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Aerospace Plane Design Challenge: Credible Computations

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Computational fluid dynamics (CFD) is necessary in the design processes of all current aerospace plane programs. Single-stage-to-orbit (SSTO) aerospace planes with air-breathing supersonic and hypersonic combustion are going to be largely designed by means of CFD. The principal challenge of the aerospace plane design is to provide credible CFD results to work from, to assess the risk associated with the use of those results, and to certify CFD codes that produce credible results. CFD uncertainties, credibility requirement, a guide for establishing credibility, and responsibility for credibility are discussed in order to establish the credibility of CFD results used in design. Quantification of CFD uncertainties helps to assess success risks and safety risks, and the development of CFD as a design tool requires code certification. This credibility challenge is managed by "designing" the designers to use CFD effectively, by teaming the computational fluid dynamicists with the designers, by ensuring continuous enhancement of credibility, and by balancing the design process to achieve a judicious balance of computations and measurements.

Introduction

DURING the 1980s, aerospace plane programs were begun in every major technological nation. Unmanned and manned, and single-stage-to-orbit (SSTO) and two-stages-to-orbit (TSTO) designs are being pursued. SSTO designs are fully reusable, whereas TSTO designs may be either fully reusable or semireusable. Some of the aerospace plane programs call for building experimental planes and some call for operational planes. Most of these programs are using largely state-of-the-art technologies. However, programs undertaken to design SSTO aerospace planes with supersonic and hypersonic combustion require critical new technologies, principally that of air-breathing propulsion over a wide range of Mach numbers. A significant and common technology among all aerospace plane programs is computational fluid dynamics (CFD), which is essential to the design process. The objective of this article is to define the challenge that designing aerospace planes presents to the computational fluid dynamics community and to present a plan for addressing this challenge.

In the 1970s the Space Shuttle was built largely with off-the-shelf technology.[1] Two approaches were used in the design process: 1) analysis and 2) measurement. The analysis was based on simplifying assumptions about the governing equations, physics, and simple shapes. It was later determined that the ground-based testing and the design methods that were used did not do a good job of predicting the aerodynamic characteristics. For example, the orbiter experienced nose-up pitching moments during entry at hypervelocities that exceeded the established limits.[2,3] Because the Shuttle was designed using tolerances (based on measurement scatters) and variations (from model to full-scale) in aerodynamic coefficients, it was possible to tolerate very large discrepancies in preflight aerodynamic data.[4] The lessons learned from the Space Shuttle flight program suggest that improved design methods must be developed. Such design methods would be based on improved ground-based measurements and on complex analyses involving the various forms of the Navier-Stokes and higher-order equations, as well as actual vehicle shapes. Furthermore, unlike aircraft such as the X-15 and SR-71 for which old-time slide rules and desk calculators provided most of the theoretical fluid-dynamics design input, the aerospace plane design will rely heavily on supercomputers.

The existing data base for designing SSTO aerospace planes with supersonic and hypersonic combustion is very limited, and the existing ground-based test facilities and test techniques are deficient for developing an adequate data base.[5,6] New facilities and modifications of existing facilities will be a great help, but ground-based testing has its limitations. There are fundamental difficulties in creating complete flight simulations in ground-based facilities. Computational fluid dynamics, on the other hand, can go a long way toward determining the performance and specifications of these planes, filling the present void in the data base, and complementing ground-based testing.

The challenge posed by all aerospace plane design efforts is to obtain credible CFD results, to assess the probable (quantified) uncertainties in those results, and to certify the codes as tools. The credibility of performance quantities is critical in the design process. The uncertainties lead to assessments of the success risk and safety risks associated with the fluid dynamics designs. The computer codes that generate credible results are certified by documenting their strengths and weaknesses, limitations, range of applicability, and the manner of their use. Moreover, this challenge is managed by "designing the designers" to properly use CFD, and by having a balance of computations and measurements. Fortunately, technical solutions for addressing this challenge are at hand.

Credibility of CFD Results Used for Design

In the absence of a flight demonstration, the credibility of the design is determined by the credibility of the computed results used in the design process. The users of the CFD results may either establish that credibility themselves or they may use appropriately certified codes. Just as credibility, or the lack of it, is a characteristic of computed results, reliability, or the lack of it, is a characteristic of codes. Certified codes are not available for the design of aerospace planes; the CFD design technology is yet to be developed (Fig. 1). Even if they were available, the use of such codes does not necessarily establish the credibility of the design, a reliable code may be used improperly. Various aspects of the credibility issue as well as recommendations for establishing that credibility are discussed below.

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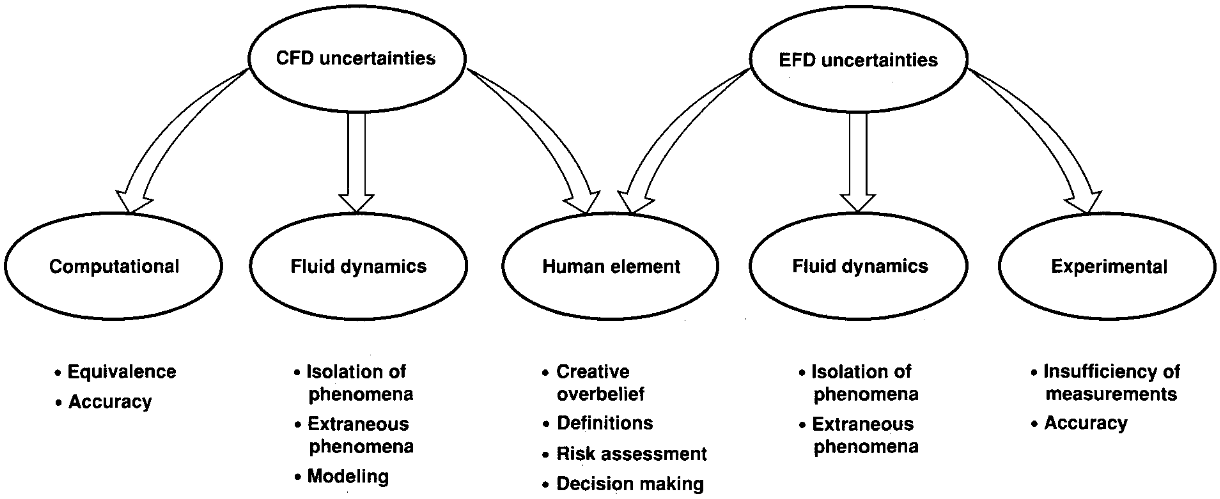

Fig. 1 Computational fluid dynamics design technology development triad.

Computational Fluid Dynamics Uncertainties

Some observations about the status of "CFD validation" and issues relevant to validation, calibration, and verification have been discussed previously.[7,8] Recently, CFD validation was declared to be a process that never achieves its objectives. "In principle, validation is a continuous never ending process."[9] And, "The development process . . . presents a dilemma because code validation is actually an open-ended process brought about by the ever-widening scope and accelerated pace of possible applications compared with the ability to provide experimental validation and by algorithm enhancements that are progressively being introduced."[10] Again, "Validation . . . is an ongoing process that parallels the development of CFD tools."[11] Such declarations may be appropriate in all types of research, except programmatic research,[7] or may be used for obtaining carte blanche to work on code (or CFD) validation, or to continually justify new test facilities and instrumentations. The outcome of an open-ended CFD validation process is of doubtful use in a design application. However, there has to be a periodical statement of the status of validation based on the state-of-the-art of CFD for a class of flow problems. In this sense, validation is a time-constrained, closed-end process.

Recently, the results of 38 computations from three codes were compared with measurements, or with the results of other computations, for the purpose of code calibration for configuration analysis.[12] That comparison study is a good starting point for CFD calibration, but the bottom line is missing: the codes are not reported to have been calibrated. What can these codes accurately predict? What is the credibility of the computed results? What are the limitations of the computed results? When should these codes be used? How well can the performance quantities be predicted? Without providing answers to these kinds of questions, such comparisons are incomplete for application to the design process. Another example is a quite good status report of the validation processes undertaken for two codes.[13] It concludes with the following statement: "Excellent agreement [is] obtained between computations and experiment for a wide variety of test cases." But it, too, fails to answer the above questions. Specifically, "excellent" needs to be quantified for design applications.

In these examples, it is not stated what code options, if any, were used when the presented results were generated. These options should be a part of the status report. If different options were used, then the various results generated with a code are not generated with the same code, even though the name of the code is the same. On the other hand, often a change is made in a code but not in its name. The details of the code are what matter, not its name.

The issue is not CFD validation, code validation, or code calibration. The issue is what is the level of credibility of computed results or what are the quantified uncertainties associated with these results for designing a fluid dynamics system so that it will meet some specific operational goals. A validated or calibrated code is not sufficient, such a code also has uncertainties. The credibility of the design of this system is no better than the credibility of the tools used for designing it. The quantification of the CFD uncertainties is necessary for managing them so that their magnitude is appreciably reduced. Moreover, the development of aerospace planes require margins that can be determined primarily by quantifying uncertainties. Recall that the Space Shuttle was designed with tolerances and variations.

There are uncertainties in both computed results and in measurements related to ground-based testing for simulating flight reality (Fig. 2). The credibility of computed results requires addressing uncertainties introduced by 1) a lack of equivalence between theoretical and computational models, 2) unsatisfactory computational accuracy, 3) isolation of phenomena, 4) extraneous phenomena, 5) improper modeling of phenomena, 6) creative overbelief, 7) definitions, 8) risk assessment, and 9) the decision-making process. The credibility of measurements requires addressing uncertainties introduced by 1) interference effects, 2) unsatisfactory measurement accuracy, 3) insufficiency of measurements, 4) isolation of phenomena, 5) extraneous phenomena, 6) creative overbelief, 7) definitions, 8) risk assessment, and 9) the decision-making process. Isolation of phenomena and extraneous phenomena include the uncertainty owing to scaling from ground-based tests to flight conditions. The crucial factors differentiating the credibility of computed results and that of measurements are modeling of phenomena and insufficiency of measurements. A discussion of various uncertainties in computed results and measurements for hypersonic flight estimates is given in Ref. 8.

Credibility Requirement

The fluid-dynamics specifications of a fluid-dynamics system are essentially determined by the performance parameters (e.g., inlet kinetic energy efficiency) and, to some extent, by the global flowfields (e.g., shock systems). These parameters and flowfields are important in the design process. The CFD credibility requirement calls for the determination of the level of credibility or quantification of the uncertainties related to CFD-determined performance estimates and global flowfields. A related issue is CFD accuracy. The utility of CFD results determines the level of accuracy required of these results. In either case, the approach is a top-down one.

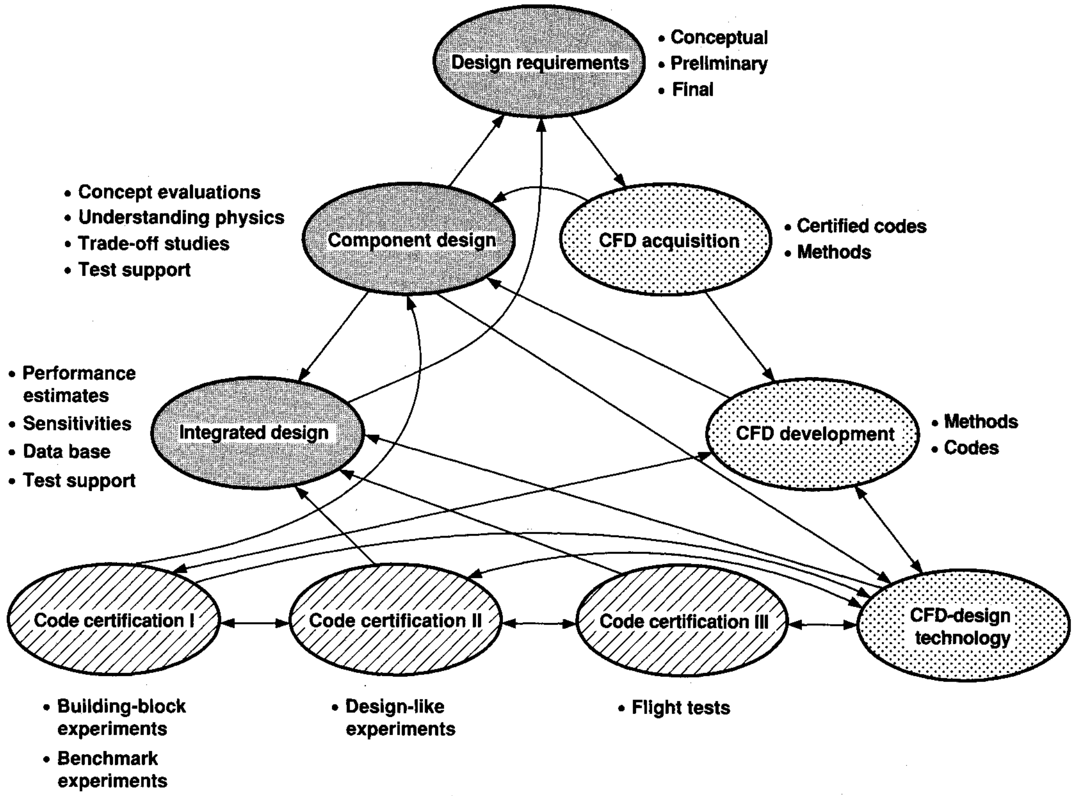

Fig. 2 Computational fluid dynamics and experimental fluid dynamics have several uncertainties in common.

The philosophy of utilizing the top-down approach is new when applied to the use of CFD in the design process.[7,14] This philosophy and computational requirements for computing hypersonic flight performance estimates to implement it have been discussed previously. Recently, Ref. 15 and a code-validation task force[16] for the first time discussed further applications of this philosophy. The performance estimates are required for making design evaluations, determining design sensitivities and optimization, establishing a design data base, and providing ground-based and flight test support. The required level of accuracy is quantified by the degree to which vehicle specifications are sensitive to performance quantities, and in turn, the degree to which performance quantities are sensitive to computational errors. These sensitivities may change as a design evolves from the conceptual to the preliminary to the final phases. The need for ascertaining the required level of accuracy is dictated by the need for keeping the computational cost affordable and for making useful computations.

The global flowfields are useful for understanding the fluid dynamics and in making tradeoff studies. The primary requirement for these flowfields is qualitative accuracy to a level determined by their utility. Herein, "accuracy" refers to the level of qualitative (physical) detail. For example, the flow structure showing small-scale turbulence eddies or the finite structure of shock waves at $M_\infty > 2$ may not be essential for some uses of global flowfields. Such accuracy is sufficient for tradeoff studies that seek to discern global trends. At times, quantitative accuracy is required when relative changes in some aspects of global flowfields are sought and when performance parameters depend on such global characteristics. An example of the latter is the accurate determination of the location of the bow shock wave at the inlet plane of an air-breathing aerospace plane so that the inlet performance parameters may be accurately computed. Either computational or fluid-dynamics uncertainties, or both, may exist. A shock-capturing numerical method without a solution-adaptive grid system may cause a computational uncertainty in identifying the exact location of the shock wave. If the physics of flow in the nose region of the aerospace plane include nonequilibrium chemistry, but if equilibrium chemistry is used for computing the flowfield, there may be a fluid-dynamic uncertainty in the location of the bow shock wave at the inlet plane. Furthermore, quantitative accuracy in the physics of interest is necessary for the modeling of that physics in simplified CFD. The sensitivity of the physics to modeling determines the level of accuracy required.

In order to determine trends or relative changes, modeled numerics and physics and CFD input parameters (except the trend-causing parameters) must be kept the same unless there is an appreciable change in the physics. Specifically, only one code, not a mixture of codes, should be used. The bias and precision of computation must be consistently preserved when trends and relative changes are being determined. The conclusions of such studies may be verified by another code.

As an example, performance parameters and global flowfield requirements for the nozzle of an SSTO aerospace plane with supersonic combustion are considered. The performance parameters are thrust, moment, and heat loads. The global flowfields involve a combination of some of the following phenomena: turbulence, relaminarization, retransition, catalyticity, chemical kinetics, combustion, shock interactions, shear-layer mixing, separation, secondary flows, combustion-nozzle interactions, aerodynamic interactions, module-to-module interactions, unsteadiness, and three-dimensionality. Computations of performance parameters and global flowfields determine the requirements for CFD. The level of computational accuracy required in performance parameters is determined by the sensitivity of these parameters to the specifications for the aerospace plane, e.g., the takeoff gross weight, such that the operational goals set for it are achieved. Moreover, these parameters are sensitive to physical models. Likewise, the utility of global flowfields determines what physical phenomena need to be captured and with what complexity. Again, the issue is sensitivity. Essential aspects of sensitivities with examples have been previously discussed.[7,8]

Guide for Establishing Credibility

There are two approaches to establishing the credibility of CFD results, one based on measurements and the other based on computations. Since CFD numerically simulates fluid dynamics reality through modeling, a comparison of computed results and measurements should determine the level of the credibility of the computed results. On the other hand, the computational approach essentially does not utilize test measurements. In this case, a sensitivity-uncertainty analysis is used. Both of these approaches are equally important and both should be used; they are complementary.

Measurements in ground-based tests or flight tests can establish the credibility of computed results if the following conditions are met: 1) flow quantities at the boundaries of the computational domain are available; 2) a relevant and sufficient quantity of qualitative and quantitative data are taken; 3) a data-uncertainty analysis is carried out to determine the bias (fixed) and precision (random and variable but deterministic) of measurements; 4) in design-like test articles, relevant performance quantities are measured; 5) redundant data are collected for cross checks; and 6) an independent evaluation of the quality of data is done. An additional condition for ground-based test measurements is that the same model is tested and the same types of data are collected in at least two different facilities. The details of conditions 1, 2, and 4 should be determined by computational fluid dynamicists and by experimental fluid dynamicists before the test articles are fabricated. They need to function as a team.

A code-validation task force has recommended a useful list of experiments to achieve CFD validation for the National Aero-Space Plane (NASP).[16] Some of the recommended experiments have not documented freestream conditions. Without knowing the freestream conditions, meaningful computations cannot be done for establishing the credibility of computational results. If these conditions are not known, then either measurements or computations should be done to define them. Computations may also be done to verify stated conditions. Furthermore, a major shortcoming of this list is that the credibility of the measurements of the recommended experiments is not evaluated. Unless measurement uncertainties are known, the uncertainties in the computed results cannot be determined with these measurements.

A statement of criteria for a successful test and CFD prediction, and a CFD prediction of how the test article is going to perform, should be completed before the test article is fabricated. This helps establish the credibility of computed results and ensure the effectiveness of the test program.

If measurement uncertainties are acceptable, then the uncertainties in CFD results are the differences between measurements and CFD results. Of course, this definition of uncertainty requires that the computed results be accurate.

The CFD results are sensitive to computational and fluid dynamics factors. The computational factors are the equivalence between theoretical and computational models and computational accuracy. The only way the sensitivity due to a lack of equivalence can be determined is by comparing two computed results, one without equivalence and the other with equivalence. The sensitivity caused by the level of computational accuracy is determined by grid-refinement studies. In the case of air-breathing SSTO space planes, the propulsion performance parameters are sensitive to global conservation of conservative variables and to the entropy condition. On the other hand, the fluid dynamics factor is the fluid dynamics model, e.g., the turbulence model and flowfield governing equations. When measurements are not available, it is sometimes possible to determine sensitivity by computing the result in question with different models. Furthermore, the sensitivity of the results to the input parameters is a factor that may be either computational or physical. These parameters include the model parameters and specifications, such as grid spacing, turbulence model constants, and the boundary conditions. A practical uncertainty analysis method for determining the uncertainties of the input parameters is based on sensitivity analysis.[17]

One of the computational requirements for hypervelocity flight performance estimates is consistency in determination of these estimates. This condition requires that the designers, computational fluid dynamicists, and experimental fluid dynamicists use the same method for making these estimates. Differences in these estimates, owing to differences in methods, are not considered to be CFD uncertainties. Because of differences in the methods, different computational fluid dynamicists may get different estimates for the same computed flowfield.

A comparison of the results of different, uncertified codes solving the same governing equations and the same fluid-dynamics problem does not necessarily establish confidence in any one of these codes. Contrary to the claim that "numerical errors can be effectively identified by solution-to-solution comparisons. . . . [resulting from] code-to-code comparisons,"[10] these errors are unlikely to be identified in such a way. All codes may produce similar or different results and similar results may all be erroneous. On the other hand, it is not at all obvious from such comparisons which one of these sets of results is the correct one. Without knowing the magnitude of computational uncertainties, it is not possible to identify the best among the sets of results. In order to understand the variations between the different sets of results, these uncertainties need to be traced to their sources. These sources are the level of grid dependency (y^+, conservation of conservative variables, etc.) and equivalence. The use of the computer codes should also be investigated. An improper use is not an error or uncertainty, it is a mistake. If there are no user mistakes in generating the results and if all similar sets of results have similar levels of precision uncertainties, then differences in these sets of results provide error bands owing to computational variations (bias) resulting from the use of different computational "wind tunnels," just as different ground-based facilities do by providing slightly different measurement values for the same conditions.

The credibility of CFD results is established as follows. First, the computational uncertainties are determined using the computational approach. Then the uncertainties resulting from fluid dynamics modeling are computed utilizing the experimental approach. If possible, the CFD results are compared with measurements that incorporate known measurement uncertainties and for the same flow conditions. Otherwise, those models, which have been validated, should be shown to be applicable to the flows of interest. Whether the uncertainties associated with validated models are applicable to the problem of interest needs to be investigated. If there are no measurements available for the flows of interest, fluid-dynamics uncertainties are computed by changing the fluid-dynamics models and model parameters. When the fluid-dynamics uncertainties are hard to determine, then the credibility is established subjectively by submitting the results to a team of independent experts for evaluation.

It is a common practice to have an independent validation and verification of software. Although it is required that this "checks and balances" practice be conducted by an organization independent of the program management structure and the organizations involved in the program, it still assists in credibility control and enchancement when instituted within a program. One of the team members is tasked to carry out 1) spot-validation of the computational and fluid dynamics modeling suggested by other members or organizations; 2) quantitative spot-verification of computed results used in design by other team members; and 3) spot-verification of trends and relative changes determined by other team members. The first of these three tasks is necessary for understanding and building confidence in the numerics and physics developed by others. The latter two help establish the credibility of computed results. These types of independent checks are meaningful only if the uncertainties of these independent results are quantified.

Responsibility for Credibility

The design CFD codes may be developed from research codes. The purpose of research codes is to develop and validate computational and fluid dynamics modeling methods. Establishing the credibility of CFD research results does not necessarily establish the credibility of CFD design results. Research laboratories are responsible for developing the research codes and for the computational and fluid dynamics modeling concepts; however, they are not responsible for the credibility of computed results used in the design process. On the other hand, the computational fluid dynamicists involved in the design process are responsible for developing design codes. Users of CFD are principally responsible for using it appropriately and for ascertaining the credibility of computed results. The burden of proof lies with the users to show that the level of complexity used when the results were generated was such that further increase in complexity would not change the conclusions drawn from these results. In addition to this issue of the level of complexity, the burden of proof also lies with the users and code developers to show that CFD uncertainties have been addressed and that the credibility of computed results has been established if the codes used have not been certified.

The primary responsibility of a CFD group in industry is to support the design process by determining performance estimates and global flowfields that are accurate and affordable. To fulfill this responsibility, this group has the following tasks: 1) develop CFD design technology, 2) participate in the design process, 3) develop and enhance CFD tools, 4) maintain and improve the credibility of computed results, 5) determine probable uncertainties in the computed results, and 6) develop guidelines for proper use of CFD. These guidelines help maintain uniformity and consistency in the use of CFD among the designers. These guidelines provide the level of complexity and the level of computational accuracy required for design applications. If it is not possible to meet these guidelines, the computed results are flagged as deficient. Thus, the CFD group is not only responsible for CFD methods, but for CFD design technology.

Success Risk Assessment

The primary requirements for credible computations are 1) that the fluid dynamics of the boundary layer, mixing, and combustion are adequately modeled; and 2) that the necessary computing resources are available. The inability to fulfill these requirements leads to uncertainties in computed results, which in turn lead to risk. Risk is never eliminated. The pertinent questions about risk are as follows: What is the magnitude of the risk? How much risk is acceptable? How should risk be managed? For establishing the level of credibility of CFD results, the first question is addressed in this section and the third is partially addressed here and elsewhere in this article. The acceptance of risk depends on the quality of risk assessment methods, the rigor with which risk abatement is carried out, and rationally formulated criteria of acceptance. In addition to these technical considerations, the acceptable level of risk may be influenced by social or political judgments.

Risk analysts generally define risk as a combination of the probability of the occurrence of an undesirable event, and each and every foreseeable consequence of that event. The System Engineering Management Guide, used by the Department of Defense, defines risk as the uncertainty in attaining a standard.[18] The National Aeronautics and Space Administration (NASA) has used the following definition: "The chance (qualitative) of loss of personnel capability, loss of system, or damage to or loss of equipment or property."[19]

There are two types of risk associated with aerospace planes: 1) success risk and 2) safety risk. Success risk is important during the conceptual and preliminary design phases; safety risk is a major concern during the final design phase and during the subsequent phases of an aerospace plane program. Success risk is the probability of not achieving the objectives of the program. Safety risks are the probability of potential failures and hazards associated with the space plane. Risk can be evaluated subjectively (qualitatively or psychologically) or objectively (quantitatively or logically). The Delphi technique of sampling experts is a subjective evaluation of risk.[18] This evaluation determines a degree of belief that events or effects will occur. Such an evaluation is appropriate during the conceptual design phase. A qualitative evaluation of risk may be feasible only after there is an experience of quantitative evaluations. On the other hand, a probabilistic risk assessment logically utilizes available evidence to quantify risk. Quantitative risk assessment is necessary during the preliminary design phase and during subsequent phases of the program.

Addressing risk is addressing uncertainties. The credibility level of the design is, in part, determined by quantifying CFD uncertainties. A margin to be built into a design requires quantification of uncertainties, because the margin is a quantitative entity. The process through which the level of CFD credibility is established requires that 1) the sensitivity of a design performance quantity (e.g., nozzle gross thrust coefficient) or specification (e.g., takeoff gross weight) of interest to computational and fluid dynamics parameters be identified; 2) the CFD uncertainties owing to these sensitivity parameters be quantified; and 3) the overall uncertainty in the chosen performance quantity or specification based on a collection of sensitivity parameters be determined. In some cases, uncertainties in more than one performance quantity may be required; e.g., in an air-breathing SSTO space plane the specific impulse depends on inlet efficiency, combustion efficiency, and nozzle thrust coefficient. Once the overall CFD uncertainty is determined, the success risk or the margin required may be determined. If the success risk is not acceptable, the design is changed. On the other hand, this risk is partly reduced by reducing the CFD uncertainties. The risk assessment process identifies the uncertainties that are significant, thereby pointing the way to effective risk management.

Finley[20] and Cribbs[21] have presented examples of the aforementioned process. Finley has attempted quantification of CFD uncertainties and sensitivity of a design to these uncertainties. First, a statistical technique is used for quantifying the credibility level in computed drag predictions. Then the effect of this credibility on the vehicle fuel fraction required to achieve orbit is determined. Cribbs has demonstrated the determination of margin, given uncertainties in performance quantities and in a specification. A Monte Carlo procedure is utilized to compute the probability distribution of the maximum velocity of hypervelocity designs to determine the probability of success as a function of velocity.

Code Certification

The development of a tool from a technology requires the identification of the strengths, weaknesses, limitations, and range of applicability of the technology. A product of the CFD design technology development triad (Fig. 1) is design CFD codes. To use a code as a tool, the user must know the characteristics of the code and how to apply it. The process of establishing the reliability and limits of applicability of the code is called code certification,[14] and it is defined as follows: "The process of evaluating a computer code in terms of its logic, numerics, fluid dynamics, and the results, to ensure compliance with specific requirements."[7] A few aspects of this process are presented below, preceded by some background information about the reliability of software.

Since the advent of the computer, the development of reliable software (computer codes) that can perform its intended function has been a challenge. This reliability is seriously determined in at least two industries, defense and nuclear, because of the criticality of performance and system safety. Because of this challenge, between 1975 and 1989, at least 18 software studies were initiated in the U.S. by the Air Force, Department of Defense, and General Accounting Office.[22] There are about 250 Department of the Defense standards and policies that specify how software should be developed and acquired. The software reliability procedures initiated by the Defense Department for software controlling the operation of weapon systems have been the starting point for the guidelines for software used in nuclear power plants. The American Nuclear Society and the American Society of Mechanical Engineers have prepared, respectively, guidelines for scientific and engineering computer codes used by nuclear industry[23] and quality assurance requirements for computer software for nuclear facility applications.[24]

The development of a software is usually done by a process referred to as a "waterfall model" or "software life-cycle phases." Generally, the model passes through the following stages: 1) requirements, 2) preliminary design, 3) detailed design, 4) coding, 5) integration and testing, 6) installation and checkout, 7) operation and maintenance, and 8) retirement. The development is categorized either as precedented or unprecedented, the main difference between these two categories being the level of understanding of the requirements.

The current development of computer codes for the CFD design process for aerospace planes falls into the unprecedented category (Fig. 1). At the completion of technology development aerospace programs, the development of computer programs for the follow-on programs would be categorized as precedented developments.

Research institutes often develop CFD codes to have "the ever-widening scope and accelerated pace of possible applications."[10] The futility of developing a code for a "wide range of applications" (Fig. 1 of Ref. 10) has been discussed previously.[7] The computational and fluid dynamics models, such as numerical models satisfying the second law of thermodynamics and turbulence models, need to be developed and validated for possible wide applications, not codes. Codes are developed for specific applications, both for model validation by the research institutes and for design application by the industry. These codes must be certified, i.e., these codes must go through a process that would assure or inform with certainty to whom it may concern that they generate reliable results.

Unless the computational uncertainties are first determined and unless the fluid-dynamics modeling uncertainties are then quantified, a fluid dynamics model cannot be validated. Unless the computational and fluid-dynamics uncertainties are quantified, design application cannot be credible. After uncertainties have been systematically documented and guidelines for using the code have been developed, the code can be a reliable tool. Code certification leads to the quantification of uncertainties and to the documentation of its reliability and utility for a specific application with specific requirements. Documentation is very important to provide traceability and to help qualify the user of the code.

Designing the Designers for Using CFD

Computational fluid dynamics may be used in the design process to achieve the following objectives: 1) understanding the fluid dynamics, 2) making tradeoff studies, 3) determining design sensitivities and optimization, 4) making design evaluations, 5) developing the design data base, and 6) supporting ground-based tests. "Aeropropulsion dynamics" designers, structural designers, and experimental fluid dynamicists, as well as computational fluid dynamicists use CFD in this design process. With CFD they can often address problems for which no design experience, data base, or test techniques exist. These kinds of problems exist, e.g., in aeropropulsion dynamics, which includes aerodynamics, heat transfer, aerothermodynamics, propulsion, and airframe-propulsion integration. In working on an SSTO aerospace plane with supersonic and hypersonic combustion, the propulsion flow-path designer has to begin his design at the nose of the plane along the lower surface of the forebody, proceed through the inlet, combustor, and internal nozzle, then along the external nozzle, and, finally, complete his design at the end of the plane. The designers need to be designed to properly use CFD if they are to produce good designs. This objective is achieved by teaming the designers with the computational fluid dynamicists.

Teamwork cuts lead time, improves quality, and, therefore, cuts costs. For example, the Ford Motor Company discarded the traditional "over-the-transom" process of product design for planning the Taurus automobile and introduced a program team approach.[25] This approach brings all resources together and blurs the distinction between research and development and manufacturing, beginning at the start of a design and development program. The people with the ideas and with the right cross-functional experience and attitude are brought together to form a multifunctional task force. In the over-the-transom process there is usually a "caste" system and a "culture" to resist change. Ideas are generally moved from one level or organization to another. People are often entrenched in their work and priorities. Teamwork is hampered by the enforcement of organizational boundaries or by functional parochialism.

The computational fluid dynamicist needs to work closely with the designer to develop credible and affordable CFD design technology for designing aerospace planes (Fig. 1). He needs to know how CFD technology and tools are used in design; what are the strengths, weaknesses, and limitations of the applicability of CFD; what are the problems in applying CFD; and whether there are disconnects between him and the various design teams and between the design teams themselves. Computational fluid dynamicists can be used solely as consultants by designers only after the CFD design technology becomes a tool.

When strengths, weaknesses, range of applicability, and limitations of the CFD design technology are known, it will become a useful design tool. A designer is effective only if he knows these characteristics of his design tools. Of course, problems cannot be solved with tools alone; knowledge and experience are also required. Given the same CFD code and the same flow conditions, two designers may compute two different sets of results if they are not trained in the proper use of the code. To quickly master the art and science of using the CFD design technology, the designer has to team up with the computational fluid dynamicist.

Balanced Design Process

A system design is optimized by trading off the performance and specifications of different parts to achieve a balance. One of four principles may be used for balancing the design: 1) equal performance, 2) equal cost, 3) equal safety, or 4) equal effectiveness. The first two principles are widely used; the third is essential, for example, for manned space activities, nuclear power generation, and chemical processes. The fourth[26] is a geometric means of resource allocations as suggested by the first two principles. A balanced design process is achieved when the tools and technology used for the design are based on one of the following principles: 1) equal credibility, 2) equal cost, or 3) equal effectiveness. The design of the SSTO aerospace plane with supersonic and hypersonic combustion requires CFD for about 70% of its flight envelope. The resources allocated for the development of the CFD design technology and its application should be appropriately scaled if the expectations of this technology are to be realized.

Historically, ground-based testing alone has not proved adequate for design purposes. Design problems associated with hypervelocity flight can be addressed properly only when ground-test data, flight-test data, and computations for a given class of aerospace planes are used together.

The development of an operational aircraft or spacecraft is traditionally done with work breakdown structures related to the operational aspects as primary line items. Although this development policy is also applicable to the development of an operational aerospace plane, there should be equal emphasis on operations and technology in the development of an experimental (research and technology development) aerospace plane, during the conceptual and preliminary design phases. At the end of the preliminary design phase, the decision to proceed further on to final design, construction, and flight-test program is primarily contingent on the status of the technology rather than on the status of operations, when the latter is difficult to establish without a flight test. Moreover, the usual practice is to identify ground-based tests and flight tests as line items. But computations are no less important than the tests. An organizational triad is required for developing and applying the CFD design technology, with the design group on one side, the CFD group on the other, and the ground-based and flight-test group on the third side of the triad.

Concluding Remarks

Computational fluid dynamics is an essential part of the design process for aerospace planes. The challenge posed by these design efforts is to obtain credible CFD results for reducing success risk and safety risks and to certify computer codes to be used as tools. This challenge is addressed by determining the level of credibility or the probable uncertainties in computed results, by improving this credibility, by risk assessment, and by code certification. The credibility of a design is no better than the credibility of the technologies and tools used in its development. Addressing the uncertainties is addressing risks. The challenge is managed by developing and applying the CFD design technology, by teaming the designers, computational fluid dynamicists, and experimental fluid dynamicists, and by balancing the design process. This challenge can be met.

Specifically, the following conclusions are noted:

1) In the design of aerospace planes, CFD is as important as ground-based and flight measurements. Because of the limitations of current ground-based facilities, in about the upper 70% of the flight envelopes of SSTO aerospace planes with supersonic and hypersonic combustion, CFD will be required to determine fluid-dynamics performance and specifications.

2) What is of a paramount concern for fluid dynamics design is not CFD code validation but quantification of CFD uncertainties so that their magnitude is appreciably reduced and so that these uncertainties are used for designing with margin.

3) Quantitative (probabilistic) risk assessment is required for credibility, success, margin, safety, and quality enhancements.

4) Model validation is a principal responsibility of research institutes, and CFD design application is a principal responsibility of industry. Both activities are carried out with CFD codes that must go through a process to inform with certainty (to certify) the reliability of the results produced by them.

5) The enchancement of design credibility for reducing the loss imparted to the society or for managing the total quality begins with the determination of credibility of computations used in the design process.

6) The designers need to be designed to properly use CFD if they are to produce good designs.

7) Teamwork between computational fluid dynamicists and designers is imperative for developing the CFD design technology, establishing credibility of computed results, and designing the designers to use CFD.

8) The principles of balancing the design process need to be used to determine the cost of computations vis-à-vis ground-based tests.

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