INTRODUCTION TO AEROSPACE ENGINEERING

BASIC PRINCIPLES OF FLIGHT

Ethirajan Rathakrishnan

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Introduction to Aerospace Engineering

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Basic Principles of Flight

Ethirajan Rathakrishnan
Indian Institute of Technology, Kanpur

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This book is dedicated to my parents,
Mr. Thammanur Shunmugam Ethirajan
and
Mrs. Aandaal Ethirajan

Ethirajan Rathakrishnan

Contents

Preface

This book has been developed to introduce the subject of Aerospace Engineering to the beginners. Introduction to aerospace engineering is a compulsory course for Aerospace Engineering students. This book, being the manuscript developed using the course material used in teaching this course for a long period, precisely presents the basics of theoretical and application aspects of the subject.

This book is developed based on the class tested material for the course Introduction to Aerospace Engineering, at BS and MS levels, taught by the author at Indian Institute of Technology Kanpur. The topics covered are; Basics, International Standard Atmosphere, Aircraft Configurations, Low-Speed Aerofoils, High-Lift Devices, Thrust, Level Flight, Gliding, Performance, Stability and Control, Manoeuvres, Rockets. All these topics are introduced in such a manner that the students studying these for the first time could comfortably follow and assimilate the material covered.

The material covered in this book is so designed that any beginner can follow it comfortably. The book is organised in a logical manner and the topics are discussed in a systematic manner.

My sincere thanks to my undergraduate and graduate students at Indian Institute of Technology Kanpur, who are directly and indirectly responsible for the development of this book.

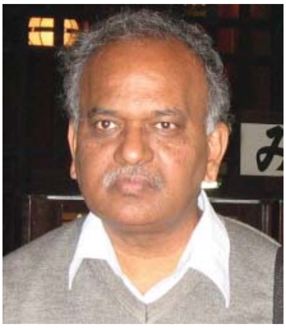
My special thanks to Dr. S.M. Aravindh Kumar, Department of Aerospace Engineering, S.R.M. Institute of Science and Technology, Chennai, for critically checking the manuscript and giving some useful suggestions.

For instructors only, a companion Solutions Manual is available from John Wiley that contains typed solutions to the end-of-chapter problems.

Chennai, India
March 23, 2021

Ethirajan Rathakrishnan

About the Author



Ethirajan Rathakrishnan is professor of Aerospace Engineering at the Indian Institute of Technology Kanpur, India. He is well known internationally for his research in the area of high-speed jets. The limit for the passive control of jets, called the *Rathakrishnan Limit*, is his contribution to the field of jet research, and the concept of *breathing blunt nose (BBN)*, which simultaneously reduces the positive pressure at the nose and increases the low pressure at the base is his contribution to drag reduction at hypersonic speeds. Positioning the twin-vortex Reynolds number at around 5000, by changing the geometry from cylinder, for which the maximum limit for the Reynolds number for positioning the twin-vortex was found to be around 160, by von Karman, to flat plate, is his addition to vortex flow theory. He has published a large number of research articles in many reputed international journals. He is a Fellow of many professional societies including the Royal Aeronautical Society. Rathakrishnan serves as the Editor-in-Chief of the *International Review of Aerospace Engineering* (IREASE) and *International Review of Mechanical Engineering* (IREME) journals. He has authored 13 other books: *Gas Dynamics*, 7th ed. (PHI Learning, New Delhi, 2020); *Fundamentals of Engineering Thermodynamics*, 2nd ed. (PHI Learning, New Delhi, 2005); *Fluid Mechanics: An Introduction*, 4th ed. (PHI Learning, New Delhi, 2021); *Gas Tables*, 3rd ed. (Universities Press, Hyderabad, India, 2012); *Theory of Compressible Flows* (Maruzen Co., Ltd. Tokyo, Japan, 2008); *Gas Dynamics Work Book*, 2nd ed. (Praise Worthy Prize, Naples, Italy, 2013); *Elements of Heat Transfer* (CRC Press, Taylor & Francis Group, Boca Raton, FL, USA, 2012); *Theoretical Aerodynamics* (John Wiley, NJ, USA, 2013); *High Enthalpy Gas Dynamics* (John Wiley & Sons Inc., 2015); *Dynamique Des Gaz* (Praise Worthy Prize, Naples, Italy, 2015); and *Instrumentation, Measurements and Experiments in Fluids*, 2nd ed. (CRC Press, Taylor & Francis Group, Boca Raton, FL, USA, 2017), *Helicopter Aerodynamics* (PHI Learning, New Delhi, 2019); *Applied Gas Dynamics* 2nd ed. (John Wiley & Sons Inc., 2019).

About the Companion Website

This book is accompanied by a companion website:

www.wiley.com/go/Rathakrishnan/IntroductiontoAerospaceEngineering

The website has solutions manual and lecture slides.

1

Basics

1.1 Introduction

Aerodynamics is the study of forces and the resulting motion of objects through the air. This word is coined with the two Greek words: *aerios*, concerning the air, and *dynamis*, meaning force. Judging from the story of Daedalus and Icarus,[1] humans have been interested in aerodynamics and flying for thousands of years, although flying in a heavier-than-air machine has been possible only in the last century. Aerodynamics affects the motion of high-speed flying machines, such as aircraft and rockets, and low-speed machines, such as cars, trains, and so on. Therefore, *aerodynamics* may be described as a branch of dynamics concerned with studying the motion of air, particularly when it interacts with a solid object. Aerodynamics is a subfield of fluid dynamics and gas dynamics. It is often used synonymously with gas dynamics, with the difference being that gas dynamics applies to all gases.

Understanding the flow field around an object is essential for calculating the forces and moments acting on the object. Typical properties calculated for a flow field include velocity, pressure, density, and temperature as a function of spatial position and time. Aerodynamics allows the definition and solution of equations for the conservation of mass, momentum, and energy in air. The use of aerodynamics through mathematical analysis, empirical approximations, wind tunnel experimentation, and computer simulations forms the scientific basis for heavier-than-air flight and a number of other technologies.

Aerodynamic problems can be classified according to the flow environment. *External aerodynamics* is the study of flow around solid objects of various shapes. Evaluating the lift and drag on an airplane or the shock waves that form in front of the nose of a rocket are examples of external aerodynamics. *Internal aerodynamics* is the study of flow through passages in solid objects. For instance, internal aerodynamics encompasses the study of the airflow through a jet engine.

Aerodynamic problems can also be classified according to whether the flow speed is below, near or above the speed of sound. A problem is called *subsonic* if all the speeds in the problem are less than the speed of sound, *transonic* if speeds both below and above the speed of sound are present, *supersonic* if the flow speed is greater than the speed of sound, and *hypersonic* if the flow speed is more than five times the speed of sound.

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[1] Daedalus – his name means 'skilled worker' – was a famous architect, inventor, and master craftsman known for having created many objects that figure prominently in various myths. He had a son named Icarus. Among the many inventions and creations crafted by Daedalus were the wooden cow he constructed for the queen Pasiphae, the Labyrinth of the Minotaur at Knossos on the island of Crete, and artificial wings for himself and his son Icarus, and he was even said to have invented images.

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The influence of viscosity in the flow dictates a third classification. Some problems may encounter only very small viscous effects on the solution; therefore the viscosity can be considered to be negligible. The approximations made in solving these problems is the viscous effect that can be regarded as negligible. These are called *inviscid flows*. Flows for which viscosity cannot be neglected are called *viscous flows*.

1.2 Overview

Humans have been harnessing aerodynamic forces for thousands of years with sailboats and windmills [1]. Images and stories of flight have appeared throughout recorded history [2], such as the legendary story of Icarus and Daedalus [3]. Although observations of some aerodynamic effects such as wind resistance (for example, drag) were recorded by Aristotle, Leonardo da Vinci, and Galileo Galilei, very little effort was made to develop a rigorous quantitative theory of airflow prior to the seventeenth century.

In 1505, Leonardo da Vinci wrote the Codex (an ancient manuscript text in book form) on the *Flight of Birds*, one of the earliest treatises on aerodynamics. He was the first to note that the centre of gravity of a flying bird does not coincide with its centre of pressure, and he describes the construction of an ornithopter with flapping wings similar to birds.

Sir Isaac Newton was the first to develop a theory of air resistance [4], making him one of the first aerodynamicists. As a part of that theory, Newton considered that drag was due to the dimensions of the body, the density of the fluid, and the velocity raised to the second power. These all turned out to be correct for low-speed flow. Newton also developed a law for the drag force on a flat plate inclined towards the direction of the fluid flow. Using F for the drag force, ρ for the density, S for the area of the flat plate, V for the flow velocity, and θ for the inclination angle, his law was expressed as

$$F = \rho \ S \ V^2 \sin^2 \theta$$

This equation is incorrect for the calculation of drag in most cases. Drag on a flat plate is closer to being linear with the angle of inclination as opposed to acting quadratically at low angles. The Newton formula can lead one to believe that flight is more difficult than it actually is, due to this overprediction of drag, and thus required thrust, which might have contributed to a delay in human flight. However, it is more correct for a very slender plate when the angle becomes large and flow separation occurs or if the flow speed is supersonic [5].

1.3 Modern Era

In 1738, the Dutch-Swiss mathematician Daniel Bernoulli published *Hydrodynamica*. In this book Bernoulli described the fundamental relationship among pressure, density, and velocity, in particular Bernoulli's principle, which is one method to calculate aerodynamic lift [6]. More general equations of fluid flow – the Euler equations – were published by Leonhard Euler in 1757. The Euler equations were extended to incorporate the effects of viscosity in the first half of the eighteenth century, resulting in the Navier–Stokes equations.

Sir George Cayley is credited as the first person to identify the four aerodynamic forces of flight – weight, lift, drag, and thrust – and the relationships between them [7, 8]. Cayley believed that the drag on a flying machine must be counteracted to enable level flight to occur. He also looked into the nature of aerodynamic shapes with low drag. Among the shapes he investigated were the cross sections of trout. This may appear counterintuitive; however, the bodies of fish are shaped to produce very low resistance as they travel through water. Their cross sections are sometimes very close to that of modern low-drag aerofoils.

Air resistance experiments were carried out by investigators throughout the eighteenth and nineteenth centuries. Drag theories were developed by Jean le Rond d'Alembert [9], Gustav Kirchhoff [10], and Lord Rayleigh [11]. Equations for fluid flow with friction were developed by Claude-Louis Navier [12] and George Gabriel Stokes [13]. To simulate fluid flow, many experiments involved immersing objects in streams of water or simply dropping them off the top of a tall building. Towards the end of this time period, Gustave Eiffel used his Eiffel Tower to assist in the drop testing of flat plates.

A more precise way to measure resistance is to place an object within an artificial, uniform stream of air where the velocity is known. The first person to experiment in this fashion was Francis Herbert Wenham, who in doing so constructed the first wind tunnel in 1871. Wenham was also a member of the first professional organisation dedicated to aeronautics, the Royal Aeronautical Society of the United Kingdom. Objects placed in wind tunnel as models are almost always smaller than in practice, so a method was needed to relate small-scale models to their real-life counterparts. This was achieved with the invention of the dimensionless Reynolds number by Osborne Reynolds [14]. In 1883, Reynolds also experimentally studied laminar to turbulent flow transition.

By the late nineteenth century, two problems were identified before heavier-than-air flight could be realised. The first was the creation of low-drag, high-lift aerodynamic wings. The second problem was how to determine the power needed for sustained flight. During this time, the groundwork was laid down for modern-day fluid dynamics and aerodynamics, with other less scientifically inclined enthusiasts testing various flying machines with little success.

In 1889, Charles Renard, a French aeronautical engineer, became the first person to reasonably predict the power needed for sustained flight [15]. Renard and German physicist Hermann von Helmholtz explored the wing loading (weight-to-wing-area ratio) of birds, eventually concluding that humans could not fly under their own power by attaching wings onto their arms. Otto Lilienthal, following the work of Sir George Cayley, was the first person to become highly successful with glider flights. Lilienthal believed that thin, curved aerofoils would produce high lift and low drag.

Octave Chanute provided a great service to those interested in aerodynamics and flying machines by publishing a book outlining all of the research conducted around the world up to 1997 [16].

1.3.1 Actual Flights

With the information contained in Chanute's book, the personal assistance of Chanute himself, and research carried out in their own wind tunnel, the Wright brothers gained enough knowledge of aerodynamics to fly the first powered aircraft on 17 December 1903. The Wright brothers' flight confirmed or disproved a number of aerodynamic theories. Newton's drag force theory was finally proved incorrect. This first widely publicised flight led to a more organised effort between aviators and scientists, leading the way to modern aerodynamics.

During the time of the first flights, Frederick W. Lanchester [17], Martin Wilhelm Kutta, and Nikolai Zhukovsky independently created theories that connected circulation of a fluid flow to lift. Kutta and Zhukovsky went on to develop a two-dimensional wing theory. Expanding upon the work of Lanchester, Ludwig Prandtl is credited with developing the mathematics [18] behind thin-aerofoil and lifting-line theories and the boundary layers. Prandtl, a professor at the University of Göttingen, instructed many students who would play important roles in the development of aerodynamics, such as Theodore von Karman and Max Munk.

1.3.2 Compressibility Issues

At low speeds, the compressibility of air is not significant in relation to aircraft design, but as the airflow nears and exceeds the speed of sound, a host of new aerodynamic effects become important in the design of aircraft. These effects, often several of them at a time, made it very difficult for World War II-era aircraft to reach speeds much beyond 800 km/h.

Some of the minor effects include changes to the airflow that lead to problems in control. For instance, the P-38 Lightning with its thick high-lift wing had a particular problem in high-speed dives that led to a nose-down condition. Pilots would enter dives and then find that they could no longer control the plane, which continued to nose-down over a distance until it crashed. The problem was remedied by adding a 'dive flap' beneath the wing that altered the centre of pressure distribution so that the wing would not lose its lift [19].

A similar problem affected some models of the Supermarine Spitfire. At high speeds the ailerons could apply more torque than the Spitfire's thin wings could handle, and the entire wing would twist in the opposite direction. This meant that the plane would roll in the direction opposite to that which the pilot intended and led to a number of accidents. Earlier models were not fast enough, for handling this was felt as a problem, and so it was not noticed until later models of Spitfire like the Mk.IX started to appear. This was mitigated by adding considerable torsional rigidity to the wings and was wholly cured when the Mk.XIV was introduced.

The Messerschmitt Bf 109 and Mitsubishi Zero had the exact opposite problem in which the controls became ineffective. At higher speeds the pilot simply could not move the controls because there was too much airflow over the control surfaces. The planes would become difficult to manoeuvre, and at high enough speeds aircraft without this problem could outturn them.

These problems were eventually solved as jet aircraft reached transonic and supersonic speeds. German scientists in World War II experimented with swept wings. Their research was applied on the MiG-15 and F-86 Sabre and bombers such as the B-47 Stratojet used swept wings that delay the onset of shock waves and reduce the drag. The all-flying tailplane which is common on supersonic planes also helps to maintain control near the speed of sound.

Finally, another common problem that fits into this category is flutter. At some speeds, the airflow over the control surfaces will become turbulent, and the controls will start to flutter. If the speed of the fluttering is close to a harmonic of the control's movement, the resonance could break the control off completely. When problems with poor control at high speeds were first encountered, they were addressed by designing a new style of control surface with more power. However, this introduced a new resonant mode, and a number of planes were lost before this was discovered.

All of these effects are often mentioned in conjunction with the term 'compressibility', but in a manner of speaking, they are incorrectly used. From a strictly aerodynamic point of view, the term compressibility should refer only to those side effects arising as a result of the change in the nature of the airflow from incompressible (similar in effect to water) to compressible (acting as a gas) as the speed of sound is approached. There are two effects in particular, wave drag and critical Mach number.

Wave drag is a sudden rise in drag on the aircraft, caused by air building up in front of it. At lower speeds this air has time to 'get out of the way', guided by the air in front of it that is in contact with the aircraft. However, at the speed of sound, this can no longer happen, and the air that was previously following the streamline around the aircraft now hits it directly. The amount of power