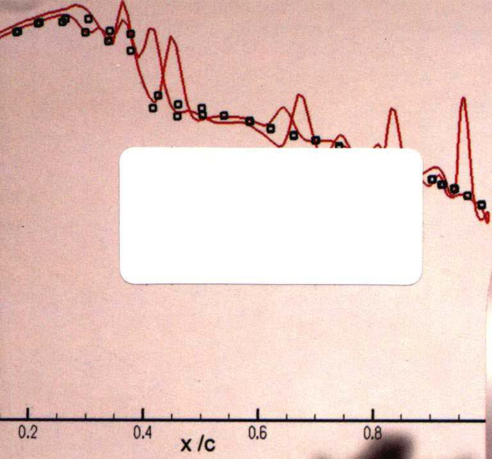
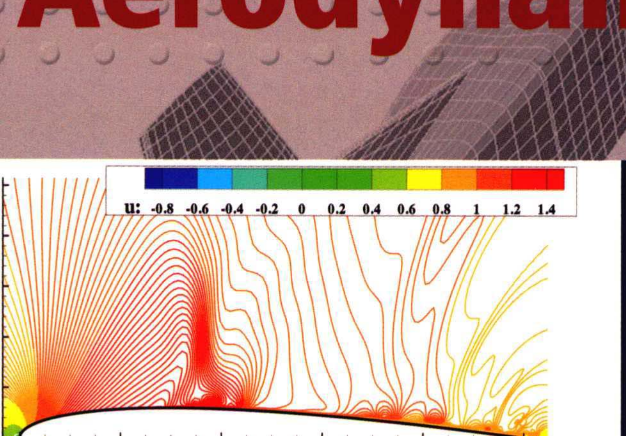


Tapan K. Sengupta

Theoretical and Computational Aerodynamics



Aerospace Series

Editors Peter Belobaba, Jonathan Cooper and Allan Seabridge

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THEORETICAL AND COMPUTATIONAL AERODYNAMICS

Tapan K. Sengupta
IIT Kanpur, India

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Series Preface

The field of aerospace is multidisciplinary and wide ranging, covering a large variety of products, disciplines and domains, not merely in engineering but in many related supporting activities. These combine to enable the aerospace industry to produce exciting and technologically advanced vehicles. The wealth of knowledge and experience that has been gained by expert practitioners in the various aerospace fields needs to be passed onto others working in the industry, including those just entering from university.

The *Aerospace Series* aims to be a practical, topical and relevant series of books aimed at people working in the aerospace industry, including engineering professionals and operators, allied professions such commercial and legal executives, and also engineers in academia. The range of topics is intended to be broad, covering design and development, manufacture, operation and support of aircraft, as well as topics such as infrastructure operations and developments in research and technology.

Aerodynamics is the fundamental enabling science that underpins the worldwide aerospace industry–without the ability to generate lift from airflow passing over aircraft wings, helicopter rotor blades and jet engine turbine blades, it would not be possible to fly the sophisticated heavier-than-air vehicles that we take for granted nowadays. Much of the development of current highly efficient aircraft has been due to the ability to model aerodynamic flows accurately, and thus to design high performance wings.

This book, *Theoretical and Computational Aerodynamics*, provides a detailed description of the underlying mathematical aerodynamic models and their computation with application to fixed wing aircraft. It is a very welcome addition to the Wiley Aerospace Series. Starting with the basic principles, the book takes the reader through aerodynamic theories in increasing complexity, from potential flow theory through to boundary layers and the Navier-Stokes equations. Of particular note are the sections relating to computational aerodynamics for incompressible and compressible flow around airfoils across the entire speed range, and a number of specific applications including drag reduction, low Reynolds number aerodynamics, high lift devices and flow control.

Peter Belobaba, Jonathan Cooper and Allan Seabridge

Preface

In writing the preface of a book, the author gets another opportunity to share with readers the thinking that motivates one to write the book. This is more so in the area of aerodynamics, where many books have been written and the reader is spoilt for choice, if not bewildered, by the multiplicity of textbooks. As the author, I would like to take the opportunity to explain what I have done here, hoping that readers understand this. I note that most books on aerodynamics emphasize classical approximate methods and less effort is spent on topics of current interests, such as transonic flows, low Reynolds number flows, natural laminar flow (NLF) airfoils and drag reductions.

Aerodynamics as a subject has been developed over more than a century and has seen extraordinary growth during this period. The Aeronautical Society of Great Britain, formed in 1866, stated as one of its initial goals the development of methods to estimate the lift and drag experienced on a flat plate! Although George Cayley laid the foundation of flight at the beginning of the nineteenth century, indicating the plausible shapes of wing, concepts of flight stability etc., it is also equally true that the correct theoretical models of fluid flow were established by Euler, Navier, Saint Venant and Stokes by 1850 (see the excellent book on the history of aerodynamics by J. D. Anderson for further details). However, these could not be used due to theoretical intractability and the search was on for further simplified models of fluid flows. This originated with the concept of velocity potential by Lagrange and its practical utility shown by Helmholtz through his vortex theorems. This route was followed over the decades with insights from conformal mapping, thin airfoil theory, finite wing theory for potential flows, which still form the bedrock of understanding the subject, as discussed here. The concurrent development of boundary layer theory to embed viscous effects helps bridge the chasm between ideal and real fluid flow as an aid in the analysis and design of aircraft for its steady state operation by focusing more on lifting surface behaviour.

Spectacular progress has been made in aerodynamics due to the growth of computing which significantly reduced the design cycle time of aircraft. Today it constitutes the preliminary step in a new design, relegating costly, time-consuming wind tunnel testing to the final stages. But a major stumbling block in understanding viscous flow is the slower progress in understanding transition and turbulence, without which the correct estimate of drag is impossible. Methods used for many decades have been semi-empirical, yet the linear viscous instability has helped in developing NLF airfoils currently used in civil aviation. Now this last barrier has been crossed and one can solve canonical flow transition problems by solving the Navier-Stokes equation from first principles, without any models.

Since the 1960s, computers have aided aerodynamics in studying viscous-inviscid interaction, a very useful analysis tool of the complete vehicle. One cannot overstate the role of panel methods to analyse complete aircraft at low speeds. Panel methods can also be used in the supersonic flight regime, which allows linearization. However, the transonic flight (the most efficient flight speed) regime evaded proper analysis until the early 1970s. Since then, the development of transonic small disturbance theory and full potential equation have made transonic flow analyses by computers amenable for aircraft and rotor craft applications. This was followed by computing Euler equation for full aircraft in the 1980s. Concurrently, computers also enabled early developments of studying fully developed time-averaged turbulent flows by solving the Reynolds averaged Navier-Stokes (RANS) equation with various turbulence models. The results thus obtained still do not allow one to study off-design performances or vehicles that depend upon unsteady aerodynamics. We also note that historically incompressible and compressible flows have been solved as belonging to distinct branches of fluid dynamics in analytical and experimental framework. This also prompted computing such flows as distinct activities. The present book shows this as unnecessary and the same computing methods work for compressible and incompressible flows, even for transonic flows.

Spectacular progress in scientific computing have enabled the study of unsteady flows using large eddy simulation (LES) and direct numerical simulation (DNS) as a unified activity. It is now feasible to study flow past aerofoils for unsteady flight conditions or even to study the flow transition from laminar to turbulent states by DNS. Such studies can refine NLF airfoils, as we understand transition phenomena better than before. Today we can simulate very high Reynolds number flows past NLF aerofoils and know how to delay transition. In the present context of high fuel cost, aerodynamics is still the pacing item for efficient aerodynamic design.

Thus, we are seeing progress in aerodynamics studies which was impossible for practical parameter ranges. For example, earlier developed theoretical analysis tools were for steady/time-averaged flows at high Reynolds numbers. Now, advances have been made for low Reynolds numbers for truly unsteady flight, such as in the flights of insects, birds and micro air vehicles. Further progress in these areas is possible by DNS/LES of such flow fields. These are all dealt with in this book.

This book can be used as a single text for two modules of courses on aerodynamics. In the first module, all chapters dealing with theoretical approaches for incompressible flows given in Chapters 1 to 7 can be covered (omitting the sections on compressible flows in Chapter 2). This can be supplemented with Chapter 13, discussing only the high lift devices part. Time permitting, one can include flow instability, as in Sections 9.1 to 9.4, and additional materials in Chapter 10 on NLF airfoils. The second module can contain Chapter 2 (as review and preparatory material for compressible flows) and from Chapters 8 to 13, for an advanced level course on the subject. This same module can also be taught as a course on computational aerodynamics by including Chapters 3 to 5.

Some of the chapters from this book can also be adapted for a special course on aerodynamics, emphasizing scientific computing as used here for transonic and low Reynolds number flows. While students can use commercial codes available to obtain time-averaged flow fields for conventional aircrafts (with limited accuracy and usage) using models for transition and turbulence, such tools are practically useless for low Reynolds number flows, which may seem easier as compared to high Reynolds number flows. Readers should note that the same numerical method has been used for transonic flow, which has been used for incompressible flow and this allows a very easy introduction to transonic flows, without going through the substantial efforts which have been invested in developing approximate theories involving transonic small perturbation theory and full potential equation.

As indicated above, there are new elements in this present book, which are not covered elsewhere. However, an aerospace professional should know these as essential minimum, which the author felt while teaching basic courses on aerodynamics at IIT Kanpur. This has motivated the author to write this book and hopefully this will be a welcome addition to the existing literature on the subject.

Any such undertaking requires the help and generosity of many peers, and also from various students and colleagues at IIT Kanpur. I am particularly indebted to Prof. T. T. Lim in providing various figures on vortex bursting in Chapter 6. Prof. Huu Duc Vo and Prof. Eric Laurendeau are gratefully acknowledged for various discussions and help with plasma models and transonic flows. I acknowledge the NPMICAV program of DRDO by supporting research on low Reynolds number aerodynamics and also acknowledge the help of Dr Mudkavi, the head of CTFD division of NAL Bangalore in providing many figures providing panel method results for Dornier DO-228 aircraft. All the results in Chapter 11 on transonic flows are due to the combined efforts of N. A. Sreejith and Ashish Bhole, two very competent graduate students. The results in Chapter 12 have been provided by Satish B. Krishnan and Pramod M. Bagade. Also acknowledged are Dr Y. G. Bhumkar and Dr Swagata Bhaumik, who provided many figures continuously. Secretarial assistance in typing using LaTeX has been done by Mrs Shashi Shukla and Baby Gaur.

I also take the opportunity to express my sincere appreciation for the unstinting support provided by my family, without which this would have been impossible. I would also like to express my gratitude to all other past and present students who have been generous with many suggestions. I accepts all responsibility for any errors or omissions and invites all readers and users of this book to point out inadvertent mistakes and provide critiques to improve the book further. Finally, I have only words of appreciation for the professional yet so accommodative team from Wiley. It is a pleasant duty to acknowledge the help provided by Tom Carter and Anne Hunt of Wiley and their team members.

Tapan K. Sengupta
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I am deeply indebted for the help and generosity of many peers, and also from various students and colleagues. Particular mention must be made for the help from Prof. T. T. Lim, Prof. Huu Duc Vo and Prof. Eric Laurendeau in the form of materials, suggestions and various discussions. I also acknowledge, ARDB and NPMICAV program of DRDO, Govt. of India, who supported researches on NLF airfoils for bypass transition, plasma actuation for flow control and low Reynolds number aerodynamics relevant for micro air vehicles. I would fail in my duty if I do not especially acknowledge the great help received from Dr. Mudkavi, the head of CTFD division, NAL Bangalore in providing many figures for panel method results obtained for Dornier DO-228 aircraft and discussions on various topics covered in the book. It is also my pleasant duty to acknowledge help provided by Tom Carter and Anne Hunt of Wiley and their team members in preparing the manuscript.

Contents

1

Introduction to Aerodynamics and Atmosphere

1.1 Motivation and Scope of Aerodynamics

Study of aerodynamics involves the ability to predict aerodynamic forces and moments acting on an airborne vehicle. However, it all began with the search for the quintessential shape that will make anything airborne in a sustained manner. Historically, the search for human flight began with lighter than air vehicles, now known variously as aerostats. While airships, blimps and/or dirigibles are still in use, the original search for vehicles heavier than air was the main attraction for human flight. In our quest for flight, we always wanted to emulate the birds, but even today this appears unattainable with present-day technologies. A bird flies in which the flapping wing performs the dual role of propulsive and aerodynamic devices. In man-made devices the propulsive device produces power or thrust for the vehicle to overcome resistance, while the aerodynamic device creates the necessary force to keep the body aloft in a dynamical equilibrium. Any device that imitates the flight of birds is known as an ornithopter and it is to the genius of Sir George Cayley (1773–1857) mankind owes a debt for the conventional aircraft shape and design. In a marked departure, he suggested that such propulsive devices did not exist and that it was more important to understand the analysis and design of aerodynamic aspect of the vehicle first. To do so, he advocated the study of powerless flight of aeronautical shapes of interest in a stable manner. This way of compartmentalizing the different aspects of flight into aerodynamics, propulsion, structures, performance, stability and control is now one essential component in the study of the discipline and was started by the need to understand the basics of flight as pioneered by Cayley. For an historic account of the development of flight and aerodynamics in particular, readers are advised to study it in Anderson (1997).

In this book, the sole motivation would be to study the aerodynamic forces and moments acting on an aircraft. Before we discuss the motivation of studying aerodynamics further, we should familiarize ourselves with different parts of an aircraft and their roles in flight. In Figure 1.1, we show the different main parts of a small aircraft as viewed externally.

Theoretical and Computational Aerodynamics, First Edition. Tapan K. Sengupta.

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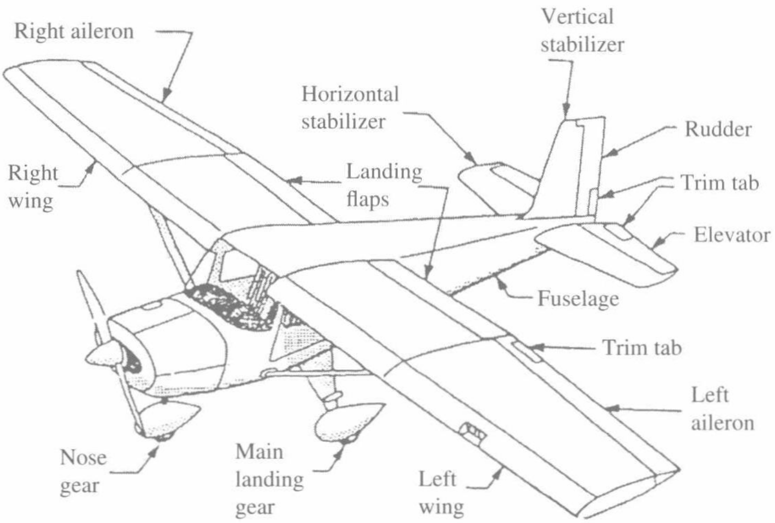

Figure 1.1 An external view of a small propeller aircraft with tricycle landing gear, identifying different parts of aerodynamic and control surfaces

The external shape of an aircraft is central to the study of aerodynamics, flight stability and controls. As an aircraft is heavier than the ambient displaced air, various surface stresses acting on different parts of the aircraft should be such that there must be a resultant force acting which will sustain the weight of the aircraft, when the aircraft is flying level and steady. This resultant force acting over the aircraft sustaining the weight is called the lift force. In a conventional aircraft, lift force is created by the flow over the wing. This is often modelled by the normal stress or the static pressure acting on the wing surface and is obtained by considering an ideal flow over the wing. When and how this is possible, will be the recurring theme of this book. Such normal stress or pressure distribution acting over the wing also creates a moment acting about a general point along the chord of the wing section and is a concomitant liability of producing the lift force. This is counteracted upon by the smaller amount of lift created on the horizontal stabilizer. One realizes that the main purpose of an aerospace vehicle is to carry payload and this is the reason for having a fuselage. Such a tubular shape of the fuselage, along with different aerodynamic and control surfaces, also creates resistance or drag for the aircraft. The required thrust to overcome drag is provided by the propeller engine located at the nose of the aircraft. The horizontal and vertical stabilizers are required for maintaining the stability of the aircraft for different flight regime.

One of the rudimentary aspects of flight operation is the cruise configuration, in which the aircraft flies level and steady at constant altitude. In Figure 1.2, we show a conventional aircraft flying level and steady in the longitudinal plane. External forces are shown to be in equilibrium, i.e. the weight of the aircraft is balanced by the vertical component of the aerodynamic forces acting on the aircraft called the lift and denoted by L. Most of it is created by the aircraft wing. The horizontal component of the aerodynamic force is termed the drag and denoted by D. Almost half the drag of an aircraft is created by the fuselage and a large portion of it is caused by the creation of lift itself. The total drag is overcome by the thrust