AIAA
G-077-1998

Guide

Guide for the Verification and Validation of Computational Fluid Dynamics Simulations

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Guide for the Verification and Validation of Computational Fluid Dynamics Simulations

Sponsor

American Institute of Aeronautics and Astronautics

Approved January 14, 1998

Abstract

This document presents guidelines for assessing the credibility of modeling and simulation in computational fluid dynamics. The two main principles that are necessary for assessing credibility are verification and validation. Verification is the process of determining if a computational simulation accurately represents the conceptual model, but no claim is made of the relationship of the simulation to the real world. Validation is the process of determining if a computational simulation represents the real world. This document defines a number of key terms, discusses fundamental concepts, and specifies general procedures for conducting verification and validation of computational fluid dynamics simulations. The document's goal is to provide a foundation for the major issues and concepts in verification and validation. However, this document does not recommend standards in these areas because a number of important issues are not yet resolved. It is hoped that the guidelines will aid in the research, development, and use of computational fluid dynamics simulations by establishing common terminology and methodology for verification and validation. The terminology and methodology should also be useful in other engineering and science disciplines.

Library of Congress Cataloging-in-Publication Data

AIAA guide for the verification and validation of computational fluid
dynamics simulations / sponsor, American Institute of Aeronautics
and Astronautics.
p. cm.
Includes bibliographical references.
ISBN 1-56347-285-6
1. Fluid dynamics--Computer simulation--Evaluation. 2. Fluid
dynamics--Mathematical models--Evaluation. I. American Institute
of Aeronautics and Astronautics.
QA911.A54 1998
620.1'064'0113--dc21 98-8138
CIP

Published by
American Institute of Aeronautics and Astronautics
1801 Alexander Bell Drive, Suite 500, Reston, VA 20191-4344

Printed in the United States of America.

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Foreword

The American Institute of Aeronautics and Astronautics (AIAA) Standards Program sponsored development of this document, *Guide for the Verification and Validation of Computational Fluid Dynamics Simulations*. This document originated within the AIAA Computational Fluid Dynamics Committee on Standards, which is composed of AIAA members and others who are not affiliated with AIAA. Committee members come from industry, government, and academia, and serve voluntarily without compensation. This document represents a consensus of the Committee's opinions on the terminology and methodology for verification and validation of computational fluid dynamics (CFD) simulations.

This document is primarily a synthesis of opinions from the published literature on verification and validation in modeling and simulation. Perspectives from a wide variety of sources were assembled in order to develop the most useful, self-consistent, and logical framework. Even though there is a variety of opinion on verification and validation in the literature, there is increasing agreement on the fundamental aspects. It is hoped that this document will promote consensus on the major issues among the CFD community at large.

The goal of this document is to support researchers, developers, and users of CFD by establishing common terminology and methodology for verification and validation of CFD simulations. The terminology and methodology should also be useful in other engineering and science disciplines.

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This document is subject to change based on developments in the state of the art and on comments received from readers. Comments are welcome from any interested party, regardless of membership affiliation with AIAA. Comments should be directed to:

American Institute of Aeronautics and Astronautics
Standards Department
1801 Alexander Bell Drive, Suite 500
Reston, VA 22091

or, by electronic mail to:

standards@aiaa.org

The first draft of this guide was prepared by Unmeel B. Mehta. This draft was prepared by William L. Oberkampf, Munir M. Sindir, and A. Terrence Conlisk. A number of comments and suggestions for improvements of the document were made by members of the AIAA Computational Fluid Dynamics Committee on Standards and by several interested individuals who were not on the Committee. We appreciate and value all input provided.

The following committee members voted on this document:

John L. Porter, Committee Chair (Sverdrup Technology)
Ramesh Agarwal (Wichita State University)

Ram S. Azad (University of Manitoba)
Donald Bain (CFD Research Corporation)
John A. Benek (Microcraft Corporation)
Bobby L. Berrier (NASA Langley Research Center)
A. Terrence Conlisk (Ohio State University)
Raymond R. Cosner (The Boeing Company)
Robert A. Delaney (Allison Engine Company)
Klaus Hoffmann (Wichita State University)
Michael S. Holden (Calspan Corporation)
Louis G. Hunter (Lockheed Martin Corporation)
Yuji Ikeda (Kobe University)
R. E. Luxton (University of Adelaide)
Joseph G. Marvin (NASA Ames Research Center)
Unmeel B. Mehta (NASA Ames Research Center)
Robert E. Melnik (Northrop Grumman Corporation)
Michele Napolitano (Politechnico Di Bari)
William L. Oberkampf (Sandia National Laboratories)
Gerald A. Paynter (The Boeing Company)
Louis A. Povinelli (NASA Lewis Research Center)
Cary Presser (National Institute of Standards and Technology)
Balu Sekar (U.S. Air Force Wright Laboratory)
Munir M. Sindir (The Boeing Company)
Ashok K. Singhal (CFD Research Corporation)
Ambady Suresh (NYMA, Inc.)
John C. Tannehill (Iowa State University)

The CFD Committee on Standards approved the document on January 14, 1998. The AIAA Standards Executive Council accepted it for publication on May 6, 1998.

Executive Summary

Computer simulations of fluid flow processes are now used to design, investigate, and operate engineered systems and to determine the performance of these systems under various conditions. Computational fluid dynamics (CFD) simulations are also used to improve understanding of fluid physics and chemistry, such as turbulence and combustion, and to aid in weather prediction and oceanography. Although CFD simulations are widely conducted in industry, government, and academia, there is presently little agreement on procedures for assessing their credibility. These guidelines are predicated upon the notion that there is no fixed level of credibility or accuracy that is applicable to all CFD simulations. The accuracy level required of simulations depends on the purposes for which the simulations are to be used.

The two main principles that are necessary for establishing credibility are verification and validation (V&V). As defined here, verification is the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model. Validation is defined as the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. These definitions point out that V&V are ongoing activities that do not have a clearly defined completion point. Completion or sufficiency is usually determined by practical issues such as budgetary constraints and intended uses of the model. All encompassing proofs of correctness, such as those developed in mathematical analysis, do not exist in complex modeling and computational simulation. The definitions of V&V also stress the evaluation of accuracy. In verification activities, accuracy is generally measured with respect to benchmark solutions of simplified model problems. In validation activities, accuracy is measured with respect to experimental data, i.e., reality.

Uncertainty and error can be considered as the broad categories that are normally associated with loss in accuracy in modeling and simulation. Uncertainty is defined as a potential deficiency in any phase or activity of the modeling process that is due to lack of knowledge. Lack of knowledge is commonly caused by incomplete knowledge of a physical characteristic or parameter, as in the inadequate characterization of the distribution of surface roughness on a turbine blade. Lack of knowledge can also be caused by the complexity of a physical process, e.g., turbulent combustion. Error is defined as a recognizable deficiency in any phase or activity of modeling and simulation that is not due to lack of knowledge. Error can be categorized as either acknowledged or unacknowledged. Examples of acknowledged errors are round-off error in a digital computer and physical approximations made to simplify the modeling of a physical process. Unacknowledged errors include blunders and mistakes, such as programming errors.

In the context of V&V, the meaning of the word "prediction" is restricted from its general usage to consider the history of validation activities with the CFD model. Prediction is defined as the use of a CFD model to foretell the state of a physical system under conditions for which the CFD model has not been validated. This definition of prediction is a subset of the general meaning of prediction because it eliminates past comparisons with experimental data. If this restriction is not made, then one is only demonstrating previous agreement with experimental data in the validation database. The processes or activities of V&V should be viewed as historical statements, i.e., reproducible evidence that a model has achieved a given level of accuracy in the solution of specified problems. Viewed in this light, it becomes clear that the V&V processes do not directly make claims about the accuracy of predictions.

The fundamental strategy of verification is the identification and quantification of error in the computational solution. In CFD simulations, there are four predominant sources of error, namely insufficient spatial discretization convergence, insufficient temporal discretization convergence, lack of iterative convergence, and computer programming. The most important activity in verification testing is systematically refining the grid size and time step. The objective of this activity is to estimate the discretization error of the numerical solution. As the grid size and time step approach zero, the discretization error should asymptotically approach zero. When the asymptotic region has been

demonstrated, Richardson's extrapolation can be used to estimate zero-grid spacing and time step. In most cases, CFD equations are highly nonlinear, and the vast majority of methods of solving these equations requires iteration. These iterations normally occur in two situations: 1) globally for boundary value problems (i.e, over the entire domain); and 2) within each time step for initial-boundary value problems. In verification testing, the sensitivity of the solution to the magnitude of the convergence criteria should be varied, and a value should be established that is consistent with the objectives of the simulation. In verification activities, comparing a computational solution to a highly accurate solution is the most accurate and reliable way to quantitatively measure the error in the computational solution. However, highly accurate solutions are known only for a relatively small number of simplified problems. These highly accurate solutions can be classified into three types: analytical solutions, benchmark numerical solutions to ordinary differential equations (ODEs), and benchmark numerical solutions to partial differential equations (PDEs). As one moves from analytical solutions to ODE solutions to PDE solutions, the accuracy of the benchmark solutions clearly becomes more of an issue.

The fundamental strategy of validation is the identification and quantification of error and uncertainty in the conceptual and computational models. The recommended validation method is to employ a building-block approach. This approach divides the complex engineering system of interest into three progressively simpler phases: subsystem cases, benchmark cases, and unit problems. The strategy in this approach is the assessment of how accurately the computational results compare with experimental data (with quantified uncertainty estimates) at multiple levels of complexity. Each phase of the process represents a different level of flow physics coupling and geometrical complexity. The complete system consists of the actual hardware or system for which a validated CFD tool is needed. Thus all the geometric and flow physics effects occur simultaneously; commonly, the complete system includes multidisciplinary physical phenomena. Subsystem cases represent the first decomposition of the actual hardware into simplified or partial flow paths. Each of these cases commonly exhibits restricted geometric or flow features compared to the complete system. Benchmark cases represent another level of successive decomposition of the complete system. For these cases, separate hardware is fabricated to represent key features of each subsystem. The benchmark cases are geometrically simpler than those at the subsystem level, as only two separate features of the flow physics and two flow features are commonly coupled in the benchmark cases. Unit problems represent the total decomposition of the complete system. High-precision, special-purpose hardware is fabricated and inspected. Unit problems are characterized by very simple geometries, one flow-physics feature, and one dominant flow feature. Each of these phases is also characterized by different quantities of experimental information available for the initial conditions and boundary conditions that are used to solve the PDEs at each phase. In addition, the estimate of experimental measurement uncertainty varies considerably from one phase to another.

1. Introduction

1.1 Background

Computational fluid dynamics (CFD) is an emerging technology. It is the merger of the classical branches of theoretical and experimental science, with the infusion of the modern element of numerical computation. The progress in CFD during the last 40 years has been extraordinary. Much of this progress has been driven by the phenomenal increases in digital computing speed. The cost of computation has decreased roughly five orders of magnitude since 1955 [1]. The power of digital computing has transformed research and engineering in fluid mechanics, just as it has in virtually all fields of human endeavor.

Computer simulations of fluid flow processes are now used to design, investigate, and operate engineered systems and to determine their performance under various conditions. The systems of interest can be existing or proposed systems operating at design conditions, off-design conditions, failure-mode conditions, or accident scenarios. CFD simulations are also used to improve understanding of fluid physics and chemistry, such as turbulence and combustion, and to aid in weather prediction and oceanography. In addition, these types of simulations are employed as an aid in developing public policy, in preparing safety procedures, and in determining legal liability. Researchers, developers, and users of CFD simulations, as well as those affected by decisions based on these simulations, are all justly concerned with the credibility of the results.

Although CFD simulations are widely conducted in industry, government, and academia, there is presently little agreement on procedures for assessing their credibility. The two main principles that are necessary for assessing credibility are verification and validation (V&V). As defined here, verification is the process of determining if a computational simulation accurately represents the conceptual model; but no claim is made of the relationship of the simulation to the real world. Validation is the process of determining if a computational simulation represents the real world. Verification determines whether the problem has been solved correctly, whereas validation determines whether the correct problem has been solved. A consistent and logical framework for V&V is needed to derive the greatest benefit from CFD modeling and simulation.

1.2 Scope

The fundamental strategy of V&V is the assessment of error and uncertainty in the computational simulation. The required methodology is a complex process because it must assess errors and uncertainties originating in all three roots of CFD: theory, experiment, and computation. Given these diverse perspectives, it is common to find disagreement and conflict in the terminology of V&V. Furthermore, because fluid dynamics is dominated by nonlinear phenomena, it is common for multiple nonlinearities to be strongly coupled. This introduces significant difficulties in modeling the phenomena and in solving the resulting nonlinear partial differential equations.

This document builds primarily on terminology established by the Society for Computer Simulation and the Defense Modeling and Simulation Office of the Department of Defense [2-4]. Concerning the methodology of V&V, however, there are no publications presenting general and comprehensive procedures in the computational sciences. It is fair to call the present state of the art for V&V methodology *ad hoc*. The purpose of this document is to promote the establishment of basic terminology and methodology for the V&V of CFD simulations.

It is important to emphasize that this document presents guidelines for V&V of CFD simulations, not standards. The AIAA Standards Procedures are segregated into three levels of state-of-the-art: guides, recommended practices, and standards. This document represents the first level, a guide. The AIAA Computational Fluid Dynamics Committee on Standards unanimously believes that the state of the art in CFD has not developed to the point where standards can be written. The Committee is dedicated to revising this document on a regular basis, following the same approach taken in the preparation of this document. That is, revisions will be made with broad input from other AIAA Technical Committees and any individuals interested in the advancement of CFD.

A few archival journals have developed editorial policies pertaining to the control of numerical accuracy in fluid flow simulations [5-8]. Numerical accuracy is one aspect of V&V, but there are many