CFD Validation Experiments: Toward a Broader Perspective

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The current literature considers a CFD validation experiment synonymously with a particular type of wind tunnel test. By drawing on the experience of the authors, this paper makes a case for broadening the definition to include a more balanced and synergistic exploitation of computational and physical testing techniques. The concept of validation dialog is introduced that, together with technique verification, is considered a key enabler in the pursuit of an improved CFD predictive capability. An outline of a lifecycle for a CFD validation experiment is also proposed to consolidate the thinking. The result, it is reasoned, 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 to complex problems, such that they are more readily broken down into smaller, more focused endeavors, while at the same time making such activities easier to fund.

I. Introduction

Experiments are fundamental components of the scientific method, a popular term used to describe an empirical process that has developed to formalize the acquisition of knowledge. In this context, an experiment is the process conducted to support or refute a hypothesis. Hypotheses may take many forms and a variety of approaches have evolved to test them. Over time, various ways of categorizing experiments have also emerged to help distinguish between the different approaches taken – the distinction between field and laboratory experiments being a familiar example. Faced with a growing number of possibilities, it is only natural to ask: what, precisely, is a CFD validation experiment? Without delving into the philosophies of science or engineering, this paper addresses this question by appealing to the personal experience of both authors.

In Section II, we briefly review how the definition of a CFD validation experiment has evolved in recent years and make a case for adopting a broader definition. In Section III, we identify two factors we consider to be crucial to the success of their conduct. Further context is provided in Section IV by recounting salient features of specific activities in which we have been (and/or continue to be) involved. Drawing on this material, an outline framework for a CFD validation experiment lifecycle is proposed in Section V. Finally, some closing remarks are provided in Section VI.

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II. CFD Validation Experiments: What Are They?

In 1988, the following definition of a Computational Fluid Dynamics (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., [2-4]). Below, we identify key stages in the recent evolution of this definition, including some of the attendant – albeit unintended – consequences. This leads us to propose an alternative definition, which encourages a broader perspective of what CFD validation experiments can involve.

A. Brief Historical Review

At the time of the quote cited above, CFD validation experiments were referred to as "concepts." Although consensus on the details had still to emerge, different types of experiment were envisaged, depending on the context. Figure 1 provides an example of the thinking at the time. Here building-block, benchmark, and design experiments are identified and synergistic interactions with key stages in the development of production codes are highlighted.

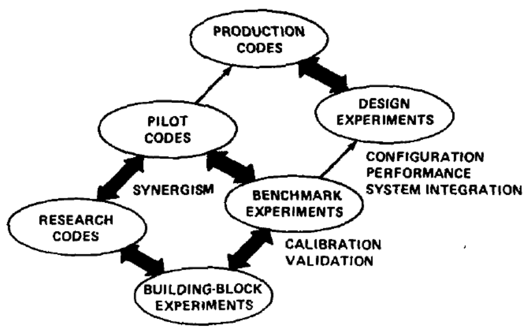

Figure 1: An early perspective on the roles of physical testing to support CFD validation (from [5]).

A decade later, guidelines for validation experiment methodology were published [2]. By this stage, the conceptual framework for CFD verification and validation had evolved beyond the notion of research codes, pilot codes, and production codes; in particular, clearer distinctions between code maturity and modelling assumptions had emerged. However, the initial issue of the AIAA Guide for the Verification and Validation of CFD Simulations did not offer an explicit definition of a CFD validation experiment. Interestingly, one of the illustrations from this document, presented as Figure 2, refers specifically to a validation test (together with a comparison and a test of agreement between a computational solution and experimental data).

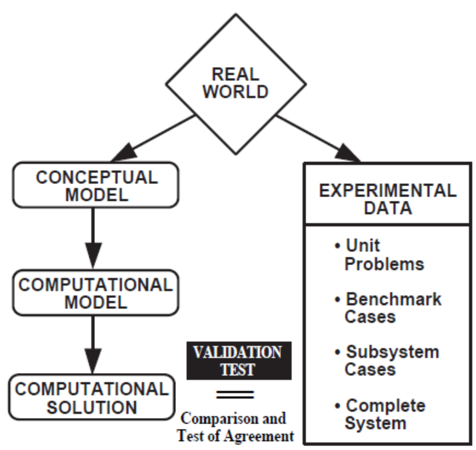

Figure 2: An early schematic of the CFD validation process (from [2]).

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., [6]), the supporting literature had become quite extensive and the conceptual framework more sophisticated (see, e.g., [7]). However, there appears to be no general consensus regarding an explicit definition of a CFD validation experiment. For instance, [7] states: "*A validation experiment is conducted for the primary goal of determining the predictive capability of a mathematical model of a physical process,*" whereas [4] 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, [7] compares a validation experiment with three other categories of "traditional experiment," distinguished on the basis of their primary intent, viz:

- To improve understanding of some physical process;
- To construct, improve or determine parameters in mathematical models of moderately well-represented physical processes; or
- To determine the reliability, performance or safety of components, subsystems or complete systems

Here, emphasis is placed on explaining the differences between validation and traditional experiments by their manner of conduct and the types and detail of data to be recorded during wind tunnel tests.

B. Current Situation – and The Need for a Broader Definition

In view of the relative novelty of the requirement and the potential magnitude of the attendant costs involved, the current focus of the CFD validation experiment literature is entirely understandable. However, by appearing to consider a validation experiment solely synonymous with the (wind tunnel) tests used to acquire physical data, the current literature can be somewhat misleading. For instance, it fails to acknowledge (i) 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 (which may have a broader bearing than the wind tunnel tests themselves) and (ii) the various forms of experimentation that may be required to prepare for the definitive wind tunnel tests, some of which might prove to be empirical in nature. Indeed, given the controls required to govern the conduct of the CFD computations feeding into assessments of CFD predictive capability, together with the difficulties that may be encountered in establishing verified model outputs, one is bound to ask: to which experiment should the term CFD validation experiment refer?

For these and other reasons outlined below, we recommend that a broader definition of a CFD validation experiment be adopted, namely:

> *"A CFD validation experiment is the process followed from the point at which physical phenomena of interest are first identified, through to that at which the results of CFD computations are compared with physical measurements in a manner that is designed specifically to assess CFD predictive capability."*

Here, the CFD validation experiment involves both wind tunnel testing and CFD. In other words, the "experiment" is not the physical test alone, but the entire process; the physical testing represents only a portion of the CFD validation experiment. This paper is not concerned with drawing precise distinctions between the use of the terms "experiment" and "test" when describing activities that contribute to the overall CFD validation experiment. For convenience, we will refer to those activities conducted in wind tunnels as "tests" and those undertaken via CFD as "studies." Nor are we concerned with defining what constitutes CFD validation, or describing how technology maturation might alter the ways in which CFD predictive capability should be assessed. Our primary concern is to draw attention to the scope of effort involved and the benefits to be gained by exploiting the synergies that exist between the various technologies and stakeholder interests.*

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* To illustrate how the objectives (or goals) of a CFD validation experiment might be framed in terms of a hypothesis, an example template for such a hypothesis might read: "The XYZ turbulence model, in conjunction with the Reynolds-averaged Navier-Stokes equations, is accurate to within abc% of predicting such-and-such quantities of interest." The goal of the CFD validation experiment would then be to either support or refute this statement. Consistent with any

III. Two Key Enablers

During the course of the authors' careers, we have found, independently, that a number of factors have played vital roles in improving the conclusiveness of the outcomes of validation experiments. Here, we outline two of them: validation dialog and technique verification.

A. Validation Dialog

As Figure 1 attests, the importance of physical testing to the pursuit of CFD validation was anticipated from the earliest days. Ensuring that computational and physical testing activities are undertaken in balanced and synergistic ways throughout has proved to be vital in improving the conclusiveness of the outcomes of validation experiments (although not necessarily in the manner implied by Figures 1 or 2). We refer to this synergy as validation dialog since (i) it involves the active participation of all stakeholders and (ii) it is most effective when informed by the computational and physical testing techniques speaking for themselves (via detailed scrutiny of systematically generated data). The latter attribute provides a powerful mechanism for identifying features that might otherwise go unnoticed or be misinterpreted, i.e., keeping activities "honest". It can also reduce reliance on heuristic judgement. Validation dialog generally serves to accelerate the pace of learning for all participants and enhance the benefit of each activity pursued.

While the benefits to be gained from an active validation dialog may be realized at any stage in the conduct of a validation experiment, they are not always anticipated. So conscious effort is required to maintain the validation dialog at all times. However, the benefits are most frequently and consistently realized during the design of wind tunnel test articles and wind tunnel test campaigns. This may involve a series of preliminary CFD studies and wind tunnel entries. Such activities help inform decision making, identify priorities for subsequent wind tunnel test campaigns and help provide justification for the attendant financial costs. For instance, given that the spatial and temporal resolutions of physical measurements are likely to be more constrained than the data generated with CFD, deliberate and thoughtful pretest CFD studies typically 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.

B. Technique Verification

A thorough understanding of the underlying principles and practicalities of both the computational and physical testing techniques being employed is essential to the successful conduct of a CFD validation experiment. While this might seem self-evident, there are a couple of implications that are worth drawing attention to:

1. It is not always clear how the practices employed in one area translate to another. Nor are the potential consequences of any attendant mismatches necessarily easily assessed. Some challenges are easier to anticipate than others. A case in point here is the establishment of reference conditions: the techniques used to impose, monitor and control these in CFD computations are typically very different to those employed in wind tunnel facilities, where the options available are usually more limited and often reliant on bespoke calibration data. However, not all such challenges are so easily identified: from the innocuous to the arcane, there are many potential reasons why differences can arise and pass unnoticed. Validation dialog can play an important role in identifying areas of difficulty in this regard and is crucial to determining how they are best addressed.

2. While the verification of both CFD and physical testing practices are of similar importance, in the context of the current paper, it is fair to elaborate some of the implications associated with CFD verification. We focus on two here:

   (i) Detailed attention must be paid to all aspects of CFD verification (from code verification through to solution verification) to ensure that the computational models are being solved correctly (i.e., without coding errors) and to a quantified numerical accuracy. Without this, there is increased risk of misinterpreting and incorrectly attributing or quantifying the reasons for, or magnitude of, any residual disparity in the computed and measured data.

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properly executed experiment within the context of the scientific method, the conclusions reached should be repeatable using any CFD code or wind tunnel.

(ii) The nature of the physical measurements required from the wind tunnel will be determined by decisions made concerning how, precisely, CFD predictive capability is to be assessed. These will include decisions regarding CFD modelling assumptions (for example, the need for Reynolds stresses for the assessment of turbulence modeling characteristics) as well as the integrated consequences of these assumptions (for example, the need to measure lift or drag coefficient). Further elaboration on the subject of the precise physical data requirements is beyond the scope of this paper. To illustrate the point, however, it is interesting to postulate the question as to whether the measurement requirements would be different if the overarching intent was to validate CFD codes implementing a Lattice-Boltzmann method versus those solving the Navier-Stokes equations. (Hopefully, the reader will, by now, be attuned to the importance of applying validation dialog to help address such questions.)

IV. Relevant Examples Drawn From Personal Experience

To supplement the material presented above, we provide some additional context in the form of succinct accounts of the salient features of specific activities in which we either have been, or are still, engaged.

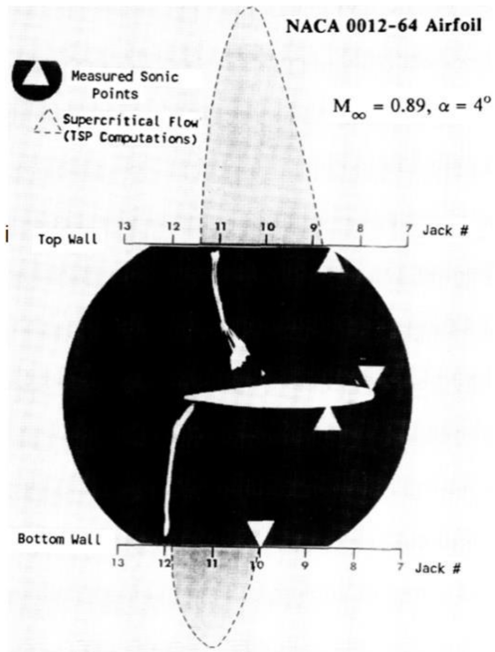
A. Past Experience: Adaptive Flexible-Walled Wind Tunnel Testing

Even in their simplest form, adaptive wall wind tunnel testing techniques, when implemented in flexible-walled test sections, have provided powerful demonstrations of what can be achieved by invoking validation dialog [8]. For instance, two-dimensional techniques, in which the roof and floor of the test section are profiled in single curvature, have proved effective in eliminating (within practical limits) wall interference from the flow about the test article. This is accomplished, iteratively, by driving a surface within each flexible wall boundary layer to follow streamlines in the equivalent free-air flow. This situation is judged to have occurred when the distribution of static pressure measured along the centerlines of each flexible wall matches that computed in the semi-infinite two-dimensional "imaginary" flow, bounded by the measured wall contour and the desired freestream boundary conditions.

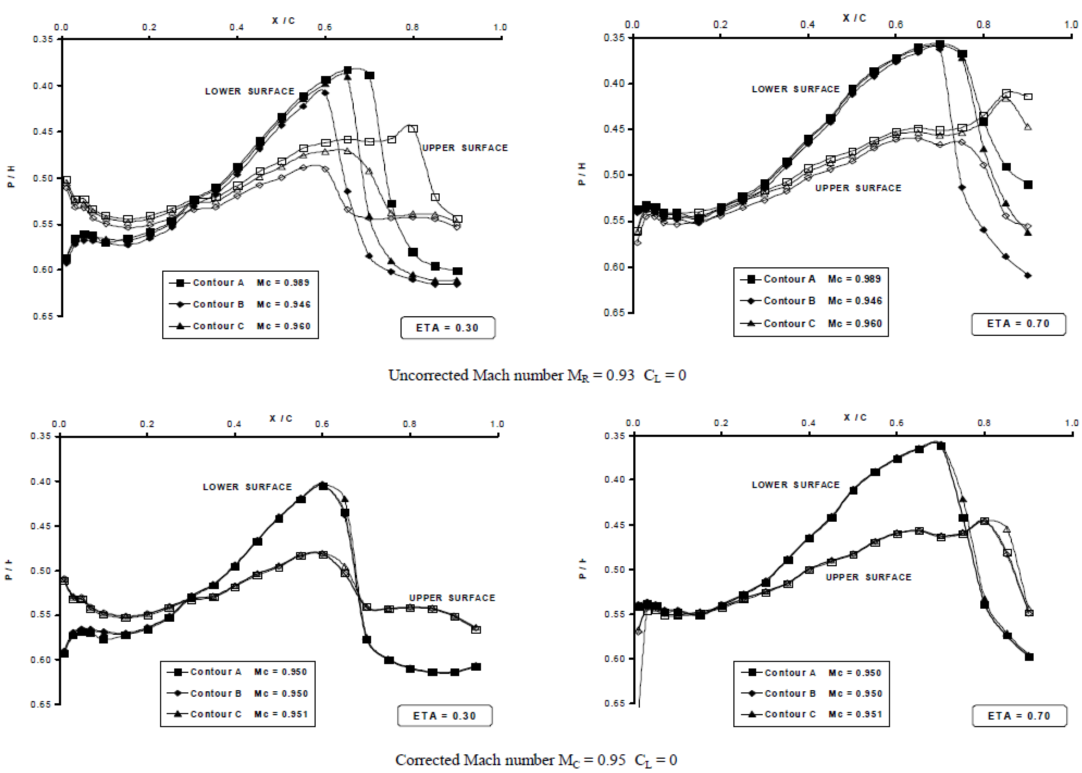
In this approach to wall adaptation, known as interface matching, validation dialog actively occurs at the interfaces between the physical and computed flows. Aside from allowing wind tunnel testing to proceed in circumstances where it was previously thought not possible (see, e.g., Figure 3[*]), research conducted in 1980s and 1990s identified a number of other benefits of validation dialog – not all of which were fully anticipated beforehand. An example was the ability to infer information about the data gathered on either side of both interfaces from the profiles of the resulting streamlines. If the objective was to calibrate the flow in an empty test section, various potential deficiencies could be diagnosed. For instance, any lack of symmetry in the top and bottom wall contours might indicate flow angularity in the test section, while localized undulations in individual wall contours might draw attention to errors in static pressure or wall position measurements.

Although activities were linked with the early development of adaptive mesh refinement schemes in the UK [11] and proposals were made for exploiting adaptive flexible-walled technology for other purposes (including CFD validation) [12], the primary motivation for the principal author's involvement was to improve wind tunnel testing capabilities. Looking back at the documentation produced at the time, the material pertaining to CFD is showing its age. (Recall that this is a similar vintage to Figure 1 and that the principal CFD code being used was solving the Transonic Small Perturbation (TSP) equations.) Nevertheless, many of the principles remain sound: who is to tell whether there may yet be a resurgence of interest in exploiting the control afforded by flexible wall adaptation in support of CFD validation.

[*] Figure 3a depicts a situation in which the test section flow is fully choked above and below the test article, but for which measured airfoil aerodynamic characteristics of a very high quality were obtained; Figure 3b shows how profiling the top and bottom flexible walls of an industrial wind tunnel (i) elevates the Mach number at which testing can proceed and (ii) improves the conclusiveness of assessments of wall interference corrections. Similar results were obtained for full-span and half-span test articles [10].



(a) Montage of a schlieren photograph of the flow about an NACA 0012-64 airfoil and the regions of supercritical flow computed above and below a "self-streamlined" test section (flow from right to left; from [9]).



(b) Pressure distributions obtained at two spanwise stations on a semispan model with a large mean aerodynamic chord, showing the effects of (i) changing the top and bottom wall contours and (ii) applying a correction for wall-induced blockage (from [10]).

Figure 3: Examples of the benefits gained by applying validation dialog to improve physical testing capabilities in adaptive flexible-walled wind tunnels.

B. Ongoing Experience: NASA Juncture Flow

The NASA Juncture Flow (JF) project was far more than a wind tunnel test campaign; it was a process that evolved over many years. A detailed description therefore serves to exemplify our expanded definition of a CFD validation experiment. Here, for clarity, it is simplified to some degree and listed as a series of steps. Further details may be found in [6]. A photograph of the JF configuration is shown in Figure 4.

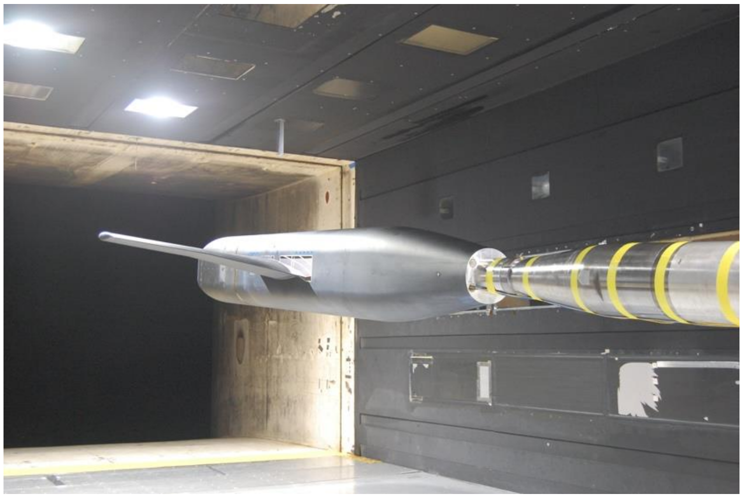


Figure 4: The NASA Juncture Flow test article installed in the NASA 14- by 22-Foot Subsonic Tunnel.

1. Identification of flow phenomena of interest.

The AIAA Drag Prediction Workshops (DPW) served as the genesis of the JF effort. A series of six DPWs were held from 2001 through 2016. There are many references available, particularly as AIAA papers. Here, we cite only a few [13-15]. Very early in the DPW effort, the flow phenomenon of wing-body corner separation near the wing trailing edge was identified to be problematic for CFD. The (mostly Reynolds-averaged Navier-Stokes, RANS) CFD results in this region tended to exhibit extraordinarily large variations in their prediction of corner separation size and extent, which were dependent on code, turbulence model, grid, and other numerical factors. This inconsistent behavior made validation assessments for the complete configuration very difficult.

2. Determination of a need for a validation experiment.

There was some indication regarding the approximate size of the corner separation from the wind tunnel data being used in the DPWs. However, this evidence was only qualitative in nature (surface oil flow) and there were no flowfield details. Therefore, CFD and turbulence modeling experts knew only vaguely what the mathematical model needed to capture. The idea of a wind tunnel test was conceived that would yield detailed juncture flowfield details over a wing-body configuration.

3. Project team instigation.

The JF team was formally initiated at NASA in the summer of 2014 (however, it is important to note that some preliminary CFD studies took place even earlier). There were champions behind this effort who were influential in setting the project in motion. The concept of making this project primarily focused on the goal of CFD validation (rather than on flow physics discovery, for example) was held from the very start. The reason for this priority was the fact that so many prior efforts to learn the reasons why CFD results disagreed with wind tunnel data were indeterminate. There were almost always significant uncertainties in knowing how to match the same conditions between CFD and wind tunnel test (comparing “apples with apples,” so to speak). This level of uncertainty typically overwhelmed the effects of CFD modeling or numerics. The original team goal was to design a nonlifting wing/body configuration that was symmetric both top-bottom and left-right, for the purpose of uncertainty quantification (UQ) experimentation. The configuration was to be designed for transonic flow, with the freestream Mach number to be used to achieve a range of attached flow through separated flow in the wing-body juncture region. Ultimately, this initial design effort was unsuccessful (see steps 4 and 5, below). An important aspect of step 3 was securing the commitment of time, people, and money at the project level to the effort. The NASA leadership was fully committed to the JF project, and considerable time was spent getting buy-in from all parties concerned.

4. Initiation of Validation Dialog.

The JF team was made up of wind tunnel, metrology and CFD specialists. The team also included a verification and validation (V&V) and UQ expert, who helped lead the drafting of a team goals document and subsequently continued to help the team remain focused on those goals. The initial stages of work were primarily CFD design and analysis studies to try to come up with a test article shape that would meet the original project goals. At the same time, the wind tunnel and metrology practitioners began to conceive of the methods and requirements for measuring the flowfield very near to the separated corner region as accurately as possible. During the initial validation dialog, other independent related work (including that of Gand et al. [16] and Bordji et al. [17]) were recognized and analyzed. Experts were brought in to give seminars and talk to the team. As a result of this initial work, the original ideas for the wind tunnel test had to be abandoned for various reasons [6]. The team ended up with the concept of a subsonic flow wing-body test, with separation size controlled by the test article angle of incidence.

5. Preliminary CFD and risk reduction wind tunnel investigations.

A variety of wing shapes were designed and explored using CFD. Both existing wing shapes as well as newly designed shapes (using inverse design methodologies) were tried, but due to CFD uncertainties it was finally decided to downselect the final shape(s) based on scaled-down risk-reduction testing experiments in several smaller wind tunnels. These risk-reduction tests relied on surface oil flow to guide in the determination of the best wing shape(s) to choose [18]. As a result of the tests, the following conclusions resulted: (1) none of the tested wing shapes yielded the desired characteristics of providing a full range of both attached and separated flow; (2) one wing shape was selected based on its reasonably large separation size, allowing for measurements both upstream and within the separated region; (3) another secondary wing shape was selected because it yielded both attached flow and incipient separation; (4) the need for a sting-mounted full-span (rather than wall-mounted semispan) test was confirmed. During this time period, the method for making flowfield measurements using Laser Doppler Velocimetry (LDV) through windows in the side of the fuselage continued to be developed and honed in a laboratory setting. This stage of the effort also included a considerable amount of back and forth between the measurement and CFD specialists regarding what and where measurements were eventually needed. Some consideration was given to how close the measurements needed to be to the junction walls, but in the end the specifications were defined somewhat loosely: "as close to the walls as possible (at least within a y+ of 100)." This looseness was justified by the belief that any flowfield measurements near the juncture region would be helpful, given the dearth of such data in the existing literature. The importance of verification in the CFD codes was well-known to the members of the team, so two independent codes were always employed throughout the JF effort, and the turbulence model implementations were verified using the NASA Turbulence Modeling Resource website [19]. Some attempts were made to measure the incoming flowfield characteristics – both empty as well as with a test article installed – in the wind tunnel where the final measurements were to be made. These measurement efforts did not provide the flow angularity details with sufficient confidence, but they did confirm total pressure inflow characteristics of the tunnel.

6. Wind tunnel tests.

The wind tunnel tests used the primary wing that provided a healthy separation zone. Although the tests were focused, structured, and well-planned, some leeway was allowed regarding measurement locations, and the validation dialog continued even during this stage. Three phases of wind tunnel testing were planned over the course of several years. Phase 1 gathered data to be used for initial CFD validation [20]. This validation was conducted not only by the team using its RANS CFD codes, but also by other external members of the CFD community, at a sequence of two AIAA special sessions (AIAA SciTech 2020 and AIAA Aviation 2020). For these special sessions, both RANS and non-RANS CFD codes were employed. The phase 2 wind tunnel test was conducted on the same configuration. It had many purposes, including providing more conditions and measurement locations, as well as answering some questions raised during the phase 1 test and subsequent CFD validation efforts. The exploration and development of Particle Image Velocimetry (PIV) capability for this configuration (which could be compared with the LDV measurements, then serve as a capability tool in future tests in NASA's major wind tunnels) was also a goal.

7. CFD validation and improvement.

The CFD validation focused on parametric studies, including assessments of the influence of wind tunnel walls. The major efforts in the wind tunnel to measure boundary conditions and tunnel flow characteristic helped considerably with this assessment. All of this allowed for more definitive conclusions to be drawn regarding the influence of turbulence modeling on the corner flow separation characteristics. As a result of the phase 1 test and subsequent CFD validation exercises, a subset of the team developed a turbulence model enhancement [21]. This enhancement not only improved CFD results for the JF configuration, it also improved results for an independent supersonic corner flow configuration. This work represented a major achievement: a wind tunnel test targeted at CFD validation quickly and directly yielded an improved CFD capability that helps not only for the specific JF flow, but also appears to have wider applicability. (Additional CFD studies are still ongoing.)

8. Follow-up efforts and resolution.

Many of the non-RANS methods used for the JF configuration in the AIAA special sessions encountered challenges. CFD efforts are continuing in those areas. Also, despite the improvements mentioned above, RANS CFD still disagrees with wind tunnel measurements in many respects, particularly downstream of separation. So additional turbulence model improvements are still required. A final phase 3 JF test is planned using the secondary wing. This test will focus on attached flow and incipient separation, providing a new set of data for additional juncture flow validation exercises. In particular, the improved RANS turbulence model developed in step 7 can be applied blind to the new configuration, then its results compared to the wind tunnel data after the phase 3 test.

C. Emerging Experience: CRM-HL and OTC1

Both authors are currently engaged, independently, in activities directed at understanding why difficulties are being encountered using CFD to predict flows of contemporary interest. These are concerned with the prediction of (i) the flow about high aspect ratio transport aircraft configurations in high-lift configurations and (ii) the roll stability of certain types of missile airframe configurations at particular flow conditions. The former challenge is centered around the Common Research Model for High Lift (CRM-HL), the latter around MBDA's Open Test Case 1 (OTC1). Further details of the challenges being faced may be found in [22] and [23,24], respectively.

It seems likely that both activities will require dedicated CFD validation experiments to progress. However, the details as to how these should be undertaken are still being established. In both cases, the flows involved are complex, involving interactions of multiple flow phenomena. In addition, anticipating the potential enormity of the tasks involved, both endeavors are being pursued collaboratively. The magnitude of their perceived importance may be judged from the scale of the activities being planned and the number of stakeholders who have either shown interest in, or are already committed to, participating.

For the CRM-HL, attention is currently focused on its ecosystem [22]. Initiated by NASA and Boeing, this is now an international initiative, involving partners from 4 continents, with interest seemingly growing all the time. While the objectives for establishing the CRM-HL ecosystem are broader than merely improving the predictive capability of CFD (for instance, improvements in wind tunnel testing techniques are also being sought), this is a main area of focus. To this end, the venture may become a very large, internationally shared, CFD validation experiment (or series thereof).

CFD validation utilizing the open CRM-HL geometry will be realized in part through public efforts such as the AIAA CFD High-Lift Prediction Workshops (HLPW). HLPW-4 is scheduled to take place in June 2021, in association with AIAA Aviation. The approach being taken in organizing this workshop differs from that of its predecessors in several regards. In the context of this paper, the most immediately relevant is the formation of Technology Focus Groups (TFGs). These function as self-organizing teams, each assembled from participants with active interests in geometry and mesh generation, flow solver development and CFD use. Six TFGs have been formed: (1) Geometry Modeling and Preparation for Meshing, (2) Fixed Grid RANS, (3) Mesh Adaptation for RANS, (4) High-Order Discretization, (5) Hybrid RANS/Large Eddy Simulation (LES), and (6) Wall-Modeled LES and Lattice-Boltzmann. Each TFG has its own goals, expressed through key questions that it is trying to answer. It is hoped that this multipronged, collaborative approach will help accelerate learning in a variety of areas pertinent to CFD V&V.

At this stage, this grand CFD validation experiment is still in its infancy, with validation dialog and technique verification activities just beginning to take place. It is envisaged that these will inform the way in which the work will develop in the future, providing justification for simplifying the flows being studied and/or investigating them in further detail, as appropriate. Synergies with other areas of application – including the missile test case referred to above – may also become clearer. By pursuing a systematic and collaborative approach, it is hoped that the various types of CFD models and methods can be improved and/or matured in their ability to predict high-lift or missile airframe flowfields reliably and accurately. Progress in this area will help advance the realization of Certification by Analysis (CbA) [25].

V. A CFD Validation Experiment Lifecycle

Drawing from the experience outlined above, we now provide an outline of what we believe to be the key aspects in the conduct of a CFD validation experiment. In view of the scope and variety of scenarios that may be encountered, not to mention the ingenuity required of the participants to navigate their way through what will often be uncharted territory, the material is neither intended to be comprehensive nor considered to be definitive. Rather, our intent is to stimulate discussion and seek community feedback on the topics raised, with a view toward supporting more systematic and formalized approaches to the task of improving the predictive capabilities of CFD and introducing it more routinely into increasingly complex situations including, for instance, Certification by Analysis.

A top-level schematic overview of the activities that comprise a CFD validation experiment is presented as Figure 5. We consider the overall lifecycle to be split into four sequential phases: Initiation, Design, Implementation and Analysis. Each of these is terminated by an output: Outline Requirement, Detailed Specification, Data and Document, respectively. It is primarily the existence (or maturity) of these outputs that determines the phase at which the participants are operating during the conduct of a CFD validation experiment.

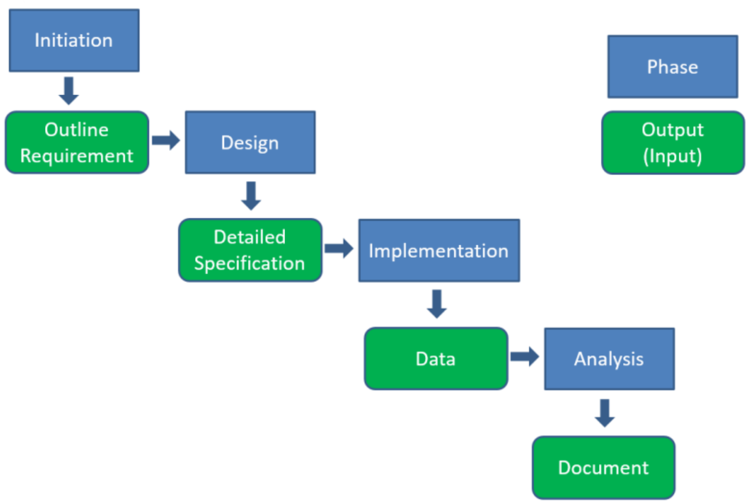


Figure 5: Simplified Schematic Overview of the Lifecycle of a CFD Validation Experiment.

Rather than contriving to propose a detailed set of metrics by which progress (or "readiness") may be judged within each phase, salient features of each of the phases are outlined below. As will become apparent, depending on what precisely is being validated, not all phases will be required all of the time. The topics identified by the red ellipses in the figures below are only intended to convey a general impression of the activities that may be undertaken. Similarly, the arrows in the figures are merely indicative of a notional sequencing of events within a particular phase.

A. Initiation

A simplified schematic overview of the activities that comprise the Initiation Phase of a CFD validation experiment is presented as Figure 6. The process starts with the originating motivation, which may be associated with particular phenomena of interest. Then, the Initiation Phase consists of a series of iterative stages. These include: confirmation, refinement, and scoping. Confirmation involves verifying, for example, that CFD is indeed unable to predict the phenomena of interest because of modeling errors, and not because of discretization errors or lack of verification. These steps may result in a reformulation of the task/problem. For example, the problem may need to be simplified in order to study it better.

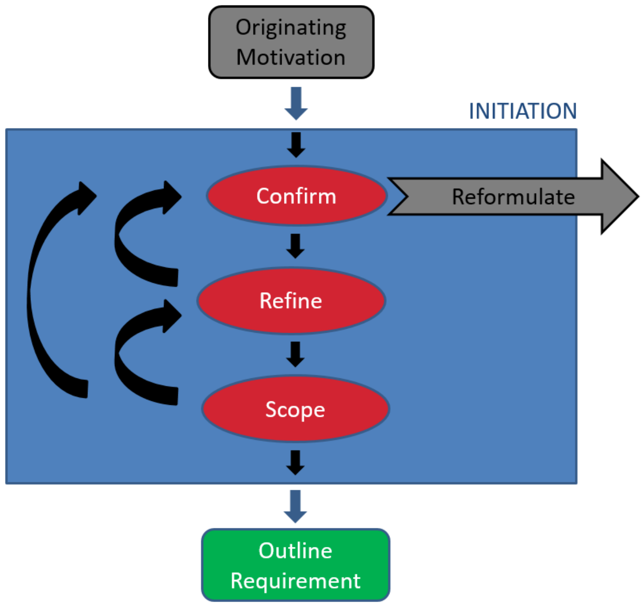


Figure 6: Simplified Schematic Overview of the Initiation Phase of a CFD Validation Experiment.

There are many potential stimuli for initiating a CFD validation experiment. Motivations may originate in the objectives of fundamental or academic research – the desire to assess the predictive capabilities of a new computational model, for instance – or derive from unexplained observations made during coordinated multifidelity, multiplatform and/or multipartner CFD studies in specific areas of CFD application – as per DPW and the JF effort. Indeed, it may be that the point of entry into the lifecycle is not clear-cut or that it may not be formally recognized until later on. Put another way, the studies involved may not initially be conceived as being part of a CFD validation experiment. This may be the case with both CRM-HL and OTC1. (In both of these examples, while unexplained deficiencies in CFD predictions have been identified, their precise causes are not currently well understood and the complexities of the associated flowfields will probably need simplifying in some way before they can be subjected to detailed, systematic study.)

In this sense, the Initiation Phase is the most nebulous of the four. Its principal objective is to clarify the requirements to the point at which (i) it is clear that further validation efforts are indeed required (i.e., that the difficulties being encountered are not primarily associated with lack of verification) and (ii) the requirements have been refined to the point at which a case may be made for formally establishing a validation dialog.

Activity during this phase is likely to be predominantly computational modelling-focused: physical testing may be undertaken, but it is likely to be relatively minor (in terms of the novelty of its configuration or conduct) and/or ad-hoc in nature. Among the likely priorities for attention will be the refinement of the scope of any subsequent activity (as alluded to above for CRM-HL and OTC1). This is likely to be iterative and, in view of the potential complexity and scale of commitment required to progress further, may even involve consolidation with other complimentary (but separately initiated) endeavors.

In order to prevent the venture from being parked, the outputs (outline requirements) must be sufficiently compelling to secure wider commitment: beyond this point, active validation dialog will be crucial for success. While a dedicated team may or may not be in evidence during the Initiation Phase, it will definitely be required during the Design Phase, with expertise in and access to facilities to support both numerical and physical experimentation, to be established. An outline plan of initial activity may also be required to secure the necessary resource and financial support.

B. Design

A simplified schematic overview of the activities that comprise the Design Phase of a CFD validation experiment is presented as Figure 7. Here, the Design Phase involves iteratively conceptualizing, prototyping, and proving, with the goal of producing a detailed specification for the Implementation Phase. Again, if the original problem is too broad or complex, this process may result in a splitting/spawning of others.

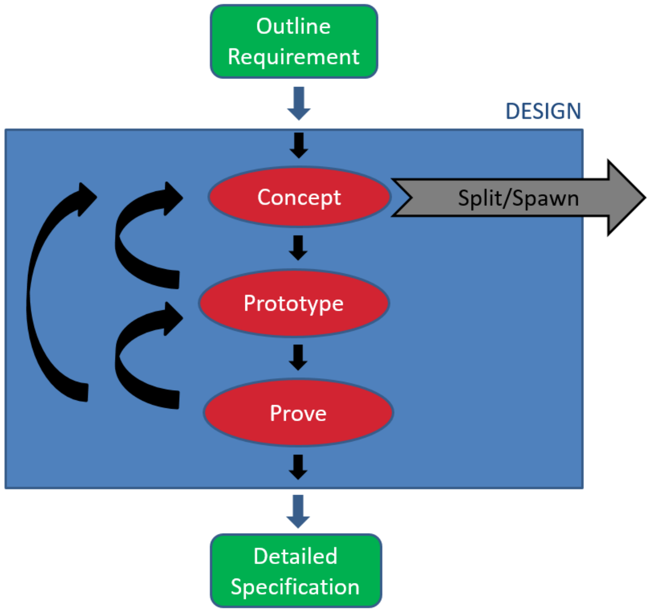


Figure 7: Simplified Schematic Overview of the Design Phase of a CFD Validation Experiment.

Like its predecessor, the Design Phase is likely to be iterative in nature. It may also involve extensive computational and physical experimentation in order to achieve its primary goal: to develop a detailed specification of the requirements for (computational and physical measurement) data to be gathered in support of the targeted assessment of CFD predictive capability. This specification should include a description of how the comparative assessment between CFD and measurements is to be conducted. It should also include explanation as to how uncertainty is to be estimated, and definitions of all relevant quantities of interest should be provided.

A key aspect of this phase is the development of a specification of a physical testing arrangement that will allow the phenomena of interest to be reproduced and characterized in the detail (and to the accuracy) required. This may involve a series of "conceptualize – prototype – refine (prioritize)" cycles in order to address the following questions: (i) which phenomena must be generated in order to facilitate the desired assessment of predictive capability? and (ii) how may they be generated in practice at the requisite scale?

The irony of not being able to use CFD to predict phenomena of interest with confidence should not be forgotten. (Recall the JF experience regarding test article design, summarized in Section IV.B, above.) However, while extensive physical testing may be required to establish a viable test arrangement, this is not to say that CFD cannot play a vital role. Indeed, systematic computational studies will likely be invaluable in supporting various aspects of decision making. A case in point is establishing the requirements for spatial resolution and accuracy for the physical measurements to be acquired.

In view of the detail and precision that may be required, this stage may also involve dedicated physical experimentation to establish (or stretch) the state-of-the-art regarding instrumentation and data processing techniques. Novel procedures for conducting the tests themselves may also need to be established in support of improved facility characterization and uncertainty quantification. Regardless of the success of the outcomes of such tests when assessed in the context of the Design Phase objectives, these types of physical experimentation may have value in their own right in the eyes of other stakeholders – metrologists and supporting hardware (or software) suppliers, for instance. A recognition that not all stakeholders will be driven purely by CFD validation goals may help secure the financial interest required to support the Design Phase, which, as JF experience shows, may last years rather than weeks or months.

Instrumentation-related decisions may have a profound influence on the viability of the overall physical test arrangement. Thus, the Design Phase may be quite dynamic, with supporting technology potentially being developed more or less in situ, and various options available for realizing the (refined) goals – although maybe not all of them at once. The importance of the roles to be played by validation dialog in supporting decision making during this phase cannot be overstated. Throughout, the validation dialog would be informed by a detailed understanding of the practicalities underlying both the computational and physical technologies involved. Consequently, the output – a detailed specification of the requirements for computations and physical testing – should reflect this understanding by clearly delineating how the requirements address the (revised) overarching goals of the validation experiment assessment. The specification should include all quantities to be computed and measured in the Design Phase and explain the basis by which comparisons will be made in the Analysis Phase.

As a final observation, it should be noted that it is not only the physical testing procedures that are being designed during this phase of the lifecycle: the computations to be used in the predictive assessment should also be planned. An important aspect of this is associated with their verification. For instance, any code verification activities that were not addressed during the Initiation Phase will need to be addressed. Without these, it will not be possible to develop a balanced specification for the data to be gathered in support of the predictive assessment. While definitive solution verification should take place during the Implementation Phase, assessment of its likely outcomes should be anticipated during the Design Phase. Otherwise, it will be difficult to develop a costed plan or avoid unexpected reliance on heuristic judgement, which may, unforeseeably, devalue the assessment. Systematic CFD studies should also be undertaken in order to determine both the scope and nature of the computations (and physical measurements) required to support the predictive assessment. Topics to be addressed might include the manner of characterizing (i) the test article's aeroelastic deformation, and (ii) the influence of wind tunnel walls and the constraints imposed further upstream and downstream of the test section, for instance. Aside from guiding the preparation of the CFD-related aspects of the requirement specification, such studies may also have a bearing on the physical measurement requirements and even the design of the physical test hardware.

C. Implementation

A simplified schematic overview of the activities that comprise the Implementation Phase of a CFD validation experiment is presented as Figure 8. In this phase, the reference test article is built, and the corresponding CFD studies and physical testing take place.

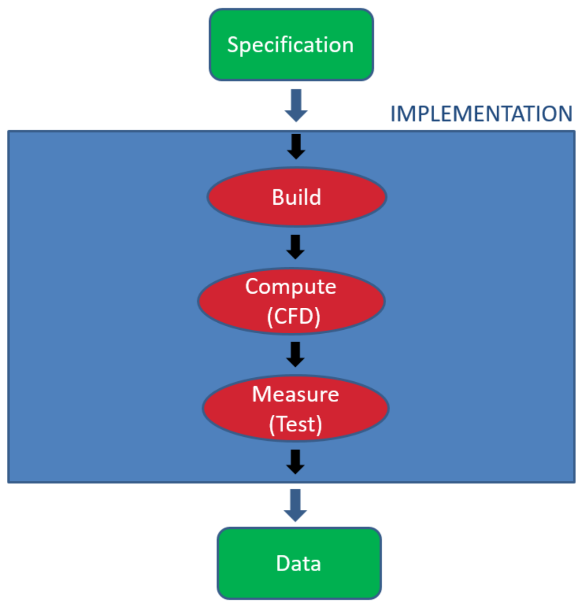


Figure 8: Simplified Schematic Overview of the Implementation Phase of a CFD Validation Experiment.

Conceptually, the Implementation Phase is the most linear of the four phases in that its purpose is "merely" to fulfill the requirements set in the detailed specification produced by the preceding Design Phase. Initially, work in this phase will focus on commissioning the necessary physical test hardware and instrumentation, since these may have the longest associated lead times. If required, additional ground test facility operational characterization may also be undertaken – although all techniques should have been proven during the Design Phase.

In principle, no iteration or experimentation should be required or scheduled. However, in practice, there are circumstances in which computations may be conducted iteratively or in parallel with physical testing. For example, during the Implementation Phase of the JF wind tunnel testing, it was discovered that the location of separation on the wing had been predicted incorrectly. Following this discovery, questions concerning the most appropriate measurement locations arose in situ. These were rapidly addressed, in (almost) real time, by performing and analyzing targeted CFD runs – a collaboration that helped to improve the value of the physical test data and save valuable testing time.

For the computations ultimately to be employed in the Analysis Phase, referred to as reference computations below, "blind" predictions are preferred, meaning that the wind tunnel test results are not known a priori. The key point here is that the subsequent assessment of CFD predictive capability should be as representative as possible of genuinely predictive scenarios. (The motivation behind this recommendation is to help mature CFD toward how it will ultimately be used, as a predictive tool: performing the CFD computations with no knowledge of the measured results reduces the possibility of unconscious bias toward achieving the "correct" results.) It may be reasoned that familiarity with the results obtained during Initiation and Design Phases may already exert an unfair bias on the CFD proceedings. However, aside from planning to bring in independent CFD practitioners who are unfamiliar with the preparatory work, there is probably little that can be done to alleviate this minor concern. All reference computations should be subject to a formal solution verification process to ensure that fully quantified estimates of data uncertainty – i.e., Quantified Uncertainty (QU) – are taken forward into the predictive assessment.

The last data to be gathered during the Implementation Phase should be the physical measurements acquired during ground testing. As with the CFD reference computations, the physical testing should be conducted in line with the detailed requirement specification and the associated data uncertainty estimated prior to entering the Analysis Phase. The final act of the Design Phase should be to clearly identify and archive the data that should be made available for use in the Analysis Phase.

D. Analysis

A simplified schematic overview of the activities that comprise the Analysis Phase of a CFD validation experiment is presented as Figure 9. The tasks of assessing, diagnosing, and consolidating ultimately lead to publication of the documentation describing the outcomes of the CFD validation experiment. The activities involved may lead to new insights into the underlying flow physics, improved CFD methods and models, or possibly new problems to be pursued in endeavors that are spawned from the current effort.

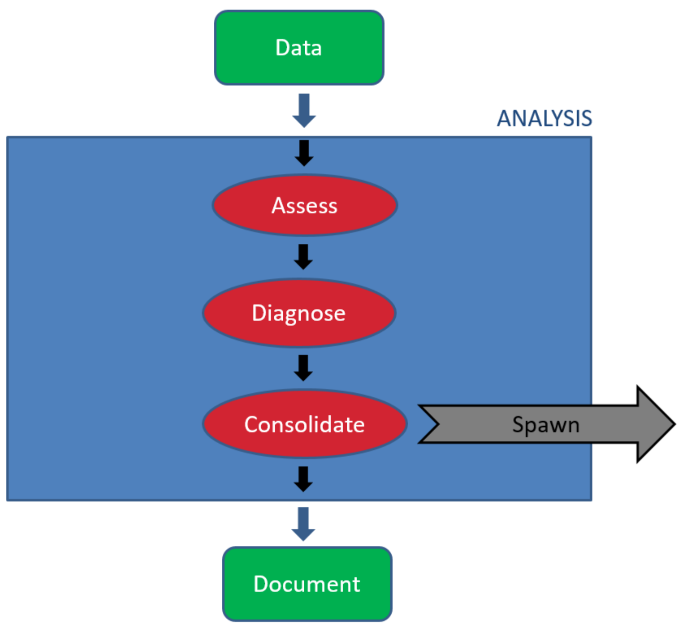


Figure 9: Simplified Schematic Overview of the Analysis Phase of a CFD Validation Experiment.

The principal task of the Analysis Phases is usually to assess CFD predictive capability in accordance with the detailed specification produced during the Design Phase. This will generally involve comparing the results of the CFD reference computations, with their accompanying QU, with the data acquired during physical testing (together with the corresponding QU). If this is the first time predictive capability has been assessed, this step may be considered sufficient – establishing a benchmark by which to judge future assessments. However, as the maturity of the predictive capability progresses through the Technology Readiness Levels, so will the need to subject the assessment to additional criteria and constraints – such as comparison with the outcomes of related validation experiments conducted for nonidentical flow conditions or previous quantified estimates of predictive uncertainty. Failure to do so will likely impede the ability to progress the maturity of CFD predictive capability. As has been stated previously, further comment on this subject is beyond the scope of this paper.

Considerable value may also be gained during this phase by diagnosing any unexpected traits in the reference data, QU, or assessment of predictive capability. This may involve conducting further computations and even additional wind tunnel testing. Developing a compelling diagnosis can be extremely challenging: it is comparatively easy to state the extent of the agreement between the computed and physical data; it is usually much harder to explain the reasons for any residual disparity. Consequently, diagnosing any unexpected traits may take a long time and/or require additional expertise.

In the authors' experience, attempts to diagnose unexpected traits in CFD validation efforts often prove inconclusive. This is usually because there are many potential sources of disagreement and it is not possible to isolate their effects. However, our contention is the following: the better executed the CFD validation experiment (including its validation dialog and technique verification), the easier it will be to diagnose unexpected traits. Accurate diagnosis is the first step toward better understanding of the flow physics and improving the CFD models. Both of these outcomes may be construed as "discovery."

Finally, in the consolidation step, lessons learned (informed by a critique of the approach taken in each of the lifecycle phases) are reviewed, recommendations made, and results are published. It is important to note that data may be reused and predictive capability reassessed in future work undertaken by the same group or by others. Additional activity may also be spawned as a consequence of discoveries made.

VI. Closing Remarks

The material presented in the paper is rooted in the experience of both authors. Our careers – and this paper – have been peppered with examples in which CFD and wind tunnel testing techniques, used in combination, have enabled technological advances to be made that would otherwise not have been possible. Developments have been most profound and benefits more diverse when their use has been guided by active validation dialog, informed by sound technique verification. The resulting instincts have led us to propose a wider interpretation of the term "CFD validation experiment" than that which is currently promoted in the literature.

By more directly acknowledging the importance of exploiting the capabilities of CFD and physical testing techniques in balanced and synergistic ways, and highlighting the centrality of the roles played by preliminary computational studies and ground tests, it is anticipated that improved engagement will result in a broader range of stakeholders. Also, we expect to see wider recognition of the value of the outcomes of what might otherwise be considered studies of lesser importance. In turn, this recognition is expected to encourage the adoption of more systematic approaches to complex problems, such that they are more readily broken-down into smaller, more focused endeavors, while at the same time making such activities easier to fund.

Our proposal, including the outline lifecycle, is not considered to be mature, robust or complete; it is presented as a starting point rather than an end state. 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 these ideas may even allow connections to be made in ways that are currently unforeseen.[*] Our conviction is that the process will be best refined by experience. To this end, we have endeavored to infuse planning behind initiatives like the CRM-HL ecosystem with its principles and look forward, keenly, to see how their evolution pans out.

[*] 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 CFD V&V challenges with that associated with the flow generated by low aspect ratio wings on classical missile airframes.

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