Cambridge University Press
978-0-521-80582-7 - Basic Aerodynamics: Incompressible Flow
Gary A. Flandro, Howard M. McMahon and Robert L. Roach
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1 Basic Aerodynamics

This was the last first in aviation, we had always said, a milestone, and that made it unique. Would we do it again? No one can do it again. And that is the best thing about it.
Jeana Yeager and Dick Rutan
"Voyager" 1987

1.1 Introduction

Aerodynamics is the study of the flow of air around and within a moving object. Its main objective is understanding the creation of forces by the interaction of the gas motion with the surfaces of an object. Aerodynamics is closely related to hydrodynamics and gasdynamics, which represent the motion of liquid and compressible-gas flows, respectively.

Aerodynamics is the essence of flight and has been the focus of intensive research for about a century. Although this might seem to be a rather long period of development, it is really quite short considering the time span usually required for the formulation and full solution of basic scientific problems. In this relatively short time, mankind has advanced from the first gliding and primitive-powered airplane flights to interplanetary spaceflight.

Perhaps the most important motivation for this rapid development is the challenge to the human spirit represented by manned flight. However, practical needs also have strongly affected these endeavors, and we often find periods of rapid growth in aerodynamic knowledge associated with the solution of compelling problems in transportation, military applications, industry, and even sporting competitions. Figure 1.1 illustrates this growth in terms of the maximum speed attained by manned aircraft. Speed is a key measure of performance in almost every aspect of flight. It is of obvious vital importance in commercial flight as well as in military operations.

Even a casual study of the history of aviation yields considerable insight into the pressures that have motivated periods of almost explosive growth in the technology of flight. Much of the increase in speed during the 1940s and several subsequent decades was motivated strongly by military considerations. However, notice that two radical departures (shown as dashed lines in Fig. 1.1) from the curve for conventional airplanes occur in the 1920s and in the two decades between 1940 and 1960.

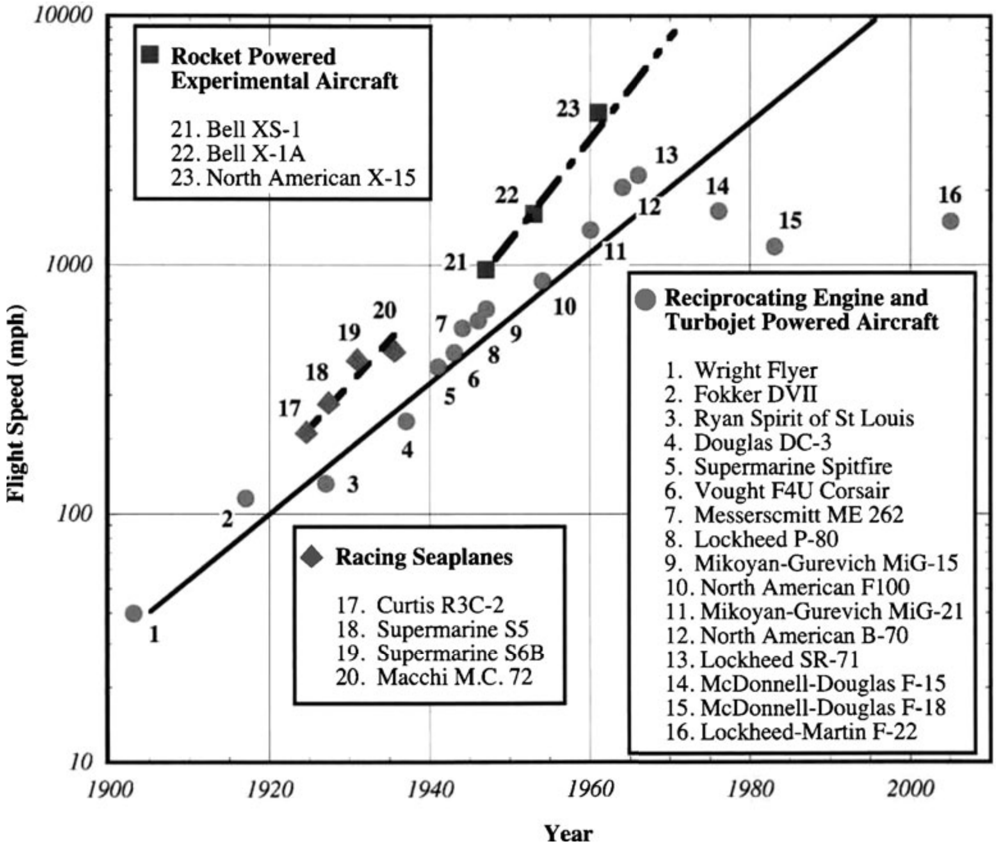

Figure 1.1. Evolution of aircraft speeds showing nearly exponential growth. Jet propelled aircraft speeds level off in the 1980's as turbojet performance Mach number limits are exceeded.

The phenomenal growth in speed from the 100 miles per hour (mph) range to over 400 mph that occurred during the period 1920–1932 was spurred by international competition in the guise of the Schneider Trophy Seaplane Races. Rapid progress not only in high-speed aerodynamics but also in aeropropulsion took place during that period. Similar growth occurred during the 1950s in supersonic flight. More recently, the international competitive spaceflight activities brought about rapid growth in propulsion, electronics, and materials, if not much in aerodynamics. There are signs that a new international competition is underway in the area of hypersonic aerodynamics and related technologies as policy decisions are made regarding the need for low-cost single-stage-to-orbit (SSTO) space vehicles.

Several of the key historical aircraft identified in Fig. 1.1 are illustrated in Figs. 1.2–1.12. Progressive improvements in aerodynamic configuration are apparent. In this textbook, we focus on the physical laws and related analytical and computational methods used to arrive at the aerodynamic-problem solutions implied in the evolving vehicle shapes depicted in the aircraft illustrated in this chapter.

Figure 1.2. Beginnings: The 1903 Wright Flyer (Smithsonian Institute).

Figure 1.3. Early Schneider Trophy seaplane: Curtis R3C-2 (1923).

Figure 1.4. Outright winner of the Schneider Trophy: Supermarine S6B (1931).

Figure 1.5. Supermarine Spitfire Mk II – an outcome of the Schneider Trophy racing seaplane research.

Figure 1.6. Messerschmitt ME 262. The first operational jet-propelled aircraft, 1944.

Figure 1.7. Bell XS-1: First supersonic airplane.

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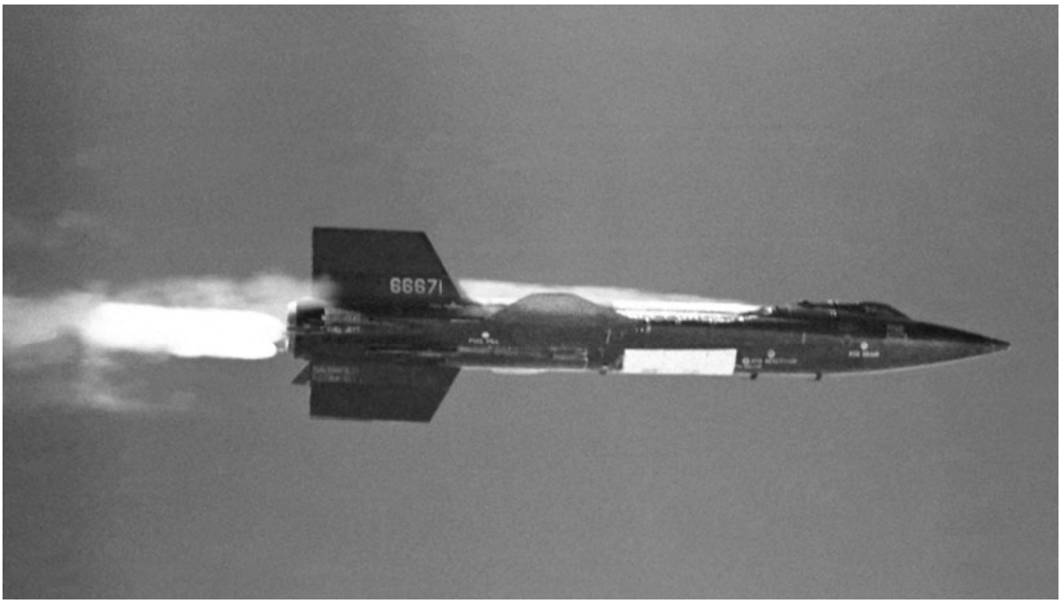

Figure 1.8. X-15: First hypersonic airplane.

Figure 1.9. Lockheed-Martin F-22 Raptor supersonic fighter.

Figure 1.10. Boeing 787 Dreamliner transonic jet transport during first flight test.

Figure 1.11. Concorde supersonic transport.

Figure 1.12. NASA X-43 hypersonic test vehicle using Scramjet propulsion.

Although it is not required to gain an understanding of the text material, the student is encouraged to supplement the text coverage with a parallel study of the history of aeronautics. Those interested in engaging in creative work as their careers in aeronautics develop will benefit greatly from this extra effort. References at the end of each chapter and frequent historical notes (usually provided as footnotes) serve as a guide for such an in-depth study. Much useful material is now available on the Internet and other large-scale computer networks.

In solving the problems of aerodynamics, those involved have been required to create basic technology along with the associated mathematical and experimental methodology. It is vital that the student understand the framework of this technology in detail and learn not only the application of the tools but also the deeper physical meaning they represent. This textbook is designed to promote this type of critical study of the subject. A carefully paced discussion of the traditional tools, such as mathematical analysis and experiment along with modern computational methods, is used to provide the student a broad understanding of both the physical meaning and the modern implementation of a wide variety of techniques and problem solutions. It is significant that the book outline follows closely the historical outline in terms of the need for each successive new idea and problem solution.

1.2 The Fundamental Problem of Aerodynamics

The basic problem addressed in this book is the accurate determination of the aerodynamic force system acting on a body moving through the air. Figure 1.13 shows a typical force system on an airplane in flight; only the resultant forces are shown. An important task is to relate these resultant effects to the distributions of pressure and frictional forces that create them. We focus only on the part of the force system related to the interaction of the airflow with the vehicle—that is, on the creation of lift (**L**) and drag (**D**), the aerodynamic forces normal and parallel to the vehicle velocity vector, as defined in the figure. However, much aerodynamic influence also is implied in the creation of thrust, as depicted by the vector **T** in Fig. 1.13. Interaction of the vehicle flow field with propellers, engine exhaust stream, cooling air inlets and outlets, and airbreathing propulsion system ducting must be accounted for. These important related aspects of applied aerodynamics are used at several points in the book to emphasize their strong dependence on knowledge of the vehicle flow field.

Aerodynamic Force System

Figure 1.13 illustrates several features of the force system on a moving body that is the focus of considerable attention throughout this book. The aerodynamic forces represent the integrated effect of a continuous distribution of pressure and shear forces acting on all of the exposed surfaces of the vehicle. The shape of the vehicle plays a crucial role in determining both the magnitude of the forces and their line

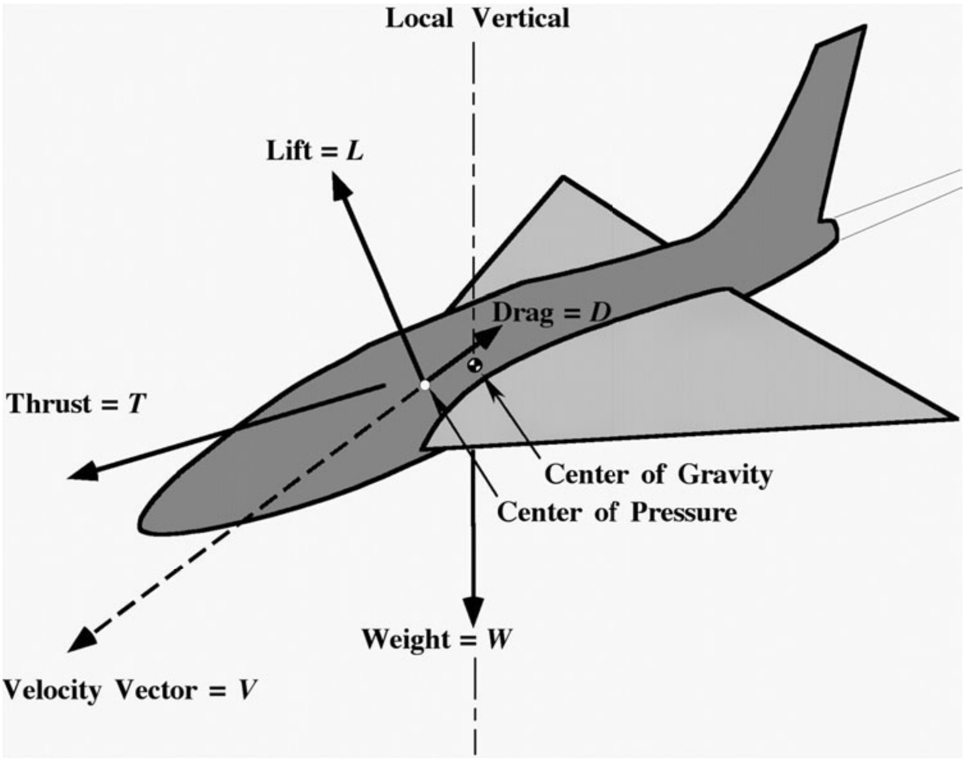

Figure 1.13. Force system on a vehicle in steady flight.

of action. In particular, notice that the net aerodynamic forces act at a point defined in the figure as the *center of pressure*. Clearly, to predict the vehicle-flight characteristics, it is necessary to know the precise location of this point relative to, say, the center of mass through which the vehicle weight acts. In level equilibrium flight, a component of the lift force is called on to balance the weight, **W**, of the airplane, expressed in vector form as $\mathbf{W} = m\mathbf{g}$, where m is the mass of the vehicle and $\mathbf{g}$ is the gravitational acceleration vector. Recalling the fundamental concepts of statics, it is clear that the balance of moments about the mass center also must be considered. Again, the latter considerations form the subject of stability and control; we concentrate here on the generation of the forces and moments and their relationship to properties of the airflow and vehicle shape.

Galilean Transformation

In Fig. 1.13, the point of view is assumed to be that of an observer fixed with respect to the atmosphere with the vehicle moving past with speed $V = |\mathbf{V}|$ in the direction of its velocity vector **V**. It often is simpler for an observer to be moving with the vehicle. Then, the airflow relative to the vehicle is in the direction $-\mathbf{V}$ at a sufficiently great distance upstream of the body—that is, far enough upstream that the effect of the presence of the vehicle has not yet affected the relative flow of the air particles. This change in point of view is useful and often referred to as a *Galilean Transformation*. As long as there are no acceleration effects present (i.e., no vehicle acceleration relative to the airmass or angular motion about the mass center), then the force system on the body can be taken to be independent of the choice of coordinate frame. This is a great convenience in aerodynamic modeling because it is often the case that the flow problem is best described in terms of the gas motion relative to the body.

The Lift-to-Drag Ratio: Aerodynamic Efficiency

Simple concepts from thermodynamics make it clear that creation of lift to balance the weight of the vehicle in flight is not without a penalty. The rule (i.e., First Law of Thermodynamics) that "you cannot get something for nothing" applies here. The drag force is a measure of the cost or penalty function for atmospheric flight. Drag results from complex interactions involving not only friction but also other fundamental loss effects involved in the lift-generation process. The aerodynamic penalty for lift generation is the production of what is called *induced drag*.

Figure 1.14(a) shows the force balance for a vehicle in level, unaccelerated flight. It is clear that if a particular level flight speed is to be maintained, a force must be introduced to balance the drag force. This is provided by the propulsion system in the form of thrust, **T**. If the vehicle is to climb or accelerate to a yet higher speed, additional energy must be expended in producing an even higher thrust force, **T**, to overcome the additional drag. The drag force always acts to retard the motion through the air. Thus, in producing sufficient lift to balance the weight in level flight, energy must be expended to counter the drag. Therefore, a measure of the efficiency of the aerodynamic design is the ratio:

$$\frac{\mathrm{L}}{\mathrm{D}} = \text{Lift to Drag Ratio} \tag{1.1}$$