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Fourth Edition

Modern Compressible Flow

With Historical Perspective

McGraw Hill

John D. Anderson

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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 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 Hypersonic Group. In 1973, he became Chairman of the Department of Aerospace Engineering at the University of Maryland, and since 1980 has been a professor of Aerospace Engineering at 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 its 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, and Glenn L. Martin Institute Professor of Engineering at the University of Maryland.

Dr. Anderson has published twelve books: *Gasdynamic Lasers: An Introduction*, Academic Press (1976), and under McGraw-Hill, *Introduction to Flight* (1978, 1985, 1989, 2000, 2005, 2008, 2012, 2016), *Modern Compressible Flow* (1982, 1990, 2003, 2021); *Fundamentals of Aerodynamics* (1984, 1991, 2001, 2007, 2011, 2017); *Hypersonic and High Temperature Gas Dynamics* (1989); and under the American Institute of Aeronautics and Astronautics (2006, 2019), *Computational Fluid Dynamics: The Basics with Applications* (1995); *A History of Aerodynamics and Its Impact on Flying Machines,* Cambridge University Press (1997); *Aircraft Performance and Design*, McGraw-Hill (1999); *The Airplane: A History of Its Technology*, American Institute of Aeronautics and Astronautics (2002); *Inventing Flight: The Wright Brothers and Their Predecessors*, Johns Hopkins University Press (2004); *X-15: The World's Fastest Rocket Plane and the Pilots Who Ushered in the Space Age* (with Richard Passman), Zenith Press (2014); and *The Grand Designers,* Cambridge University Press (2018). He is the author of over 130 papers in radiative gasdynamics, re-entry 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 a member of the National Academy of Engineering, an Honorary Fellow of the American Institute of Aeronautics and Astronautics (AIAA), and a Fellow of the Royal Aeronautical Society, London. He is also a Fellow of the Washington Academy of Sciences, and 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. More recently, he was honored by the AIAA with its 2000 von Karman Lectureship in Astronautics and with its History Book Award for 2002 for *A History of Aerodynamics*. In 2002, he was awarded the position of Honorary Fellow of the AIAA, the Institute's highest award. In 2012, he received the inaugural Hypersonic Systems and Technology Award from the AIAA. In 2017, the National Aeronautic Association awarded him the Frank G. Brewer Trophy, awarded annually "to an individual, a group of individuals, or an organization for significant contributions of enduring value to aerospace education in the United States." In 2018, he was awarded the Benjamin G. Lamme Meritorious Achievement Medal by the College of Engineering of The Ohio State University.

Dr. Anderson is active and known for his professional and educational activities both nationally and internationally. He has given more than 40 short courses to the major aerospace companies, the Air Force Academy, the government, and in Europe at Rolls-Royce in England and the von Karman Institute in Belgium. This includes a pioneering hypersonic aerodynamic course jointly sponsored by the AIAA and the University of Maryland and televised live nationally by satellite. In terms of the publishing world, in 1987 McGraw-Hill chose Dr. Anderson to be the senior consulting editor on the McGraw-Hill Series in Aeronautical and Astronautical Engineering. Recently, McGraw-Hill officially named the Anderson Series, with the statement: "John D. Anderson's textbooks in aeronautical and aerospace engineering have been a cornerstone of McGraw-Hill's success for over two decades. McGraw-Hill proudly celebrates the impact that the Anderson Series has had on aerospace engineers and on students past and present."

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PREFACE TO THE FOURTH EDITION

The purpose of this book is to provide an understandable and enjoyable teaching instrument in the classroom or independently for the study of compressible fluid flow. It is intentionally written in a rather informal style to *talk* to the reader, to gain his or her interest, and to keep the reader absorbed from cover to cover. It is aimed primarily at the senior undergraduate and first-year graduate student in aerospace, mechanical, and chemical engineering. However, it is also written for use by the practicing engineer and scientist who is striving to obtain a cohesive picture of the subject of compressible flow from a modern perspective. This book is meant to be read, not just used as a handbook to search for the equation that will solve a given problem. Compressible flow is a beautiful intellectual technical subject, and I believe that, like a masterwork painting made up of an inestimable number of brushstrokes, every word in this book is like a brushstroke in the whole canvas of compressible flow. Every word should be read and thought about in order for the reader to truly appreciate the "masterpiece" intellectual nature of this subject.

The response to the first three editions of this book from students, faculty, and practicing professionals has been overwhelmingly favorable. Therefore, the fourth edition carries over much of the fundamental content of the previous edition, plus adding the following important components:

1. End-of-chapter problems have been added to those few chapters that originally had no problems listed. Those particular chapters are heavily theoretically based, and the original purpose was to allow the reader to concentrate on absorbing the theoretical concepts without the additional activity of problem solving. In this new edition, however, problems have been added to these particular chapters in order to obtain a type of "full closure" on understanding the material.

2. At the end of every chapter, and just before the list of problems, a "Suggestions" section has been added. The purpose of these suggestions is to help the reader better understand each end-of-chapter problem and to get started on a right path for the solution of each problem (please note that for many of the problems, there may be several "right paths"). Moreover, each of the suggestions for problem solving helps to more strongly connect the reader with the particular relevant physical and theoretical content in the text reading material.

3. Chapter 15 on Hypersonic Flow has been expanded to recognize the greatly increased interest and current activity in the hypersonic flight regime. Hypersonic flow has many important physical and theoretical features that distinguish it from basic supersonic flow, and these differences are highlighted in Chap. 15. The author feels that the current new activity and interest in the hypersonic flight regime will be long lasting, and Chap. 15 has been expanded with new content and figures with such matters in mind. This expansion is solidly in keeping with the title of this text, namely the "modern" aspects of *Modern Compressible Flow*.

4. Continuing with the theme of "modern" that has permeated the previous editions, this new edition maintains the content devoted to computational fluid dynamics and high-temperature gas dynamics, two fields of intellectual endeavor that are intrinsically woven into most modern applications of compressible flow.

Taken in total, the book provides the twenty-first-century student with a balanced treatment of both the classical and modern aspects of compressible flow.

Special thanks are given to various people who have been responsible for the materialization of this fourth edition:

1. My students, as well as students and readers from all over the world, who have responded so enthusiastically to the first three editions, and who have provided the ultimate joy to the author of being an engineering educator.

2. My family, who provide the other ultimate joy of being a husband, father, and grandfather.

3. My colleagues at the University of Maryland and the National Air and Space Museum, and at many other academic and research institutions, as well as industry, around the world who have helped to expand my horizons.

4. My editors at McGraw-Hill who have looked after me in the most professional, knowledgeable, understanding, and gentle manner possible.

Finally, compressible flow is an exciting subject—exciting to learn, exciting to use, exciting to teach, and exciting to write about. The purpose of this book is to excite the reader and to make the study of compressible flow an enjoyable experience. So this author says—read on and enjoy.

John D. Anderson, Jr.

CHAPTER 1

Compressible Flow—Some History and Introductory Thoughts

It required an unhesitating boldness to undertake a venture so few thought could succeed, an almost exuberant enthusiasm to carry across the many obstacles and unknowns, but most of all a completely unprejudiced imagination in departing so drastically from the known way.

J. van Lonkhuyzen, 1951, in discussing the problems faced in designing the Bell XS-1, the first supersonic airplane

PREVIEW BOX

Modern life is fast paced. We put a premium on moving fast from one place to another. For long-distance travel, flying is by far the fastest way to go. We fly in airplanes, which today are the result of an exponential growth in technology over the last 100 years. In 1930, airline passengers were lumbering along in the likes of the Fokker trimoter (Fig. 1.1), which cruised at about 100 mi/h. In this airplane, it took a total elapsed time of 36 hours to fly from New York to Los Angeles, including 11 stops along the way. By 1936, the new, streamlined Douglas DC-3 (Fig. 1.2) was flying passengers at 180 mi/h, taking 17 hours and 40 minutes from New York to Los Angeles, making three stops along the way. By 1955, the Douglas DC-7, the most advanced of the generation of reciprocating engine/propeller-driven transports (Fig. 1.3), made the same trip in 8 hours with no stops. However, this generation of airplane was quickly supplanted by the jet transport in 1958. Today, the modern Boeing 777 (Fig. 1.4) whisks us from New York to Los Angeles nonstop in about 5 hours, cruising at 0.83 the speed of sound. This airplane is powered by advanced, third-generation turbofan engines, such as the Pratt and Whitney 4000 turbofan shown in Fig. 1.5, each capable of producing up to 84,000 pounds of thrust.

Modern high-speed airplanes and the jet engines that power them are wonderful examples of the application of a branch of fluid dynamics called *compressible flow*. Indeed, look again at the Boeing 777 shown in Fig. 1.4 and the turbofan engine shown in Fig. 1.5—they are compressible flow personified. The principles of compressible flow dictate the external aerodynamic flow over the airplane. The internal flow through the turbofan—the inlet, compressor, combustion chamber, turbine, nozzle, and the fan—is all compressible flow. Indeed, jet engines are one of the best examples in modern technology of compressible flow machines.

Today we can transport ourselves at speeds faster than sound—supersonic speeds. The Anglo-French Concorde supersonic transport (Fig. 1.6) was such a vehicle. (Several years ago I had the opportunity to cross the Atlantic Ocean in the Concorde, taking off from New York's Kennedy Airport and arriving at London's Heathrow Airport just 3 hours and 15 minutes later—what a way to travel!) Supersonic flight is accompanied by shock waves generated in the air around the vehicle. Shock waves are an important aspect of compressible flow—they occur in almost all practical situations where supersonic flow exists. In this book, you will learn a lot about shock waves. When the Concorde flew overhead at supersonic speeds, a "sonic boom" was heard by those of us on the earth's surface. The sonic boom is a result of the shock waves emanating from the supersonic vehicle. The environmental impact of the sonic boom limited the Concorde to supersonic speeds only over water. However, modern research is striving to find a way to design a "quiet" supersonic airplane. Perhaps some of the readers of this book will help to unlock such secrets in the future—maybe even pioneering the advent of practical hypersonic airplanes (more than five times the speed of sound). In my opinion, the future applications of compressible flow are boundless.

Compressible flow is the subject of this book. Within these pages you will discover the intellectual beauty and the powerful applications of compressible flow. You will learn to appreciate why modern airplanes are shaped the way they are, and to marvel at the wonderfully complex and interesting flow processes through a jet engine. You will learn about supersonic shock waves, and why in most cases we would like to do without them if we could. You will learn much more. You will learn the *fundamental* physical and mathematical aspects of compressible flow, which you can apply to any flow situation where the flow speeds exceed that of about 0.3 the speed of sound. In the modern world of aerospace and mechanical engineering, an understanding of the principles of compressible flow is essential. The purpose of this book is to help you learn, understand, and appreciate these fundamental principles, while at the same time giving you some insight as to how compressible flow is practiced in the modern engineering world (hence the word "modern" in the title of this book).

Compressible flow is a fun subject. This book is designed to convey this feeling. The format of the book and its conversational style are intended to provide a smooth and intelligible learning process. To help this, each chapter begins with a preview box and road map to help you see the bigger picture, and to navigate around

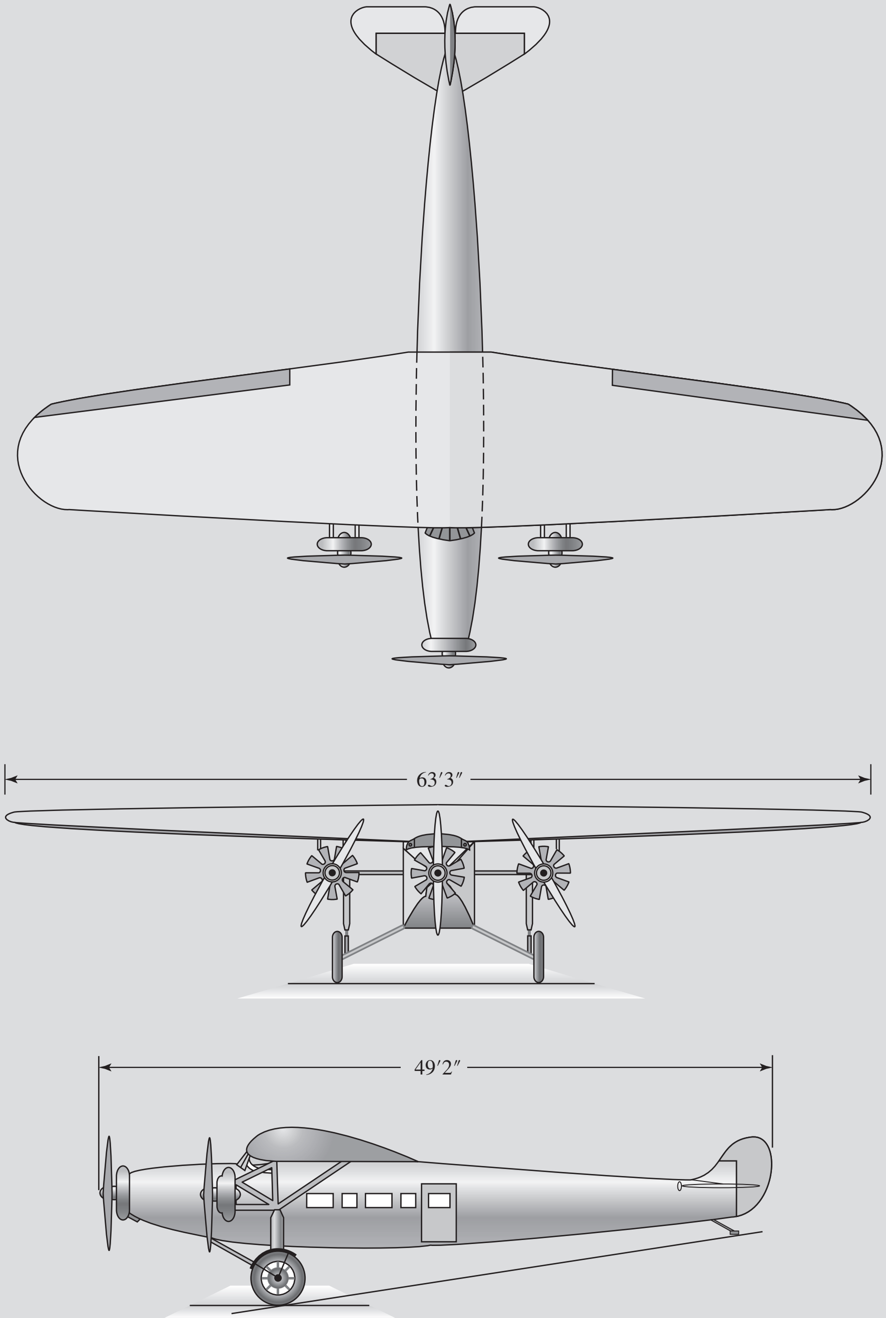

Figure 1.1 | Fokker Trimoter airliner, from the late 1920s.

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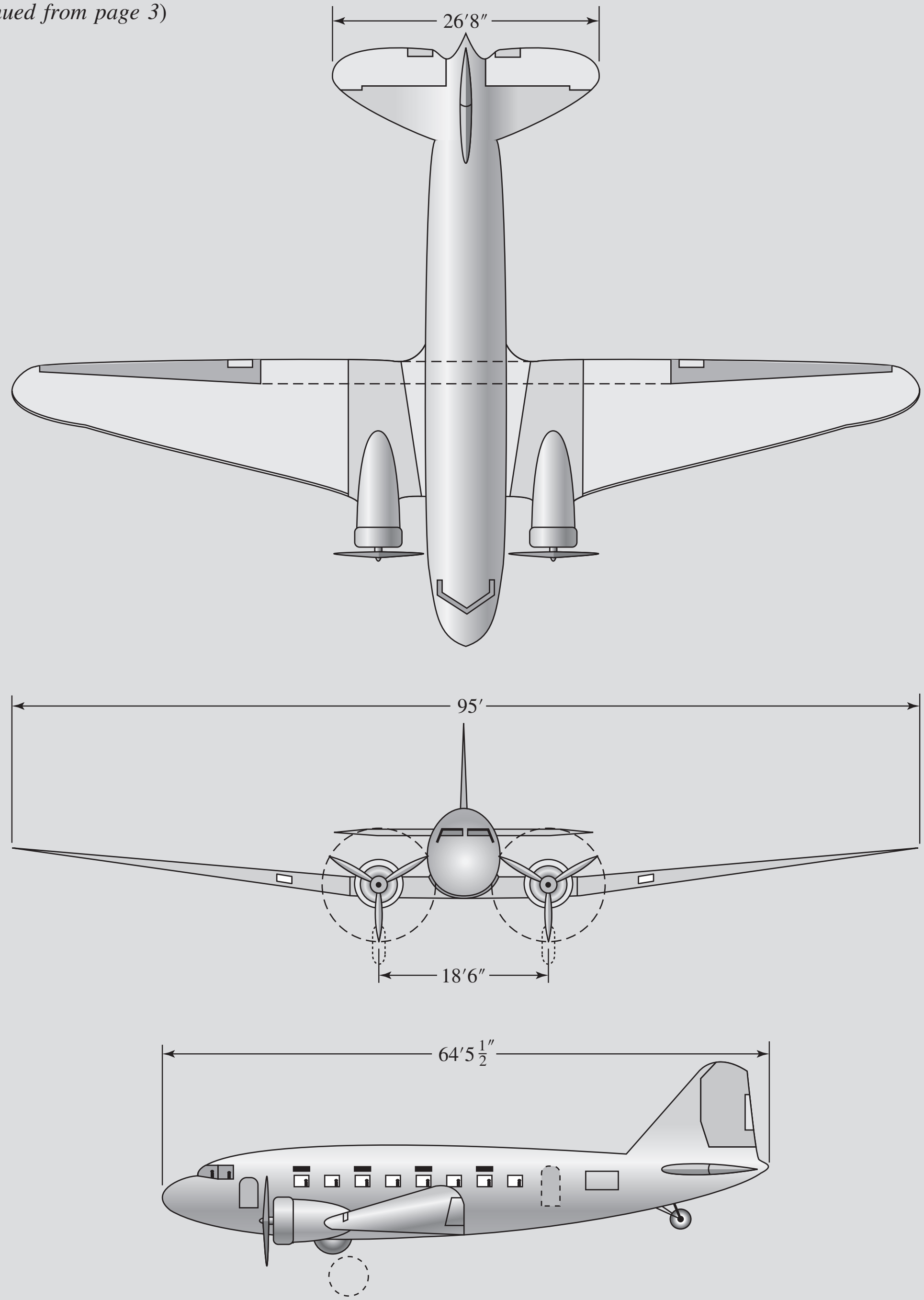

Figure 1.2 | Douglas DC-3 Airliner, from the middle 1930s.

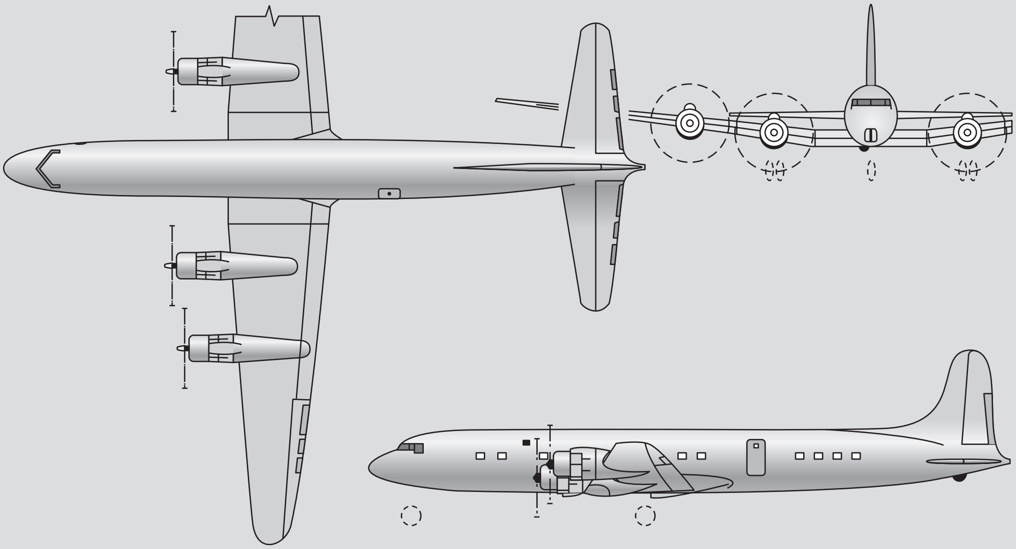

Figure 1.3 | Douglas DC-7 airliner, from the middle 1950s.

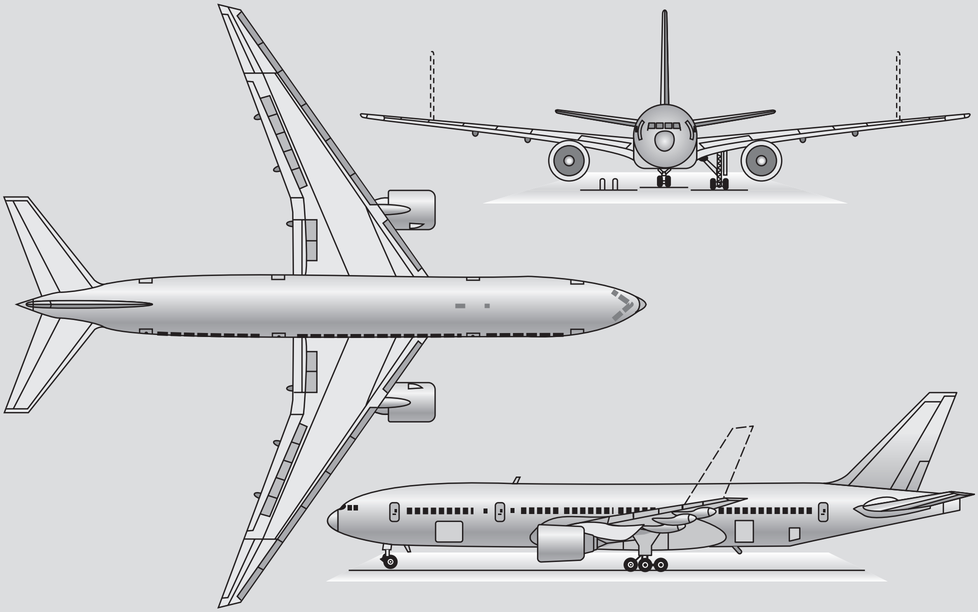

Figure 1.4 | Boeing 777 jet airliner, from the 1990s.

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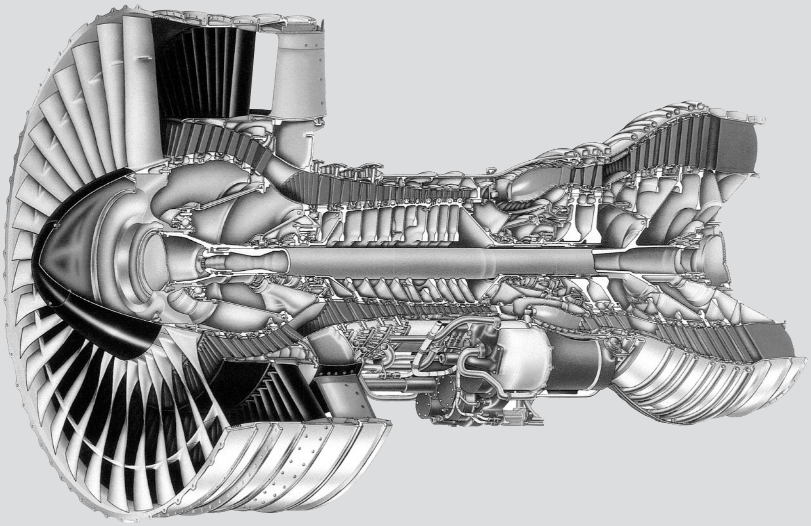

Figure 1.5 | Pratt and Whitney 4000 turbofan engine. Third-generation turbofan for widebody transports. Produces up to 84,000 lb (329.2 kN) of thrust. Powers some versions of the Boeing 777 (see Fig. 1.4).

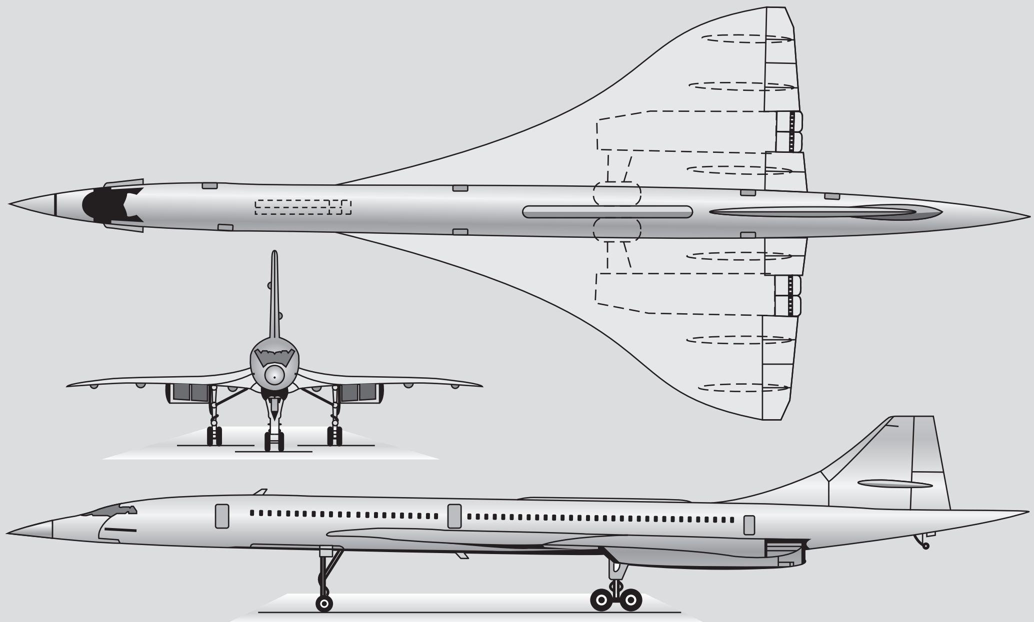

Figure 1.6 | The Anglo-French Aerospatiale/BAC Concorde supersonic airliner.

some of the mathematical and physical details that are buried in the chapter. The road map for the entire book is given in Fig. 1.7. To help keep our equilibrium, we will periodically refer to Fig. 1.7 as we progress through the book. For now, let us just survey Fig. 1.7 for some general guidance. After an introduction to the subject and a brief review of thermodynamics (box 1 in Fig. 1.7), we derive the governing fundamental conservation equations (box 2). We first obtain these equations in integral form (box 3), which some people will argue is philosophically a more fundamental form of the equations than the differential form obtained later in box 7. Using just the integral form of the conservation equations, we will study one-dimensional flow (box 4), including normal shock waves, oblique shock, and expansion waves (box 5), and the quasi-one-dimensional flow through nozzles and diffusers, with applications to wind tunnels and rocket engines (box 6). All of these subjects can be studied by application of the integral form of the conservation equations, which usually reduce to algebraic equations for the application listed in boxes 4–6. Boxes 1–6 frequently constitute a basic "first course" in

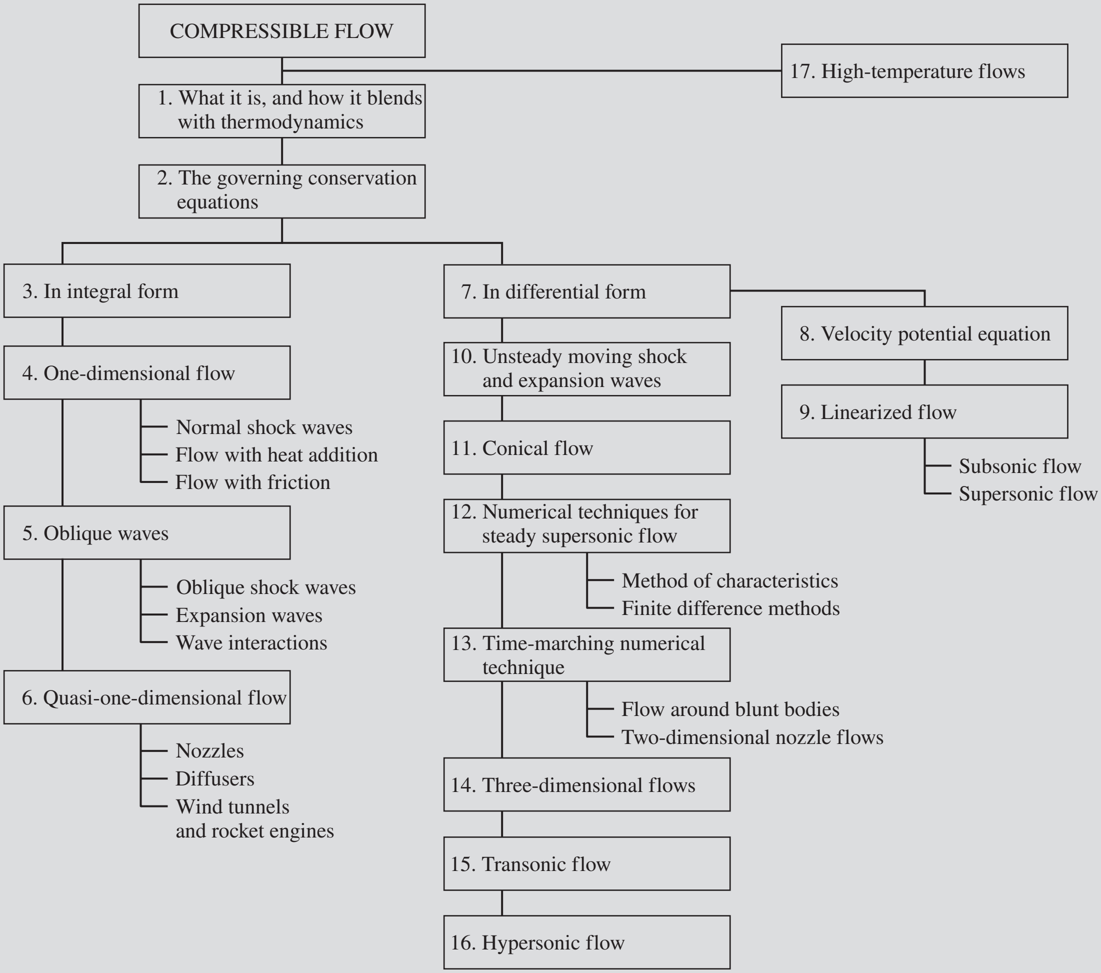

Figure 1.7 | Road map for the book.

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compressible flow, and the mathematics usually does not go beyond that of algebra. However, to deal with unsteady and/or multidimensional flows, we have to step to box 7 and obtain the governing conservation equations in differential form. They take the form of a system of coupled, highly nonlinear, partial differential equations. In some special cases for subsonic and supersonic flows, they can be linearized (boxes 8 and 9), leading to so-called "linearized flow." However, in most cases, we must cope with the nonlinear equations. The way we do this, and the fascinating physical phenomena we discover along the way, is told in boxes 10–16 dealing with unsteady flow, flow over cones, flows over supersonic blunt-nosed bodies, three-dimensional flows over bodies at an angle of attack to a uniform free stream, and the very special characteristics of transonic and hypersonic flows.

Our treatment of the material covered in boxes 4–6 and 8–16 in Fig. 1.7 assumes the gas to be calorically perfect, i.e., to have constant values of specific heats. This is valid as long as the temperature in the flow does not exceed about 1000 K. The vast bulk of compressible flow applications satisfy this criterion, including the flow around the Concorde when it was cruising at Mach 2. However, the flow over higher speed vehicles, as well as the flow through parts of a jet engine, will encounter temperatures high enough that the assumption of a calorically perfect gas is not valid. Witness the flow over parts of the Space Shuttle as it entered the atmosphere at Mach 25, where flow temperatures were as high as 8000 K, and the flow through rocket engines where temperatures on the order of 4000 K or higher occur in the combustion chamber. At these temperatures, the flow is chemically reacting, and the analysis of compressible flow applications at these conditions must include the appropriate physical-chemical effects. Hence, to round out our study of compressible flow, toward the end of this book we identify, discuss, and analyze these high-temperature flow effects. This subject is somewhat self-contained and is relatively independent of the earlier chapters; for this reason in Fig. 1.7 we show high-temperature flows in box 17 in an adjunct position somewhat separate from the main structure. However, this is not to minimize its importance. In many high-speed flow applications today, high-temperature effects are very important. Any study of *modern* compressible flow must include box 17.

We note that all of the material in this book, boxes 1–17 in Fig. 1.7, assumes *inviscid* flow, i.e., flow with no friction, thermal conduction, or mass diffusion, except for the special case of one-dimensional flow with friction (box 4 in Fig. 1.7). Flows where the dissipative transport processes of friction, thermal conduction, and mass diffusion are important are called *viscous* flows. Viscous flow is a subject all by itself and is beyond the scope of this book. The assumption of inviscid flow may at first sound ideal and restrictive—flows in the real world are not so ideal. However, the important physics that dictates compressible flow, such as the propagation of pressure waves through the flow, is essentially an inviscid phenomenon. Moreover, for the vast majority of compressible flow applications, the influence of the dissipative transport phenomena is limited to small regions, such as the boundary layer along a solid surface. Hence, the inviscid flows treated in this book are indeed very practical and apply to a vast majority of everyday applications of compressible flow.

All of this constitutes a preview for the material that is covered in this book—a broad, general view to give you a better, almost philosophical feeling for what compressible flow is about. As we continue, each chapter has its own preview box in order to enhance a broader understanding of the material in the chapter and to relate it to the general view. In this fashion, the detailed material in each chapter will more readily come to life for you.

In regard to the present chapter, we start out with some historical high-water marks in the application of compressible flow, and then discuss some introductory thoughts that are essential for our understanding of compressible flow in the subsequent chapters. For example, in this chapter we give a brief review of thermodynamics—but *only* those aspects of thermodynamics that relate directly to our subsequent discussions. Compressible flows are usually high-energy flows. Imagine that you are driving down the highway at 65 mph, and you stick your hand out of the window; your hand will literally feel the energy of the 65-mph airstream, and it feels impressive. But 65 mph is really a low velocity in the scheme of compressible flow applications. Rather, imagine the energy you would feel if you were traveling at 650 mph, near the speed of sound, and you stick your hand out of the window (definitely not recommended). You would feel a lot of energy in the flow. High-speed flows are high-energy flows. Thermodynamics is the study of energy changes and their effects on the properties of a system. Hence, compressible flow embraces thermodynamics. I know of no compressible flow problem that can be understood and solved without involving some aspect of thermodynamics. So that is why we start out with a review of thermodynamics.

The remainder of this chapter simply deals with other introductory thoughts necessary to provide you with smooth sailing through the rest of the book. I wish you a pleasant voyage.

1.1 | HISTORICAL HIGH-WATER MARKS

The year is 1893. In Chicago, the World Columbian Exposition has been opened by President Grover Cleveland. During the year, more than 27 million people visit the 666-acre expanse of gleaming white buildings, specially constructed from a composite of plaster of paris and jute fiber to simulate white marble. Located adjacent to the newly endowed University of Chicago, the Exposition commemorates the discovery of America by Christopher Columbus 400 years earlier. Exhibitions related to engineering, architecture, and domestic and liberal arts, as well as collections of all modes of transportation, are scattered over 150 buildings. In the largest, the Manufacturer's and Liberal Arts Building, engineering exhibits from all over the world herald the rapid advance of technology that will soon reach explosive proportions in the twentieth century. Almost lost in this massive 31-acre building, under a roof of iron and glass, is a small machine of great importance. A single-stage steam turbine is being displayed by the Swedish engineer Carl G. P. de Laval. The machine is less than 6 ft long; designed for marine use, it has two independent turbine wheels, one for forward motion and the other for the reverse direction. But what is novel about this device is that the turbine blades are driven by a stream of hot, high-pressure steam from a series of unique convergent–divergent nozzles. As sketched in Fig. 1.8, these nozzles, with their convergent–divergent shape representing a complete departure from previous engineering applications, feed a high-speed flow of steam to the blades of the turbine wheel. The deflection and consequent change in momentum of the steam as it flows past the turbine blades exerts an impulse that rotates the wheel to speeds previously unattainable—over 30,000 r/min. Little does de Laval realize that his convergent–divergent steam nozzle will open the door to the supersonic wind tunnels and rocket engines of the mid-twentieth century.

The year is now 1947. The morning of October 14 dawns bright and beautiful over the Muroc Dry Lake, a large expanse of flat, hard lake bed in the Mojave Desert in California. Beginning at 6:00 A.M., teams of engineers and technicians at the Muroc Army Air Field ready a small rocket-powered airplane for flight. Painted orange and resembling a 50-caliber machine gun bullet mated to a pair of straight, stubby wings, the Bell XS-1 research vehicle is carefully installed in the bomb bay of a four-engine B-29 bomber of World War II vintage. At 10:00 A.M. the B-29 with its soon-to-be-historic cargo takes off and climbs to an altitude of 20,000 ft. In the cockpit of the XS-1 is Captain Charles (Chuck) Yeager, a veteran P-51 pilot from the European theater during the war. This morning Yeager is in pain from two broken ribs incurred during a horseback riding accident the previous weekend. However, not wishing to disrupt the events of the day, Yeager informs