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Arguing from the Real Physics

DOUG McLEAN

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Foreword

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

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

John J. Tracy
Chief Technology Officer
The Boeing Company
September 2012

Series Preface

The field of aerospace is wide ranging and multi-disciplinary, 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 and topical series of books aimed at engineering professionals, operators, users and allied professions such as commercial and legal executives in the aerospace industry, and also engineers in academia. The range of topics is intended to be wide ranging, covering design and development, manufacture, operation and support of aircraft as well as topics such as infrastructure operations and developments in research and technology. The intention is to provide a source of relevant information that will be of interest and benefit to all those people working in aerospace.

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

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

Peter Belobaba, Jonathan Cooper, Roy Langton and Allan Seabridge

Preface

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

A real understanding of aerodynamics must go beyond mastering the mathematical formalism of the theories and come to grips with the physical cause-and-effect relationships that the theories represent. In addition to the math, which applies most directly at the local level, intuitive physical interpretations and explanations are required if we are to understand what happens at the flowfield level. Developing this physical side of our understanding is surprisingly difficult, however. It requires navigating a conceptual landscape littered with potential pitfalls, and an acceptable path is to be found only through recognition and rejection of multiple faulty paths. It is really a process of argumentation, thus the "arguing" in the title. This kind of argumentation is underemphasized in other books, in which the path is often made to appear straighter and simpler than it really is. This book explores a broader swath of the conceptual landscape, including some of the false paths that have led to errors in 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 in wide circulation and of erroneous physical explanations that have found their way into our folklore. In any case where a misconception has been widely enough propagated, the "right" explanation would not be complete without the debunking of the "wrong" one. I have tried to do this kind of debunking wherever it seemed appropriate and have not hesitated to say so when I think something is wrong. This is part of what makes aerodynamics so much fun. It's one of those little perversities of human nature that coming up with a good explanation is much more satisfying when you know there are people out there who have got it wrong. But debunking bad explanations serves a pedagogical purpose as well, 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 more time on some topics than some will likely think necessary. I realize some parts of the discussion are 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 by the ever-advancing capabilities of computers. In the 1960s, we began to calculate practical numerical solutions to linear equations for inviscid flows in 3D. In the 1970s, it became economical to compute solutions to nonlinear equations for inviscid transonic flows

in 3D and to include viscous effects through boundary-layer theory and viscous/inviscid coupling. By the 1990s, we were routinely calculating solutions to the Reynolds-averaged Navier-Stokes (RANS) equations for full airplane configurations. These computational fluid dynamics (CFD) capabilities have revolutionized aerodynamics analysis and design and have made possible dramatic improvements in design technology. CFD is now such a vital part of our discipline that this book would not be complete if it did not address it in some way. While this is not a book about CFD methods or about how to use CFD, there are conceptual aspects of CFD that are relevant to our focus, and these are considered in chapter 10.

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

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

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

As we'll see in chapter 1, the *subject matter* of aerodynamics consists of physical principles, conceptual models, mathematical theories, and descriptions and physical explanations of flow phenomena. Some of this subject matter has direct practical applications, and some doesn't. We'll spend considerable time on some topics that have no apparent practical import, for example, physical explanations of things for which we have perfectly good quantitative theories and esoterica such as how lift is felt in the atmosphere at large. We'll

do these things because they provide general fluid-mechanics insight and because they serve to expand our appreciation of the *cognitive dimension* of the subject, the processes by which we *think about* aerodynamic phenomena and the practical problems that arise from them. They also help us to see how mistaken thinking can arise and how to avoid it. The medical profession in recent years has begun to pay more attention to the cognitive dimension of their discipline, studying how doctors think, in an effort to improve the accuracy of their diagnoses 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 a multitude of detailed flow phenomena. The subject is correspondingly multifaceted, with a rich web of interconnections among the phenomena themselves and the conceptual models that have been developed to represent them. Such a subject has a logical structure of course, but it is not well suited to exposition in a single linear narrative, and there is therefore no ideal solution to the problem of organizing it so that it flows completely naturally as a single string of words. The organization I have chosen is based not on the historical development or on a progression from "easy" concepts to "advanced," but on a general conceptual progression, from the basic physics, to the flow phenomena, and finally to the conceptual models. I have tried to organize the material so that it can be read straight through and understood without the need to skip forward. I have also tried to provide direct references whenever I think referring back to previous chapters would be helpful and to alert the 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 in chapter 1. Then we consider the basic *physics* as embodied in the NS equations in chapters 2 and 3. We turn to the phenomenological aspects of *general flows* in boundary layers and around bodies in chapters 4 and 5. We then enter the more specific realm of *aerodynamic forces* and their manifestations in flowfields to deal with drag in chapter 6 and lift generation, airfoils, and wings in chapters 7 and 8. All of this sets the stage for a bit of a regression into *theory*, with discussions of 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 a booklet with a collection of helpful ways of looking at aerodynamic phenomena and a catalog of common misconceptions and how to avoid them. As the project progressed, it became clear that effective explanations required more background than I had anticipated, and the book gradually grew more comprehensive. The first draft in something close to the final form was completed in late 2008 and was reviewed by several Boeing colleagues (acknowledged below). Their feedback was incorporated into a second draft that was used in a 20-week after-hours class for Boeing engineers in 2009. Feedback from class participants and others led to significant revisions for the final draft. As it turned out, the general argumentative approach I've taken to the subject extended to the writing 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, my wife, Theresa, who put up with the many, many weekends that I spent in front of our home computer. Then The Boeing Company, which allowed me to spend considerable company time on the project, Boeing editors, Andrea Jarvela, Lisa Fusch Krause, and Charlene Scammon, who turned my raw Word files and graphics into a presentable draft and helped me take that draft through several revisions, and Boeing graphics artist John Jolley, who redrew nearly half the graphics. Finally, the friends and colleagues without whose help

the book would have been much poorer. Mark Drela (MIT), Lian Ng, Ben Rider, Philippe Spalart, and Venkat Venkatakrishnan provided very detailed feedback and suggestions for improvement. Steve Allmaras and Mitch Murray made special CFD calculations just for the book. My former Boeing colleague Guenter Brune wrote the excellent 1983 Boeing report on flow topology that introduced me to the topic and served as the basis of much of Section 5.2.3. Another former Boeing colleague, Pete Sullivan, did the CFD calculations plotted in Section 6.1.5. And many others contributed feedback on various drafts of the manuscript: Anders Andersson, John D. Anderson (University of Maryland), Byram Bays-Muchmore, Bob Breidenthal (University of Washington), Julie Brightwell, Tad Calkins, Dave Caughey (Cornell University), Tony Craig, Jeffrey Crouch, Peg Curtin, Bruce Detert, Scott Eberhardt, Winfried Feifel, David Fritz, Arvel Gentry, Mark Goldhammer, Elisabeth Gren, Rob Hoffenberg, Paul Johnson, Wen-Huei Jou, T. J. Kao, Edward Kim, Alex Krynytsky, Brenda Kulfan, Louie LeGrand, Adam Malachowski, Adam Malone, Tom Matoi, Mark Maughmer (Penn State University), the late John McMasters, Kevin Mejia, Robin Melvin, Greg 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 (New York Maritime College), and Jong Yu.

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Doug McLean,
April 2012.

List of Symbols

Many of the symbols listed below have different meanings in different contexts, as indicated when multiple definitions are given. When an example of usage (a figure or equation) is listed, it is not 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)
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
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
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)
$\boldsymbol{\omega}$	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)
$\perp$	Perpendicular
perp	Perpendicular to constant-percent-chord lines (figure 8.6.11)
$\parallel$	Parallel

Greek Subscripts

$\delta*$	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
$\wedge$	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

1

Introduction to the Conceptual Landscape

The objective of this book is to promote a solid *physical understanding* of aerodynamics. In general, 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 ellipses

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

In fluid mechanics and aerodynamics, I see the conceptual framework as consisting of four major 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 idealized 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 basic 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 of difficulties they entail, and how they relate to each other.

Understanding Aerodynamics: Arguing from the Real Physics, First Edition. Doug McLean.

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

The equations themselves define local physical balances that the flow must obey, but they don't predict what will happen in an overall flowfield unless we solve them, either by brute force numerically or by introducing simplified models. There is a wide gulf in complexity between the relatively simple physical balances that the equations represent and the richness of the phenomena that typically show up in actual flows. The raw physical laws thus provide no direct predictions and little insight into actual flowfields. Solutions to the equations provide predictions, but they are not always easy to obtain, and they are limited in the insight they can provide as well. Even the most accurate solution, while it can tell us *what* happens in a flow, usually provides us with little understanding as to *how* it happens or *why.*

Phenomenological knowledge of what happens in various flow situations is a necessary ingredient if we are to go beyond the limited understanding available from the raw physical laws and from solutions to the equations. Here I am referring not just to descriptions of flowfields, but to the recognition of common flow patterns and the physical processes they represent. The phenomenological component of our conceptual framework provides essential ingredients to our 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 an important role. Until fairly recently, solving the "full" equations for any but the simplest flow situations was simply not feasible. To make any progress at all in understanding and predicting the kinds of flow that are of interest in aerodynamics, the pioneers in our field had to develop an array of different simplified theoretical models applicable to different idealized flow situations, generally based on phenomenological knowledge of the flow structure. Though the levels of physical fidelity of these models varied greatly, even well into the second half of the twentieth century they provided the only practical means for obtaining quantitative predictions. The simplified models not only brought computational tractability and accessible predictions but also provided valuable ways of "thinking about the problem," powerful mental shortcuts that enable us to make mental predictions of what will happen, predictions that are not directly available from the basic physics. They also aid understanding 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 they also have a downside: They involve varying levels of mathematical abstraction. The problem with mathematical abstraction is that, although it can greatly simplify complicated phenomena and make some global relationships clearer, it can also obscure some of the underlying physics. For example, basic physical cause-and-effect relationships are often not clear at all from the abstracted models, and some outright misinterpretations of the mathematics have become widespread, as we'll see. Thus some diligence is required on our part to avoid misinterpretations and to keep the real physics clearly in view, while taking advantage of the insights and shortcuts that the simplified models provide.