

CFD Validation Experiments: Toward a Broader Perspective

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1. Overview

In 1988, the following definition of a CFD validation experiment was proposed:[1]

“an experiment that is designed to provide detailed building block data for developing CFD codes. This objective requires that the data be taken in the form and detail consistent with CFD modelling requirements and that the accuracy and limitations of the experimental data be thoroughly understood and documented”

Much has been written on the subject since these early days and the supporting literature is now quite extensive (see, e.g., Refs. [2-4]). However, the term is often used synonymously with a specific type of wind tunnel test (or physical data gathering activity). This focus can have some rather unfortunate – albeit unintended – consequences. To illustrate, this paper will consider how the definition of a “CFD validation experiment” has evolved in recent years and will make a case for adopting a broader definition. The benefits to be accrued by so doing will be outlined and supported by appealing to the personal experience of both authors. Finally, by developing the concept of validation dialog [5], guidance is provided as to how a broader framework might be established to support – and link – a range of contemporary initiatives aimed at improving the predictive capabilities of CFD. A more detailed outline of the final paper’s content is provided below.

2. CFD Validation Experiments: What Are They?

Building on the approach used in Ref. [6], which focused on the topic of CFD validation, the evolution of the definition of a CFD validation experiment will be examined by comparing it against the meaning of the term experiment in the context of scientific method. Various categories of scientific experiment will be identified to illustrate the empirical connotations of the word, whether used as a noun (“*a scientific procedure performed to validate a hypothesis*”) or a verb (“*experimentation is used to test existing theories or new hypotheses in order to support or disprove them*”). Key stages in the development of the literature associated with CFD validation experiments will then be reviewed. Following this, a broader definition will be proposed.

1. Brief Historical Perspective

From as early as 1988, where CFD validation experiments were referred to as being “concepts”, the roles of different types of physical testing were envisaged, as illustrated in Figure 1.

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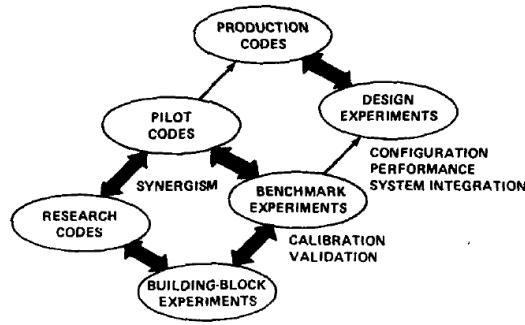


Figure 1: An early perspective on the roles of physical testing to support CFD validation (from Ref. [7]).

A decade later, guidelines for validation experiment methodology had been published [2] although the initial issue of the AIAA Guide for the Verification and Validation of CFD Simulations did not offer a definition for the term. Interestingly, one of the illustrations from this document, presented as Figure 2, refers specifically to a validation test (and experimental data).

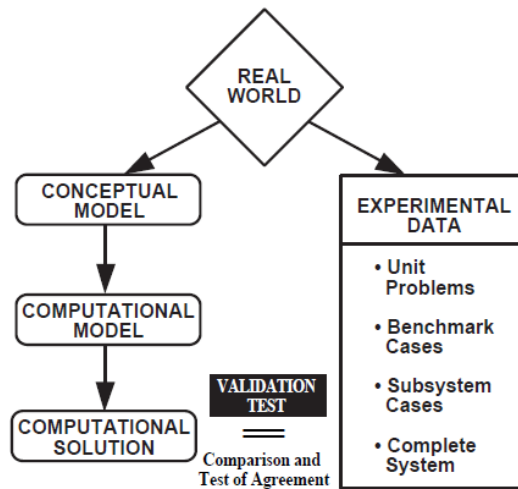


Figure 2: The validation process (from Ref. [2]).

Skipping forward two decades – following the conduct of several wind tunnel tests designed specifically for the purpose of providing physical data to support CFD validation (see, e.g., Ref. [8]) – the supporting literature had become quite extensive and the conceptual framework more sophisticated – the introduction of Strong Sense Benchmarks, for example, Ref. [9]. However, there appears to be no general consensus on an explicit definition of the term validation experiment. For instance, Ref. [4] states: “A validation experiment is conducted for the primary goal of determining the predictive capability of a mathematical model of a physical process,” whereas [9] states: “A validation experiment is a physical realization of a properly posed applied mathematics problem with initial conditions, boundary conditions, material properties, and external forces” and “Validation experiments are performed to generate data for assessing the accuracy of the mathematical model via simulation outcomes produced by the verified computational model”

The differences are subtle. However, both sources appear to consider a validation experiment synonymous with the (wind tunnel) test used to acquire the physical data to be used in subsequent validation assessments. Indeed, Ref. [9] compares a validation experiment with three other categories of “traditional experiment,” distinguished on the basis of their primary intent:

- To improve understanding of some physical process
- To construct, improve or determine parameters in mathematical models of moderately well-represented physical processes

- To determine the reliability, performance or safety of components, subsystems or complete systems

Emphasis is placed on explaining the differences in the manner of conduct of and the types and detail of data to be recorded during wind tunnel tests designed specifically to support CFD validation and other forms of wind tunnel test.

2. *Current Situation – and the need for a broader definition*

In view of the relative novelty of the requirement and the magnitude of the attendant costs involved, the current focus of the validation experiment literature is entirely understandable. However, by appearing to consider a validation experiment synonymous with the (wind tunnel) test used to acquire the physical data, is somewhat misleading. For instance, it fails to acknowledge the importance of the roles played by CFD in preparing for such wind tunnel tests or of the lessons that may be learned during its use for this purpose [10] – which may have a broader bearing than the wind tunnel test itself. It also fails to acknowledge the empirical nature of the processes associated with the term “experiment” in the wider scientific community.

For these and other reasons to be described in the paper, it is recommended that a broader definition of validation experiment be adopted, namely, *“the process from the point at which a flow phenomenon of interest is first identified, through to that at which the results of CFD predictions are compared with detailed physical measurements in controlled tests designed specifically for that purpose.”* The remainder of the paper will elaborate on the reasons for proposing broadening the definition in this way.

3. **CFD Validation Experiments: How Do They Affect Us?**

1. *Validation Dialog*

The conclusiveness of the outcomes of CFD validation assessments will depend on a number of factors, including the ways in which both wind tunnel models and wind tunnel test campaigns are designed. This may involve a series of preliminary CFD studies and wind tunnel entries. Such studies help inform decision making and identify priorities for more definitive wind tunnel test campaigns. For instance, given that the spatial and temporal resolution of physical measurements are likely to be more constrained than the data generated with CFD, deliberate and thoughtful pretest CFD studies will help prioritize measurement requirements. In view of the relative difficulty and expense associated with characterizing the flow in wind tunnel facilities, such preparatory activities should include simplified CFD-based sensitivity studies to address the potential impact of any anticipated deficiencies in the planned physical measurements.

It is vital that preliminary computational and wind tunnel-based studies are coordinated in a balanced and synergistic way to maximize mutual benefit. We refer to this synergy as a “validation dialog.” This type of collaborative effort is exemplified by the NASA Juncture Flow experiment [8]. Establishing an effective validation dialog not only accelerates the pace of learning with regard to CFD, but the iterative nature of performing the coordinated studies may also provide additional insights to the broader community [5].

By more directly acknowledging the importance of the roles played by preliminary computational and ground test studies, it is expected that this will encourage improved engagement with a broader range of stakeholders and wider recognition of the value of the outcomes of what might otherwise be considered studies of lesser importance. In turn, this is expected to encourage the adoption of more systematic approaches, where complex problems are more readily broken-down into smaller, more focused endeavors, whilst at the same time making such activities easier to fund.

The challenges posed by the detail with which physical data are required to support CFD validation are multifaceted. While the implications for instrumentation are reasonably well appreciated, the implication for the phenomena of interest are not so easily anticipated. Put another way, once phenomena of interest have been identified as candidate subjects for a validation experiment, the understanding of these phenomena may be subject to change as a result of the subsequent study. When viewed in this way, it may be seen that the pursuit of CFD validation places CFD and wind tunnel testing techniques, when combined, at the forefront of flow physics discovery.

2. *The Importance of Verification*

Another benefit to be expected from raising the profile of preliminary CFD studies is an increased awareness of the importance of CFD verification. As the standards demanded of CFD continue to rise, deficiencies in many aspects of the current verification practice – from code to solution verification – are becoming increasingly apparent [5,10]. An increased focus on (i) blind computations (conducted prior to wind tunnel testing) and (ii) understanding the sensitivity of the predicted solutions to various forms of numerical error, will surely lead to improvements in this crucial aspect of CFD usage.

Once again, there is an element of a virtuous circle in action here. Generally speaking, as engineers, we should understand (and be able to justify) the assumptions we are invoking [10]. Their active monitoring and review is central to CFD validation assessment – after all, we are not involved in a game of chance. However, it is interesting to consider whether the requirements for physical data would be different if one were intending to validate CFD codes solving forms of the Navier-Stokes equations or a code implementing a Lattice Boltzmann Method. The validation dialog that will ensue as a result of an improved, physics-based appreciation of the mathematical models being invoked, is likely to result in both improved wind tunnel test planning and better CFD user awareness [5,10].

3. A Proposed Conceptual Deconstruction

Having developed a rationale for proposing a wider definition of a CFD validation experiment, the final paper will also develop an outline framework by which it is proposed that the status of a validation experiment be monitored and assessed. This will involve:

- Identifying the key stages in a process lifecycle (from initial identification of a candidate flow phenomenon of interest, through to the completion of an initial comparison of the results predicted by blind CFD studies with the physical data acquired via definitive wind tunnel testing), and
- Developing measures by which the readiness of each lifecycle phase may be assessed (the availability of clear and achievable requirements, for instance)

4. Closing Remarks

The material presented in the paper will be rooted in the experience of both authors. It is hoped that a number of contemporary initiatives aimed at improving the predictive capabilities of CFD will be supported by its dissemination. Moreover, it is possible that it may even allow connections to be made in ways that are currently unforeseen. An example of one such unlikely scenario that has already been realized is the interest of the missile aerodynamics community in the development of the CRM-HL ecosystem. (Here, interest is focused on the formation and subsequent development of the nacelle chine vortices – the computational simulation of which shares many challenges with that associated with the flow generated by low aspect ratio wings on classical missile airframes [11].)

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