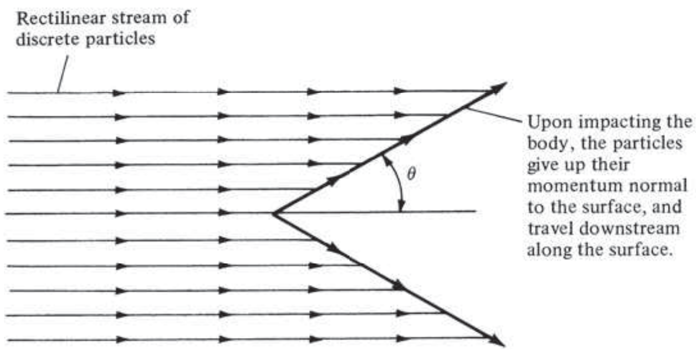


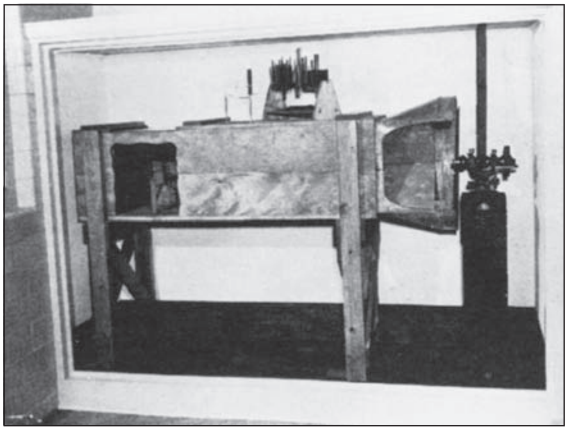
Figure 1.7 Isaac Newton's model of fluid flow in the year 1687. This model was widely adopted in the seventeenth and eighteenth centuries but was later found to be conceptually inaccurate for most fluid flows.

maneuverability of ships. To increase the speed of a ship, it is important to reduce the resistance created by the water flow around the ship's hull. Suddenly, the drag on ship hulls became an engineering problem of great interest, thus giving impetus to the study of fluid mechanics.

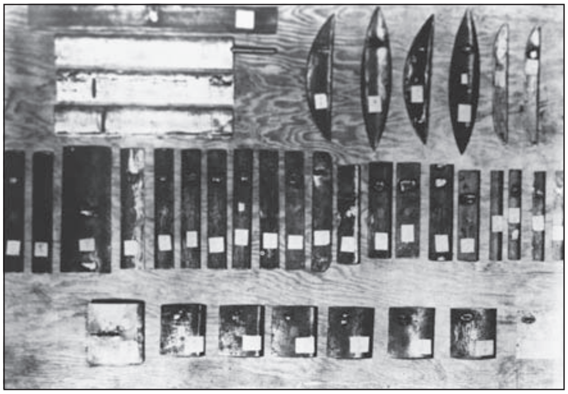
This impetus hit its stride almost a century later, when, in 1687, Isaac Newton (1642–1727) published his famous *Principia,* in which the entire second book was devoted to fluid mechanics. Newton encountered the same difficulty as others before him, namely, that the analysis of fluid flow is conceptually more difficult than the dynamics of solid bodies. A solid body is usually geometrically well defined, and its motion is therefore relatively easy to describe. On the other hand, a fluid is a "squishy" substance, and in Newton's time it was difficult to decide even how to qualitatively model its motion, let alone obtain quantitative relationships. Newton considered a fluid flow as a uniform, rectilinear stream of particles, much like a cloud of pellets from a shotgun blast. As sketched in Figure 1.7, Newton assumed that upon striking a surface inclined at an angle θ to the stream, the particles would transfer their normal momentum to the surface but their tangential momentum would be preserved. Hence, after collision with the surface, the particles would then move along the surface. This led to an expression for the hydrodynamic force on the surface which varies as $\sin^2\theta$. This is Newton's famous sine-squared law (described in detail in Chapter 14). Although its accuracy left much to be desired, its simplicity led to wide application in naval architecture. Later, in 1777, a series of experiments was carried out by Jean LeRond d'Alembert (1717–1783), under the support of the French government, in order to measure the resistance of ships in canals. The results showed that "the rule that for oblique planes resistance varies with the sine square of the angle of incidence holds good only for angles between 50 and 90° and must be abandoned for lesser angles." Also, in 1781, Leonhard Euler (1707–1783) pointed out the physical inconsistency of Newton's model (Figure 1.7) consisting of a rectilinear stream of particles impacting without warning on a surface. In contrast to this model, Euler noted that the fluid moving toward a body "*before* reaching the latter, bends its direction and its velocity so that when it reaches the body it flows past it along the surface, and exercises no other force on the body except the pressure corresponding to the single points of contact." Euler went on to present a formula for resistance that attempted to take into account the shear stress distribution along the surface, as well as the pressure distribution. This expression became proportional to $\sin^2\theta$ for large incidence angles, whereas it was proportional to $\sin\theta$ at small incidence angles. Euler noted that such a variation was in reasonable agreement with the ship-hull experiments carried out by d'Alembert.

This early work in fluid dynamics has now been superseded by modern concepts and techniques. (However, amazingly enough, Newton's sine-squared law has found new application in very high-speed aerodynamics, to be discussed in Chapter 14.) The major point here is that the rapid rise in the importance of naval architecture after the sixteenth century made fluid dynamics an important science, occupying the minds of Newton, d'Alembert, and Euler, among many others. Today, the modern ideas of fluid dynamics, presented in this book, are still driven in part by the importance of reducing hull drag on ships.

Consider a second historical example. The scene shifts to Kill Devil Hills, 4 mi south of Kitty Hawk, North Carolina. It is summer of 1901, and Wilbur and Orville Wright are struggling with their second major glider design, the first being a stunning failure the previous year. The airfoil shape and wing design of their glider are based on aerodynamic data published in the 1890s by the great German aviation pioneer Otto Lilienthal (1848–1896) and by Samuel Pierpont Langley (1934–1906), secretary of the Smithsonian Institution—the most prestigious scientific position in the United States at that time. Because their first glider in 1900 produced no meaningful lift, the Wright brothers have increased the wing area from 165 to 290 ft^2 and have increased the wing camber (a measure of the airfoil curvature—the larger the camber, the more "arched" is the thin airfoil shape) by almost a factor of 2. But something is still wrong. In Wilbur's words, the glider's "lifting capacity seemed scarcely one-third of the calculated amount." Frustration sets in. The glider is not performing even close to their expectations, although it is designed on the basis of the best available aerodynamic data. On August 20, the Wright brothers despairingly pack themselves aboard a train going back to Dayton, Ohio. On the ride back, Wilbur mutters that "nobody will fly for a thousand years." However, one of the hallmarks of the Wrights is perseverance, and within weeks of returning to Dayton, they decide on a complete departure from their previous approach. Wilbur later wrote that "having set out with absolute faith in the existing scientific data, we were driven to doubt one thing after another, until finally after two years of experiment, we cast it all aside, and decided to rely entirely upon our own investigations." Since their 1901 glider was of poor aerodynamic design, the Wrights set about determining what constitutes good aerodynamic design. In the fall of 1901, they design and build a 6 ft long, 16 in square wind tunnel powered by a two-bladed fan connected to a gasoline engine. A replica of the Wrights' tunnel is shown in Figure 1.8*a*. In their wind tunnel they test over 200 different wing and airfoil shapes, including flat plates,



(*a*)



(*b*)

Figure 1.8 (*a*) Replica of the wind tunnel designed, built, and used by the Wright brothers in Dayton, Ohio, during 1901–1902. (*b*) Wing models tested by the Wright brothers in their wind tunnel during 1901–1902. ((*a*) *NASA;* (*b*) *Courtesy of John Anderson*).

curved plates, rounded leading edges, rectangular and curved planforms, and various monoplane and multiplane configurations. A sample of their test models is shown in Figure 1.8*b*. The aerodynamic data are taken logically and carefully. Armed with their new aerodynamic information, the Wrights design a new glider in the spring of 1902. The airfoil is much more efficient; the camber is reduced considerably, and the location of the maximum rise of the airfoil is moved closer to the front of the wing. The most obvious change, however, is that the ratio of the length of the wing (wingspan) to the distance from the front to the rear of the airfoil (chord length) is increased from 3 to 6. The success of this glider during the summer and fall of 1902 is astounding; Orville and Wilbur accumulate over a thousand flights during this period. In contrast to the previous year, the Wrights return to Dayton flushed with success and devote all their subsequent efforts to powered flight. The rest is history.

The major point here is that good aerodynamics was vital to the ultimate success of the Wright brothers and, of course, to all subsequent successful airplane designs up to the present day. The importance of aerodynamics to successful manned flight goes without saying, and a major thrust of this book is to present the aerodynamic fundamentals that govern such flight.

Consider a third historical example of the importance of aerodynamics, this time as it relates to rockets and space flight. High-speed, supersonic flight had become a dominant feature of aerodynamics by the end of World War II. By this time, aerodynamicists appreciated the advantages of using slender, pointed body shapes to reduce the drag of supersonic vehicles. The more pointed and slender the body, the weaker the shock wave attached to the nose, and hence the smaller the wave drag. Consequently, the German V-2 rocket used during the last stages of World War II had a pointed nose, and all short-range rocket vehicles flown during the next decade followed suit. Then, in 1953, the first hydrogen bomb was exploded by the United States. This immediately spurred the development of long-range intercontinental ballistic missiles (ICBMs) to deliver such bombs. These vehicles were designed to fly outside the region of the earth's atmosphere for distances of 5000 mi or more and to reenter the atmosphere at suborbital speeds of from 20,000 to 22,000 ft/s. At such high velocities, the aerodynamic heating of the reentry vehicle becomes severe, and this heating problem dominated the minds of high-speed aerodynamicists. Their first thinking was conventional—a sharp-pointed, slender reentry body. Efforts to minimize aerodynamic heating centered on the maintenance of laminar boundary layer flow on the vehicle's surface; such laminar flow produces far less heating than turbulent flow (discussed in Chapters 15 and 19). However, nature much prefers turbulent flow, and reentry vehicles are no exception. Therefore, the pointed-nose reentry body was doomed to failure because it would burn up in the atmosphere before reaching the earth's surface.

However, in 1951, one of those major breakthroughs that come very infrequently in engineering was created by H. Julian Allen at the NACA (National Advisory Committee for Aeronautics) Ames Aeronautical Laboratory—he introduced the concept of the *blunt* reentry body. His thinking was paced by the following concepts. At the beginning of reentry, near the outer edge of the atmosphere, the vehicle has a large amount of kinetic energy due to its high velocity and a large amount of potential energy due to its high altitude. However, by the time the vehicle reaches the surface of the earth, its velocity is relatively small and its altitude is zero; hence, it has virtually no kinetic or potential energy. Where has all the energy gone? The answer is that it has gone into (1) heating the body and (2) heating the airflow around the body. This is illustrated in Figure 1.9. Here, the shock wave from the nose of the vehicle heats the airflow around the vehicle; at the same time, the vehicle is heated by the intense frictional dissipation within the boundary layer on the surface. Allen reasoned that if more of the total reentry