UNDERSTANDING AERODYNAMICS

Arguing from the Real Physics

DOUG McLEAN

WILEY

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Foreword

The job of the aeronautical engineer has changed dramatically in recent years and will continue change. Advanced computational tools have revolutionized design processes for all types of flig vehicles and have made it possible to achieve levels of design technology previously unheard of. An as performance targets have become more demanding, the individual engineer's role in the desig process has become increasingly specialized.

In this new environment, design work depends heavily on voluminous numerical computations. Th computer handles much of the drudgery, but it can't do the thinking. It is now more important tha ever for a practicing engineer to bring to the task a strong physical intuition, solidly based in th physics. In this book, Doug McLean provides a valuable supplement to the many existing books o aerodynamic theory, patiently exploring what it all means from a physical point of view. Students an experienced engineers alike will surely profit from following the thought-provoking arguments an discussions presented here.

John J. Trac
Chief Technology Offic
The Boeing Compan
September 20

Series Preface

The field of aerospace is wide ranging and multi-disciplinary, covering a large variety of product disciplines and domains, not merely in engineering but in many related supporting activities. The combine to enable the aerospace industry to produce exciting and technologically advanced vehicle The wealth of knowledge and experience that has been gained by expert practitioners in the vario aerospace fields needs to be passed onto others working in the industry, including those just enterin from University.

The *Aerospace Series* aims to be a practical and topical series of books aimed at engineerin professionals, operators, users and allied professions such as commercial and legal executives in th aerospace industry, and also engineers in academia. The range of topics is intended to be wid ranging, covering design and development, manufacture, operation and support of aircraft as well topics such as infrastructure operations and developments in research and technology. The intention to provide a source of relevant information that will be of interest and benefit to all those peop working in aerospace.

Aerodynamics is the fundamental enabling science that underpins the world-wide aerospace indust —without the ability to generate lift from airflow passing over wings, helicopter rotors and oth lifting surfaces, it would not be possible to fly heavier-than-air vehicles as efficiently as is taken f granted nowadays. Much of the development of today's highly efficient aircraft is due to the ability accurately model aerodynamic flows using sophisticated computational codes and thus design hig performance wings; however, a thorough understanding and insight of the aerodynamic flows is vit for engineers to comprehend these designs.

This book, *Understanding Aerodynamics*, has the objective of providing a physical understanding aerodynamics, with an emphasis on how and why particular flow patterns around bodies occur, an what relation these flows have to the underlying physical laws. It is a welcome addition to the Wile Aerospace Series. Unlike most aerodynamics textbooks, there is a refreshing lack of detaile mathematical analysis, and the reader is encouraged instead to consider the overall picture. As well consideration of classical topics—continuum fluid mechanics, boundary layers, lift, drag and the flo around wings, etc.—there is also a very useful coverage of modelling aerodynamic flows usin Computational Fluid Dynamics (CFD).

Peter Belobaba, Jonathan Cooper, Roy Langton and Allan Seabrid

Preface

This book is intended to help students and practicing engineers to gain a greater physic understanding of aerodynamics. It is not a handbook on how to do aerodynamics, but is motivate instead by the assumption that engineering practice is enhanced in the long run by a robu understanding of the basics.

A real understanding of aerodynamics must go beyond mastering the mathematical formalism of th theories and come to grips with the physical cause-and-effect relationships that the theories represen In addition to the math, which applies most directly at the local level, intuitive physic interpretations and explanations are required if we are to understand what happens at the flowfie level. Developing this physical side of our understanding is surprisingly difficult, however. It require navigating a conceptual landscape littered with potential pitfalls, and an acceptable path is to be foun only through recognition and rejection of multiple faulty paths. It is really a process of argumentatio thus the “arguing” in the title. This kind of argumentation is underemphasized in other books, which the path is often made to appear straighter and simpler than it really is. This book explores broader swath of the conceptual landscape, including some of the false paths that have led to errors the past, with the hope that it will leave the reader less likely to fall victim to misconceptions.

We'll encounter several instances of serious misinterpretations of mathematical theory that are wide circulation and of erroneous physical explanations that have found their way into our folklore. any case where a misconception has been widely enough propagated, the “right” explanation wou not be complete without the debunking of the “wrong” one. I have tried to do this kind of debunkin wherever it seemed appropriate and have not hesitated to say so when I think something is wrong. Th is part of what makes aerodynamics so much fun. It's one of those little perversities of human natu that coming up with a good explanation is much more satisfying when you know there are people o there who have got it wrong. But debunking bad explanations serves a pedagogical purpose as we because the contrast provided by the wrong explanation can strengthen understanding of the right one

This effort devoted to basic physical rigor and avoiding errors comes at a cost. We'll spend mor time on some topics than some will likely think necessary. I realize some parts of the discussion a long and are not easy, but I hope most readers will find it worth the effort.

We are now well into what I would call the computational era in aerodynamics, made possible b the ever-advancing capabilities of computers. In the 1960s, we began to calculate practical numeric solutions to linear equations for inviscid flows in 3D. In the 1970s, it became economical to compu solutions to nonlinear equations for inviscid transonic flows in 3D and to include viscous effec through boundary-layer theory and viscous/inviscid coupling. By the 1990s, we were routine calculating solutions to the Reynolds-averaged Navier-Stokes (RANS) equations for full airplan configurations. These computational fluid dynamics (CFD) capabilities have revolutioniz aerodynamics analysis and design and have made possible dramatic improvements in desig technology. CFD is now such a vital part of our discipline that this book would not be complete if did not address it in some way. While this is not a book about CFD methods or about how to use CF there are conceptual aspects of CFD that are relevant to our focus, and these are considered in chapt 10.

I believe that although we now rely on CFD for much of our quantitative work, it is vitally importa for a practicing engineer to have a sound understanding of the underlying physics and to be famili with the old simplified theories that our predecessors so ingeniously developed. These things not on ~~provide us with valuable ways of thinking about our problems, they also can help us to be~~ mo effective users of CFD.

The unusual scope of the book is deliberate. The book is not intended to be a handbook. Nor is intended as a substitute for the standard textbooks and other sources on aerodynamic theory, as I hav omitted the mathematical details whenever the physical understanding I seek to promote can b conveyed without them. This applies especially to the discussion of the basic physics in the ear chapters. Those looking for rigorous derivations of the mathematical details will have to loo elsewhere. Also, exhaustive scope is not a practical goal. So, for the details on many of the topi treated here, and for any treatment at all of the many topics neglected here, the reader will have consult other sources. This book is also not intended as an introduction to the subject. Though it wou not be impossible for someone with no prior exposure to follow the development given here, son experience with the subject will make it much easier. And while I assume no prior knowledge of th subject, I do assume a higher level of technical sophistication than is often assumed in undergraduat level texts.

An understanding of the physical basics is more secure if it includes an appreciation of the “b picture,” the logical structure of the body of knowledge and the collection of concepts we ca aerodynamics. I have tried to at least touch on all of the topics that are so basic that the overa framework could not stand without them. I also devote more attention than most aerodynami textbooks to the relationships between the parts, to how it all “fits together.” Beyond that, sever considerations have guided my choice of topics and the kinds of treatment I've given them. One is m own familiarity and experience. Another is my observation of some common knowledge gaps, thin that don't seem to be covered well in the usual aero engineering education. But we'll also spend a goo part of our time on some of the very familiar things that we tend to take for granted. O understanding of these things is never so good that it can't benefit from taking a fresh look. We'll put different spin on some familiar topics, for example, what the Biot-Savart law really means and why causes so much confusion, what “Reynolds number” and “incompressible flow” really mean, and real physical explanation for how an airfoil produces lift.

As we'll see in chapter 1, the *subject matter* of aerodynamics consists of physical principle conceptual models, mathematical theories, and descriptions and physical explanations of flo phenomena. Some of this subject matter has direct practical applications, and some doesn't. We' spend considerable time on some topics that have no apparent practical import, for example, physic explanations of things for which we have perfectly good quantitative theories and esoterica such how lift is felt in the atmosphere at large. We'll do these things because they provide general flui mechanics insight and because they serve to expand our appreciation of the *cognitive dimension* of th subject, the processes by which we *think about* aerodynamic phenomena and the practical problen that arise from them. They also help us to see how mistaken thinking can arise and how to avoid The medical profession in recent years has begun to pay more attention to the cognitive dimension their discipline, studying how doctors think, in an effort to improve the accuracy of their diagnos and to avoid mistakes. Doing some of the same would be good for us as well.

Aerodynamics as a subject encompasses a wide variety of flow situations that in turn involve multitude of detailed flow phenomena. The subject is correspondingly multifaceted, with a rich web interconnections among the phenomena themselves and the conceptual models that have bee developed to represent them. Such a subject has a logical structure of course, but it is not well suite to exposition in a single linear narrative, and there is therefore no ideal solution to the problem organizing it so that it flows completely naturally as a single string of words. The organization I hav ~~chosen is based not on the historical development or on a progression from "easy" concepts~~ "advanced," but on a general conceptual progression, from the basic physics, to the flow phenomen and finally to the conceptual models. I have tried to organize the material so that it can be rea straight through and understood without the need to skip forward. I have also tried to provide dire references whenever I think referring back to previous chapters would be helpful and to alert th reader when further discussion of a topic is being deferred until later.

The general flow of the book is as follows. First, we take an overview of the conceptual landscape chapter 1. Then we consider the basic *physics* as embodied in the NS equations in chapters 2 and We turn to the phenomenological aspects of *general flows* in boundary layers and around bodies chapters 10 and 5. We then enter the more specific realm of *aerodynamic forces* and the manifestations in flowfields to deal with drag in chapter 6 and lift generation, airfoils, and wings chapters 7 and 8. All of this sets the stage for a bit of a regression into *theory*, with discussions theoretical approximations and CFD in chapters 9 and 10.

When I started writing I had something less ambitious in mind, something more on the scale of booklet with a collection of helpful ways of looking at aerodynamic phenomena and a catalog common misconceptions and how to avoid them. As the project progressed, it became clear th effective explanations required more background than I had anticipated, and the book gradually gre more comprehensive. The first draft in something close to the final form was completed in late 200 and was reviewed by several Boeing colleagues (acknowledged below). Their feedback w incorporated into a second draft that was used in a 20-week after-hours class for Boeing engineers 2009. Feedback from class participants and others led to significant revisions for the final draft. As turned out, the general argumentative approach I've taken to the subject extended to the writin process itself. Many sections saw multiple and substantial rewrites as my thinking evolved.

I gratefully acknowledge the help of many people in getting me through this long process. First, m wife, Theresa, who put up with the many, many weekends that I spent in front of our home compute Then The Boeing Company, which allowed me to spend considerable company time on the projec Boeing editors, Andrea Jarvela, Lisa Fusch Krause, and Charlene Scammon, who turned my raw Wor files and graphics into a presentable draft and helped me take that draft through several revisions, an Boeing graphics artist John Jolley, who redrew nearly half the graphics. Finally, the friends an colleagues without whose help the book would have been much poorer. Mark Drela (MIT), Lian N Ben Rider, Philippe Spalart, and Venkat Venkatakrishnan provided very detailed feedback an suggestions for improvement. Steve Allmaras and Mitch Murray made special CFD calculations ju for the book. My former Boeing colleague Guenter Brune wrote the excellent 1983 Boeing report o flow topology that introduced me to the topic and served as the basis of much of Section 5.2. Another former Boeing colleague, Pete Sullivan, did the CFD calculations plotted in Section 6.1. And many others contributed feedback on various drafts of the manuscript: Anders Andersson, Joh D. Anderson (University of Maryland), Byram Bays-Muchmore, Bob Breidenthal (University o Washington), Julie Brightwell, Tad Calkins, Dave Caughey (Cornell University), Tony Craig, Jeffre Crouch, Peg Curtin, Bruce Detert, Scott Eberhardt, Winfried Feifel, David Fritz, Arvel Gentry, Mar Goldhammer, Elisabeth Gren, Rob Hoffenberg, Paul Johnson, Wen-Huei Jou, T. J. Kao, Edward Kin Alex Krynytsky, Brenda Kulfan, Louie LeGrand, Adam Malachowski, Adam Malone, Tom Mato Mark Maughmer (Penn State University), the late John McMasters, Kevin Mejia, Robin Melvin, Gre Miller, Deepak Om, Ben Paul, Tim Purcell, Steve Ray, Matt Smith, John Sullivan (Purdue University Mary Sutanto, Ed Tinoco, David Van Cleve, Paul Vijgen, Dave Witkowski, Conrad Youngren (Nev

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Doug McLea
April 201

List of Symbols

Many of the symbols listed below have different meanings in different contexts, as indicated whe multiple definitions are given. When an example of usage (a figure or equation) is listed, it is n necessarily the only example.

English Symbols

a	Acceleration
	Speed of sound
A	Streamtube area
	Amplitude of a disturbance in laminar-flow stability theory
A_1, A_2	Coefficients of induced-drag polar (equation 8.3.17)
A_i	Coefficients of sin-series spanloads (equation 8.3.20)
A_θ	Wake momentum area (equation 6.1.6)
AR	Aspect ratio = b^2/s
b	Wingspan
b_o	Span between the centers of trailing vortex cores (figure 8.3.3)
B	Constant in law of wall (equation 4.4.10)
c	Airfoil chord
c_{avg}	Wing average chord
$\bar{c}$	Wing average chord (figure 8.3.7)
c_p	Specific heat at constant pressure
c_v	Specific heat at constant volume
C	Cylindrical part of the outer boundary of a control volume (figure 6.1.1)
C_d	Drag coefficient (2D or per unit span)
C_D	Drag coefficient (3D)
C_{Di}	Induced-drag coefficient (3D)
C_{Dimin}	Minimum induced drag coefficient on induced-drag polar (equation 8.3.19)
C_{Dio}	Induced drag coefficient at zero lift (equation 8.3.17)
C_{Do}	Drag coefficient at zero lift (equation 8.3.15)
C_f	Skin-friction coefficient
C_l	Lift coefficient (2D or per unit span)
C_L	Lift coefficient (3D)
C_{Lmax}	Maximum lift coefficient of a 3D wing
C_m	Pitching moment coefficient (2D or per unit span)
C_M	Pitching moment coefficient (3D)
C_n	Sectional normal-force coefficient (figure 8.3.7)
C_N	Total normal-force coefficient (figure 8.3.7)
C_p	Pressure coefficient
$\overline{C_p}$	Smith's canonical pressure coefficient (equation 7.4.1)
C^*	Attachment-line Reynolds number (equation 8.6.15)
$\mathbf{d}$	Viscous drag vector of a propeller blade section (figure 6.1.17)
d_b	Diameter of fuselage (equation 8.3.29)
D	Drag

D_i	Induced drag (equation 8.3.5)
e	Thermodynamic internal energy
	Base of natural logs
	Induced-drag efficiency factor (equation 8.3.14)
e_{NT}	Induced-drag efficiency factor of untwisted version of a wing (equation 8.3.19)
e_o	Oswald efficiency factor (equation 8.3.15)
F	Force
f	Function
g	Genus of a region of a surface (equation 5.2.2)
h	Enthalpy
	Height of a vortex generator
	Height of an excrescence (figure 6.2.1)
	Height above the ground (equation 7.4.2)
h_p	Riblet protrusion height (figure 6.3.6)
H	Total enthalpy
	Boundary-layer shape factor
i	Unit vector in x direction (equation 6.1.1)
	Square root of minus one
I	Index of a region of a surface (equation 5.2.3)
I_{CF}	Cumulative skin-friction integral (equation 6.1.13)
I_{ENS}	Enstrophy integral (equation 6.1.15)
J	Propeller advance ratio = V/nd_p
k	Thermal conductivity
	Roughness height
$\mathbf{k}$	Unit curvature vector (figure 4.2.4)
	Unit vector in z direction (equation 5.4.1)
k_s	Equivalent sand-grain height
l	Length
l	Lift per unit span of a wing or propeller blade
L	Length
	Lift in 3D (equation 5.4.1)
L_b	Carry-through lift on fuselage (figure 8.3.15)
L_t	Lift on tail or canard (figure 8.3.17)
L_w	Lift on exposed wing (figure 8.3.15)
M	Mach number
	Propeller shaft torque (equation 6.1.19)
M_{BR}	Wing-root bending moment (equation 8.3.28)
m	Mass
	Exponent in power-law velocity distributions for laminar boundary layers (section 4.3.2)
	Excrescence-drag magnification factor (figure 6.1.13)
	Exponent in Smith's power-law airfoil velocity distributions (figure 7.4.12)
$\dot{m}$	Mass flux of a source or sink (equation 8.3.3)
n	Normal direction
	Propeller revolutions per unit time
$\mathbf{n}$	Unit normal vector (figure 3.3.6)
N	Nodal-point singularity (figure 5.2.6)
p	Pressure
P	Propeller shaft power (equation 6.1.20)
Pr	Prandtl number
q	Dynamic pressure = $1/2\rho_{ref}\ u_{ref}^2$
R	Ideal gas constant
	Reynolds number (any subscript indicates reference length used)

	Radius from airplane to a point on the ground (figure 8.5.3)

$\overline{R}$	Attachment-line Reynolds number parameter (equation 8.6.16)
R_a	Average of absolute value of roughness height
R_{crit}	Critical Reynolds number, at onset of instability (figure 4.4.3)
r	Radius
	Recovery factor (equation 4.6.4)
r_1	Radius to the maximum-velocity point in a trailing vortex core (figure 8.1.8)
r_2	Radius to the point of effectively zero vorticity in a vortex core (figure 8.1.8)
r_b	Radius of fuselage (figure 8.3.14)
r_c	Radius of vortex core (equation 8.3.6)
s	Arc length
	Riblet spacing
	Wing area
s_p	Propeller disc area
S	Entropy
	Saddle-point singularity (figure 5.2.6)
	Denotes integration over a surface (equation 6.1.1)
T	Temperature
	The Trefftz plane (figure 6.1.1)
	Thrust of a propeller (equation 6.1.18)
t	Time
t	Unit tangent vector
u	Cartesian x-velocity component
	Perturbation velocity in the x direction (figure 7.4.1 (a))
u_τ	Friction velocity $u_\tau = \sqrt{\tau_w/\rho}$
U_∞	Undisturbed freestream velocity in the x direction
v	Cartesian y-velocity component
	Perturbation velocity in the y direction (figure 7.4.1 (a))
V	Velocity vector
V	Velocity magnitude
	Volume
w	Cartesian z-velocity component
	Perturbation velocity in the z direction (equation 8.3.5)
W	Outer function in the law of the wake (equation 4.4.13)
x	Cartesian space coordinate
y	Cartesian space coordinate
z	Cartesian space coordinaten

Greek Symbols

α	Wavenumber in x direction (equation 4.4.1)
	Angle of attack
α_o	Angle of attack at zero total lift (equation 8.3.16)
β	Flow direction angle
	Laminar boundary-layer similarity parameter (figures 4.3.5 and 4.3.6)
	Turbulent boundary-layer similarity parameter (equation 4.3.8)
	Wavenumber in z direction (equation 4.4.1)
δ	Boundary-layer thickness
δ	Boundary-layer thickness
δ^*	Boundary-layer displacement thickness (equation 4.2.13)

δ^*_{loc} Local δ^* integral (equation 4.2.14)
ϕ Velocity potential (equation 3.10.1)
γ Ratio of specific heats, c_p/c_v
Γ Circulation
Γ_o Circulation of vortex core (equation 8.3.6)
η Dimensionless spanwise coordinate on a wing = 2y/b
η Propeller efficiency = thrust work out/shaft work in (equation 6.1.21)
η_i Propeller induced efficiency
κ Streamline curvature (figure 4.2.4)
Von Karman constant (equation 4.4.10)
Λ Wing sweep (figure 8.6.1)
λ Mixing length
μ Coefficient of shear viscosity
Propeller torque coefficient (equation 6.1.19)
μ_{eff} Effective viscosity, sum of viscous and turbulent (equation 6.1.15)
ν Kinematic viscosity, μ/ρ
π pi = 3.14159…
Π Constant in the law of the wake (equation 4.4.13)
θ Boundary-layer momentum thickness (equation 4.2.11)
Angular coordinate around circular cylinder (figure 5.1.3)
Flow angles entering and leaving a cascade (figure 7.4.23 (b))
Dihedral angle (equation 8.3.11)
ρ Density
σ Propeller power loading (equation 6.1.20)
τ Shear stress
Propeller thrust loading (equation 6.1.18)
ω Vorticity magnitude
Frequency (equation 4.4.1)
$\boldsymbol{\omega}$ Vorticity vector
ψ Transformed spanwise coordinate (equation 8.3.22)

Subscripts

1 In the boundary-layer x direction (equation 4.2.15)
Denotes conditions upstream of a cascade (figure 7.4.23 (b))
Denotes conditions upstream of the shock on a transonic airfoil (figure 7.4.31)
2 Denotes conditions downstream of a cascade (figure 7.4.23 (b))
Denotes conditions downstream of the shock on a transonic airfoil (figure 7.4.31)
3 In the boundary-layer z direction (equation 4.2.15)
b Of the boundary-layer coordinate system (figure 4.2.2)
c Pertaining to a vortex core (figure 8.3.3)
Cross-flow component (figure 4.1.7)
Airfoil chord
ch Chordwise (figures 4.3.11 and 4.3.12)
cut Pertaining to a cut through a wake (figure 6.1.3)
d Based on diameter
Drag per unit span
D Drag
e At the edge of the boundary layer
f Friction
i Incompressible
Induced, as applied to a propeller

j	Pertaining to a blowing jet (equation 4.5.1)
K	Kinematic (equation 4.6.8)
l	Lift per unit span
L	Based on length L
	Lift
local	Denoting the effective local freestream condition for an excrescence
m	Pitching moment per unit span
n	Connectivity of a 2D domain (equation 5.2.5)
	Direction normal to wake cut (equation 8.3.10)
o	Denotes conditions at the start of an airfoil pressure recovery (equation 7.4.1)
p	At constant pressure
	Propeller
ref	Reference
rms	Root-mean-square
s	Relative to streamwise direction at boundary-layer edge (figure 4.1.8)
sep	Denotes conditions at separation (discussion of figure 7.4.13)
sp	Spanwise (figures 4.3.11 and 4.3.12)
sw	From steamwise at boundary-layer edge to the wall (figure 4.1.8)
t	Turbulent (equation 3.7.5)
	Total (or stagnation) (equations 3.8.3–6)
T	Thermal (equation 4.6.2)
v	At constant volume
w	At the wall
x	Based on x
∞	At infinite distance, far field
	At infinite height from ground (figure 8.3.12)
⊥	Perpendicular
perp	Perpendicular to constant-percent-chord lines (figure 8.6.11)
‖	Parallel

Greek Subscripts

δ*	Based on displacement thickness
μ	Momentum, as in C_μ (equation 4.5.1)
θ	Based on momentum thickness
τ	Friction velocity, in $u_\tau = \sqrt{\tau_w/\rho}$

Superscripts

′	Fluctuating part
	Independent variable in integration
	Denotes a half singularity at a boundary of a surface (equation 5.2.5)
—	Time average
	Averaged along the length
∧	Nondimensional
*	Denotes conditions at Mach 1 (equations 3.11.4 and 3.11.5)
	Displacement thickness, when used with δ
+	Turbulent-boundary-layer wall variables (equations 4.4.3 and 4.4.4)
=	Tensor (equation 5.4.1)

Acronyms and Abbreviations

1D	One dimensional
2D	Two dimensional
3D	Three dimensional
BC	Boundary condition
BLC	Boundary-layer control
CFD	Computational fluid dynamics
CF	Cross-flow
CPU	Central processing unit
DES	Detached-eddy simulation
DNS	Direct numerical simulation
ESDU	Engineering Sciences Data Unit
GGNS	General geometry Navier-Stokes
HLFC	Hybrid laminar flow control
LES	Large-eddy simulation
LFC	Laminar flow control
LTA	Lighter than air
NACA	National Advisory Committee for Aeronautics
NASA	National Aeronautics and Space Administration
NLF	Natural laminar flow
NS	Navier-Stokes
ODE	Ordinary differential equation
ONERA	Office National d'Etude et Recherches Aérospatiales
PC	Personal computer
PDE	Partial differential equation
RABL	Reynolds-averaged boundary-layer equations
RANS	Reynolds-averaged Navier-Stokes equations
SA	Spalart-Allmaras
SBVG	Sub-boundary-layer vortex generator
SST	Shear Stress Transport
TKE	Turbulence kinetic energy
TS	Tollmien-Schlichting
URANS	Unsteady Reynolds-averaged Navier-Stokes
VG	Vortex generator
WINGOP	Wing Optimization

Chapter 1

Introduction to the Conceptual Landscape

The objective of this book is to promote a solid *physical understanding* of aerodynamics. In genera any understanding of physical phenomena requires conceptual models:

> *It seems that the human mind has first to construct forms independently before we can find them in things. Kepler's marvelous achievement is a particularly fine example of the truth that knowledge cannot spring from experience alone but only from the comparison of the inventions of the intellect with observed fact.*
>
> —Albert Einstein on Kepler's discovery that planetary orbits are ellips

Einstein wasn't an aerodynamicist, but the above quote applies as well to our field as to his. T understand the physical world in the modern scientific sense, or to make the kinds of quantitativ calculations needed in engineering practice, requires conceptual models. Even the mo comprehensive set of observations or experimental data is largely useless without a conceptu framework to hang it on.

In fluid mechanics and aerodynamics, I see the conceptual framework as consisting of four maj components:

1. Basic physical conservation laws expressed as equations and an understanding of the cause-and effect relationships those laws represent,

2. Phenomenological knowledge of flow patterns that occur in various situations,

3. Theoretical models based on simplifying the basic equations and/or assuming an idealize model for the structure of the flowfield, consistent with the phenomenology of particular flows and

4. Qualitative physical explanations of flow phenomena that ideally are consistent with the basi physics and make the physical cause-and-effect relationships clear at the flowfield level.

By way of introduction, let's take a brief look at what these components encompass, the kinds difficulties they entail, and how they relate to each other.

The fundamental *physical conservation laws* relevant to aerodynamic flows can be expressed in variety of ways, but are most often applied in the form of partial-differential equations that must b satisfied everywhere in the flowfield and that represent the local physics very accurately. By solvin these basic equations, we can in principle predict any flow of interest, though in practice we mu always accept some compromise in the physical accuracy of predictions for reasons we'll come understand in Chapter 3.

The equations themselves define local physical balances that the flow must obey, but they don predict what will happen in an overall flowfield unless we solve them, either by brute forc numerically or by introducing simplified models. There is a wide gulf in complexity between th relatively simple physical balances that the equations represent and the richness of the phenomen that typically show up in actual flows. The raw physical laws thus provide no direct predictions an little insight into actual flowfields. Solutions to the equations provide predictions, but they are n ~~always easy to obtain, and they are limited in the insight they can provide as well.~~ Even the mo accurate solution, while it can tell us *what* happens in a flow, usually provides us with litt understanding as to *how* it happens or *why*.

Phenomenological knowledge of what happens in various flow situations is a necessary ingredient we are to go beyond the limited understanding available from the raw physical laws and fro solutions to the equations. Here I am referring not just to descriptions of flowfields, but to th recognition of common flow patterns and the physical processes they represent. Th phenomenological component of our conceptual framework provides essential ingredients to o simplified theoretical models (component 3) and our qualitative physical explanations (component 4

Simplified theoretical models appeared early in the history of our discipline and still play a important role. Until fairly recently, solving the "full" equations for any but the simplest flo situations was simply not feasible. To make any progress at all in understanding and predicting th kinds of flow that are of interest in aerodynamics, the pioneers in our field had to develop an array different simplified theoretical models applicable to different idealized flow situations, general based on phenomenological knowledge of the flow structure. Though the levels of physical fidelity these models varied greatly, even well into the second half of the twentieth century they provided th only practical means for obtaining quantitative predictions. The simplified models not only broug computational tractability and accessible predictions but also provided valuable ways of "thinki about the problem," powerful mental shortcuts that enable us to make mental predictions of what wi happen, predictions that are not directly available from the basic physics. They also aid understandi to some extent, but not always in terms of direct physical cause and effect.

So the simplified theoretical models ease computation and provide some degree of insight, but th also have a downside: They involve varying levels of mathematical abstraction. The problem wi mathematical abstraction is that, although it can greatly simplify complicated phenomena and mal some global relationships clearer, it can also obscure some of the underlying physics. For exampl basic physical cause-and-effect relationships are often not clear at all from the abstracted models, a some outright misinterpretations of the mathematics have become widespread, as we'll see. Thus so diligence is required on our part to avoid misinterpretations and to keep the real physics clearly view, while taking advantage of the insights and shortcuts that the simplified models provide.

We've looked at the roles of formal theories (components 1 and 3) and flow phenomenolog (component 2), and it is clear that the combination, so far, falls short of providing us with completely satisfying physical understanding. Physical cause-and-effect at the local level is cle from the basic physics, but at the flowfield level it is not. Thus to be sure we really understand th physics at all levels, we should also seek *qualitative physical explanations* that make the cause-an effect relationships clear at the flowfield level. This is component 4 of my proposed framework.

Qualitative physical explanations, however, pose some surprisingly difficult problems of their ow We've already alluded to one of the main reasons such explanations might be difficult, and that is th wide gulf in complexity between the relatively simple physical balances that the raw physical la enforce at the local level and the richness of possible flow patterns at the global level. Another is th the basic equations define implicit relationships between flow variables, not one-way cause-and-effe relationships. Because of these difficulties, misconceptions have often arisen, and many of th physical explanations that have been put forward over the years have flaws ranging from subtle fatal. Explanations aimed at the layman are especially prone to this, but professionals in the field ha

also been responsible for errors. Given this history, we must all learn to be on the lookout for errors i
our ~~physical explanations. If this book helps you to become more vigilant, I'll consider it a success~~.

This completes our brief tour of the conceptual framework, with emphasis on the major difficulti inherent in the subject matter. My intention in this book is to devote more attention to addressin these difficulties than do the usual aerodynamics texts. Let's look briefly at some of the ways I hav tried to do this.

The theoretical parts of our framework (components 1 and 3) ultimately rely on mathematic formulations of one sort or another, which leads to something that, in my own experience at least, ha been a pedagogical problem. It is common in treatments of aerodynamic theory for much of th attention to be given to mathematical derivations, as was the case in much of the coursework I w exposed to in school. While it is not a bad thing to master the mathematical formulation, there is tendency for the meaning of things to get lost in the details. To avoid this pitfall, I have tried t encourage the reader to stand back from the mathematical details and understand “what it all mean in relation to the basic physics. As I see it, this starts with paying attention to the following:

1. Where a particular bit of theory fits in the overall body of physical theory, that is, what physica laws and/or ad hoc flow model it depends on; and

2. How it was derived from the physical laws, that is, the simplifying assumptions that wer made;

3. The resulting limitations on the range of applicability and the physical fidelity of the results and

4. The implications of the results, that is, what the results tell us about the behavior o aerodynamic flows in more general terms.

The brief tour of the physical underpinnings of fluid mechanics in Chapters 2 and 3 is an attempt set the stage for this kind of thinking.

How computational fluid dynamics (CFD) fits into this picture is an interesting issue. CFD mere provides tools for solving the equations of fluid motion; it does not change the conceptual landsca in any fundamental way. Still, it is so powerful that it has become indispensable to the practice aeronautical engineering. As important and ubiquitous as CFD has become, however, it is not on a pa with the older simplified theories in one significant respect: CFD is not really a *conceptual model* the same level; and a CFD solution is rightly viewed as just a *simulation* of a particular real flow, some level of fidelity that depends on the equations used and the numerical details. As such, a CF solution has some of the same limits to its usefulness as does an example of the real flow: In bo cases, you can examine the flowfield and see *what* happened, and, of course, a detailed examination a flowfield is much easier to carry out in CFD than in the real world. But in both CFD and real-wor flowfields, it is difficult to tell much about *why* something happened or what there is about it th might be applicable to other situations.

Before we proceed further, a bit of perspective is in order: While correct understanding is vital important, we mustn't overestimate what we can accomplish by applying it. As we'll see, the physic phenomena we deal with in aerodynamics are surprisingly complicated and difficult to pin down precisely as we would like, and it is wise to approach our task with some humility. We should expe that we will not be able to predict or even measure many things to a level of accuracy that would gi us complete confidence. The best we'll be able to do in most cases is to try to minimize our unease b applying the best understanding and the best methods we can bring to bear on the problem. And w can take some comfort in the fact that the aeronautical community, historically speaking, has bee

able to design and build some very successful aeronautical machinery in spite of the limitations on o
ability to quantify everything to our satisfaction.

Chapter 2

From Elementary Particles to Aerodynamic Flows

Step back for a moment to consider the really big picture and ponder how aerodynamics fits into tl whole body of modern physical theory. The tour I'm about to take you on will be superficial, but hope it will help to put some of the later discussions in perspective.

First, consider some of the qualitative features of the phenomena we commonly deal with aerodynamics. Even in flows around the simplest body shapes, there is a richness of possible glob flow patterns that can be daunting to anyone trying to understand them, and most flows have loc features that are staggeringly complex. There are complicated patterns in how the flow attaches itse to the surface of the body and separates from it (Figure 2.1a, 2.1b), and these patterns can be differe depending on whether you look at the actual time-dependent flow or the "mean" flow with the tin variations averaged out. Even in flows that are otherwise steady, the shear layers that form next to tl surface and in the wake are often unsteady (turbulent). This shear-layer turbulence contains flo structures that occur randomly in space and time but also display a surprising degree of organizatio over a wide range of length and time scales. Examples include vortex streets in wakes and the variou instability "waves," "spots," "eddies," "bursts," and "streaks" in boundary layers. Examples are show in Figure 2.1c–f, and many others can be found in Van Dyke (1982). Such features usually displa extreme sensitivity to initial conditions and boundary conditions, so that their apparent randomness real, for all practical purposes. The "butterfly effect" we've all read about doesn't just apply to tl weather; the details of a small eddy in the turbulent boundary layer on the wing of a 747 are just unpredictable.

Figure 2.1 Examples of complexity in fluid flows, from Van Dyke (1982). (a) Horseshoe vortices in laminar boundary layer ahead of a cylinder. Photo by S. Taneda, © SCIPRESS. Used with permission (b) Rankine ogive at angle of attack. Photo by Werle (1962), courtesy of ONERA. (c) Tollmien-Schlichting waves and spiral vortices on a spinning axisymmetric body, visualized by smoke. From Mueller, *et al*. (1981). Used with permission. (d) Emmons turbulent spot in a boundary layer transitioning from laminar to turbulent. From Cantwell, et al (1978). Used with permission of *Journa of Fluid Mechanics*. (e) Eddies of a turbulent boundary layer, as affected by pressure gradients. Top: Eddies stretched in a favorable pressure gradient. Bottom: Boundary layer thickens and separates in adverse pressure gradient. Photos by R. Falco from Head and Bandyopadhyay (1981). Used with permission of *Journal of Fluid Mechanics*. (f) Streaks in sublayer of a turbulent boundary layer. Fron Kline, et al (1967). Used with permission of *Journal of Fluid Mechanics*