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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.

We've looked at the roles of formal theories (components 1 and 3) and flow phenomenology (component 2), and it is clear that the combination, so far, falls short of providing us with a completely satisfying physical understanding. Physical cause-and-effect at the local level is clear from the basic physics, but at the flowfield level it is not. Thus to be sure we really understand the physics at all levels, we should also seek *qualitative physical explanations* that make the cause-and-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 own. We've already alluded to one of the main reasons such explanations might be difficult, and that is the wide gulf in complexity between the relatively simple physical balances that the raw physical laws enforce at the local level and the richness of possible flow patterns at the global level. Another is that the basic equations define implicit relationships between flow variables, not one-way cause-and-effect relationships. Because of these difficulties, misconceptions have often arisen, and many of the physical explanations that have been put forward over the years have flaws ranging from subtle to fatal. Explanations aimed at the layman are especially prone to this, but professionals in the field have also been responsible for errors. Given this history, we must all learn to be on the lookout for errors in 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 difficulties inherent in the subject matter. My intention in this book is to devote more attention to addressing these difficulties than do the usual aerodynamics texts. Let's look briefly at some of the ways I have tried to do this.

The theoretical parts of our framework (components 1 and 3) ultimately rely on mathematical formulations of one sort or another, which leads to something that, in my own experience at least, has been a pedagogical problem. It is common in treatments of aerodynamic theory for much of the attention to be given to mathematical derivations, as was the case in much of the coursework I was exposed to in school. While it is not a bad thing to master the mathematical formulation, there is a tendency for the meaning of things to get lost in the details. To avoid this pitfall, I have tried to encourage the reader to stand back from the mathematical details and understand "what it all means" 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 physical 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 were 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 of aerodynamic flows in more general terms.

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

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

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