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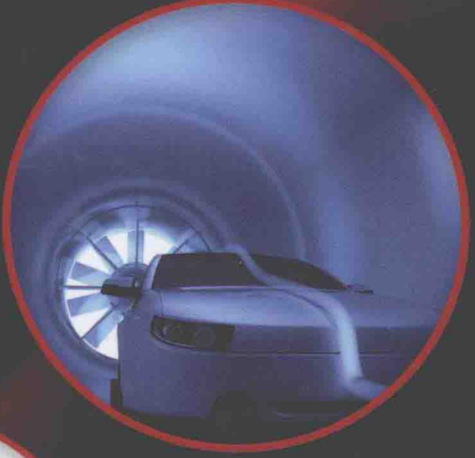
AUTOMOTIVE AERODYNAMICS

JOSEPH KATZ



$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{q} = 0$$

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AUTOMOTIVE AERODYNAMICS

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Series Preface

The automobile touches nearly every part of our lives. The manufacture of the automobile generates significant economic benefits, which is clear by the efforts that nations make to secure automobile manufacturing plants within their borders. Furthermore, issues such as emissions and fuel economy are critical to providing a sustainable path for the human race well into the future. Not only is the automobile a critical aspect of our lives, it is interwoven into our society, culture, and global wellbeing, as well as being a very fertile platform for tremendous technical advancements.

The primary objective of the *Automotive Series* is to publish practical and topical books for researchers, and practitioners in industry, and postgraduate/advanced undergraduate educators in the automotive engineering sector. The series addresses new and emerging technologies in automotive engineering supporting the development of more fuel efficient, safer and more environmentally friendly vehicles. It covers a wide range of topics, including design, manufacture, and operation, and the intention is to provide a source of relevant information that will be of interest and benefit to people working in the field of automotive engineering.

A critical aspect of vehicle system performance is the aerodynamic characteristics of the vehicle. These characteristics are major factors in vehicle performance, efficiency, safety, and marketability. This text, *Automotive Aerodynamics,* follows in the strong tradition of the *Automotive Series*, in that it presents classical fundamental concepts in aero and fluid mechanics in a pragmatic and concise fashion using the automobile as the primary exemplar. The text is designed to be used in an introductory aero/fluid mechanics course, and grounds the theoretical concepts in vehicle system examples that provide a familiar foundation to the students. Moreover, it does go beyond the basic aero/fluid topics addressing related issues such as heat-transfer, cooling, and aeroacoustics. Using the automobile as an example for these concepts provides the students with a critical touchstone to their life experiences.

Automotive Aerodynamics covers a number of classical topics including basic fluid mechanics, internal and external flows, viscosity and drag, as well as providing an introduction to numerical simulations, which are critical given the increasing access engineers have to cloud and high performance computing. Given that the text is well grounded in fundamentals, and has relevant and in-depth examples of modern systems, it is also a valuable professional reference. This book is an excellent text that is both relevant and forward thinking. It is written by a recognized expert in the field and is a welcome addition to the *Automotive Series*.

Thomas Kurfess
November 2015

Preface

This text was planned for engineering students as a first course in the complex field of aero/fluid mechanics. It does contain complex math, mainly to serve as the foundation for future studies. But the chapters focus on more applied examples, which can be solved in class using elementary algebra. Thus, the intention is not to avoid complex physical problems, but to keep them simple. Therefore, emphasis is placed on providing complete solutions, which can be solved in class. The material provided is self-contained and the reader is not directed elsewhere for more detailed formulations. On the other hand, the automobile is a part of our everyday life and the first complete engineering system fascinating the younger generations. As such, focusing on automotive examples can provide the much needed inspiration, and accelerate the attention and learning curve of the students.

Aero/fluid mechanics is a complex science and some problems cannot be solved by simple intuition. The reason behind this is the complex nonlinear differential equations, which have no closed form solutions. Historically, simple models were developed for some specific cases, and one educational approach is to present a series of case studies based on those localized solutions. However, when following this approach, the connection among the case-studies is unclear and long term learning benefits diminish. In addition, numerical solutions matured recently and most CAD programs have modules that can generate "a solution" by a simple "run" command. This usually leads to an iterative "learning curve" without understanding the main variables affecting the solution. Therefore, presenting the governing equations early on (as painful as it can be), and explaining the possible simplifications will provide a clear roadmap that will pay-off at the end of the course.

The first objective of this text, as advocated in the previous paragraphs, is to provide a systematic approach to the field of aero/fluid mechanics and to serve as a long-term reference. Also, some engineering programs are forced to shorten the curriculum and require only one course related to thermo/fluid mechanics. Consequently, the second objective is to introduce related areas not covered in traditional curriculum, such as heat-transfer, cooling, and aeroacoustics.

A Word to the Instructor

A first course in aero/fluid mechanics is always challenging due to the numerous new concepts that weren't used in previous engineering courses. The students were usually exposed to statics and dynamics, and will not easily adjust to "control volume" methods. Thus, after short introduction (Chapter 1), I suggest formulating the integral continuity and momentum equation. This allows opportunity to dwell on the principles of conservation (of mass and momentum) and allows the introduction of the differential form of the same equations. By the way, in some program this subject is taught throughout a whole semester, as a prelude to courses on "transport phenomena". Once the student understands the meaning of the various terms in the equations, simple examples can follow, in hope of explaining the mechanisms responsible for skin friction, pressure distribution and eventually lift, and drag of various vehicles.

A one-semester introductory course (~45 hours total) may cover the following sections (in the order presented):

Chapter 1 This is basically an introduction. A survey of engineering units is recommended, and Section 1.7 can be omitted.

Chapter 2 The fluid dynamic equations. The integral form (Section 2.6) is easily developed in class, but the differential form (Section 2.7) is more difficult. Sections 2.8–2.11 can be omitted in an introductory course. The suggested objective here is for the students to recognize the various terms (e.g., acceleration, body force, etc…).

Chapter 3 After a rather complex discussion in Chapter 2, simple one-dimensional examples serve to demonstrate the conservation of mass and momentum. It is suggested to cover Sections 3.1 through 3.4.2, and 3.5.

Chapter 4 This chapter serves as an introduction to the following chapters dealing with high Reynolds number flows. It also explains the relation between aerodynamics and the more general field of fluid mechanics. It is suggested to cover the whole chapter quickly and demonstrate the method of neglecting smaller terms in the governing equations.

Chapter 5 This chapter demonstrates the effect of viscosity and the mechanism for friction drag. Sections 5.6 and 5.7 can be omitted.

Chapter 6 This introduces the concept of ideal flow. Note that only the velocity potential is presented, because in more advanced courses it can be extended to three-dimensional flows. The approach is to present a case which can be solved in class (e.g., the flow over a cylinder), based on which experimental data base can be used for lift and drag. This chapter is the main topic in this course and requires most of the attention. Usually, Sections 6.4–6.10 are covered with examples from Chapter 7.

Chapter 9 This chapter introduces viscous flow examples, with the flow in pipes being the main topic. Usually, Sections 9.4–9.9 are included.

Chapter 8 A short discussion on numerical solution can be included at the end of the semester. Most programs will offer an additional one-semester course on CFD.

Chapter 10–Chapter 12 These chapters introduce additional practical examples related to aerodynamics. Topics can be included in more advanced courses or be used in the future for quick reference.

Contents

9 Viscous Incompressible Flow: "Exact Solutions" 339

10 Fluid Machinery 411

1

Introduction and Basic Principles

1.1 Introduction

Wind and water flows played an important role in the evolution of our civilization and provided inspiration in early agriculture, transportation, and even power generation. Ancient ship builders and architects of the land all respected the forces of nature and tried to utilize nature's potential. At the onset of the industrial revolution, as early as the nineteenth century, motorized vehicles appeared and considerations for improved efficiency drove the need to better understand the mechanics of fluid flow. Parallel to that progress the mathematical aspects and the governing equations, called the **Navier–Stokes** (NS) equations, were established (by the mid-1800s) but analytic solutions didn't follow immediately. The reason of course is the complexity of these nonlinear partial differential equations that have no closed form analytical solution (for an arbitrary case). Consequently, the science of fluid mechanics has focused on simplifying this complex mathematical model and on providing partial solutions for more restricted conditions. This explains why the term fluid mechanics (or dynamics) is used first and not aerodynamics. The reason is that by neglecting lower-order terms in the complex NS equations, simplified solutions can be obtained, which still preserve the dominant physical effects. Aerodynamics therefore is an excellent example for generating useful engineering solutions via "simple" models that were responsible for the huge progress in vehicle development both on the ground and in the air. By focusing on automobile aerodynamics, the problem is simplified even more and we can consider the air as incompressible, contrary to airplanes flying at supersonic speeds.

At this point one must remember the enormous development of computational power in the twenty-first century, which made numerical solution of the fluid mechanic equations a reality. However, in spite of these advances, elements of modeling are still used in those

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Automotive Aerodynamics, First Edition. Joseph Katz.

solutions and the **understanding** of the "classical" but limited models is essential to successfully use those modern tools.

Prior to discussing the airflow over vehicles, some basic definitions, the engineering units to be used, and the properties of air and other fluids must be revisited. After this short introduction, the fluid dynamic equations will be discussed and the field of aerodynamic will be better defined.

1.2 Aerodynamics as a Subset of Fluid Dynamics

The science of fluid mechanics is neither really new nor biblical; although most of the progress in this field was made in the latest century. Therefore, it is appropriate to open this text with a brief history of the discipline with only a very few names mentioned.

As far as we could document history, fluid dynamics and related engineering was always an integral part of human evolution. Ancient civilizations built ships, sails, irrigation systems, or flood management structures, all requiring some basic understanding of fluid flow. Perhaps the best known early scientist in this field is Archimedes of Syracuse (287–212 BC), founder of the field now we call "fluid statics", whose laws on buoyancy and flotation are used to this day.

Major progress in the understanding of fluid mechanics begun with the European Renaissance of the fourteenth to seventeenth centuries. The famous Italian painter sculptor, Leonardo da Vinci (1452–1519) was one of the first to document basic laws such as the conservation of mass. He sketched complex flow fields, suggested viable configuration for airplanes, parachutes, or even helicopters, and introduced the principle of streamlining to reduce drag.

During the next couple of hundred years, sciences gradually developed and then suddenly were accelerated by the rational mathematical approach of Englishman, Sir Isaac Newton (1642–1727) to physics. Apart from his basic laws of mechanics, and particularly the second law connecting acceleration with force, Newton developed the concept for drag and shear in a moving fluid, principles widely used today.

The foundations of fluid mechanics really crystallized in the eighteenth century. One of the more famous scientists, Daniel Bernoulli (1700–1782, Dutch-Swiss) pointed out the relation between velocity and pressure in a moving fluid, the equation of which bears his name in every textbook. However, his friend Leonhard Euler (1707–1783, Swiss born), a real giant in this field is the one actually formulating the Bernoulli equations in the form known today. In addition Euler, using Newton's principles, developed the continuity and momentum equations for fluid flow. These differential equations, the Euler equations are the basis for modern fluid dynamics and perhaps the most significant contribution in the process of understanding fluid flows. Although Euler derived the mathematical formulation, he didn't provide solution to his equations.

Science and experimentation in the field advanced but only in the next century were the governing equations finalized in the form known today. Frenchman, Claude-Louis-Marie-Henri Navier (1785–1836) understood that friction in a flowing fluid must be added to the force balance. He incorporated these terms into the Euler equations, and published the first