COMPUTATIONAL UNCERTAINTY: *ACHILLES' HEEL* OF SIMULATION BASED AIRCRAFT DESIGN (INVITED)

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ABSTRACT

In today's marketplace for military aircraft, technological superiority at affordable cost *remains the overarching demand of the customer community. Traditional design practices, which rely on extensive experimental testing to generate data for configuration design and on developing physical prototypes to verify functional and operational characteristic, cannot effectively tackle this challenge. Simulation based design (SBD) promises to rectify the deficiencies of traditional design practices by combining the ever increasing power of computers with increasingly sophisticated modeling and simulation technologies. SBD aims at producing a virtual prototype which can faithfully represent the functional and operational characteristics of the real airplane to be built. High-fidelity physics based computational methods are the key enablers. They are expected to generate credible estimates of data to meet SBD needs. However our ability to assess the credibility of computational estimates is severely hampered by our inability to quantify the associated computational uncertainty. Examples of computational fluid dynamics (CFD) applications from recent aircraft design efforts are presented to substantiate this assertion. It is imperative that we find effective ways of quantifying and mitigating computational uncertainty. Then only can we realize the full potential benefits of SBD—and its promise of helping aircraft industry deliver technologically superior aircraft at affordable cost.*

1.0   INTRODUCTION

At the dawn of the 20th century, 17 December 1903 to be precise, an event lasting only 12 seconds fundamentally altered the course of human history. The event of course was the first manned, powered, controlled flight of the Wright brothers. It was soon thereafter that airplanes demonstrated their military utility in World War I (1914-1918). The two decades following WWI saw tremendous advances in aeronautical sciences, design techniques and manufacturing processes. These advances resulted in the development of very capable airplanes that were employed in World War II (1939-1945). By virtue of their proven military effectiveness, airplanes have become an integral part of any credible military strategy of the U.S. and her NATO allies (as well as of the adversaries) ever since.

The Cold War that started right after WWII and lasted through 1990 provided a strong impetus for the development of highly maneuverable fighters (F-15, F-16, F-18, F-22), tactical and strategic airlifters (C-130, C-5, C-17), heavy bombers (B-52, B-1, B-2), and superb reconnaissance aircraft (U-2, SR-71). Resulting advances in aircraft capabilities significantly impacted the rules of military engagement for war as well as for

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operations other than war such as peacekeeping, humanitarian and drug interdiction missions.

For most of the 20th century, increasingly sophisticated aircraft were introduced with each passing decade. Whereas they provided impressive improvements in performance, their costs also escalated dramatically. As illustrated in Figure 1, the cost of tactical aircraft has grown by a factor of four every ten years [1]. The post-Cold War era saw dramatic reductions in defence budgets. It forced military aircraft industry and military acquisition community to more seriously focus on reversing the cost escalation trend without sacrificing technological superiority. The overarching challenge for the industry became: ***develop and field technologically superior aircraft at an affordable cost.*** This paper focuses on the promise of simulation based design (SBD) for successfully tackling this challenge and on hurdles one faces in realizing its full potential benefits.

The remainder of the paper is organized along the following lines. In Section 2 we discuss the deficiencies of traditional design practices for developing technologically superior yet affordable aircraft. In Section 3 we outline the promise of simulation based design (SBD) and designers' expectations of the computational methods that enable SBD. In Section 4, selected applications of computational fluid dynamics (CFD) methods are presented by way of illustrating the key hurdles that computational methods in general must overcome for meeting designers' expectations. A few concluding remarks in Section 5 complete the paper.
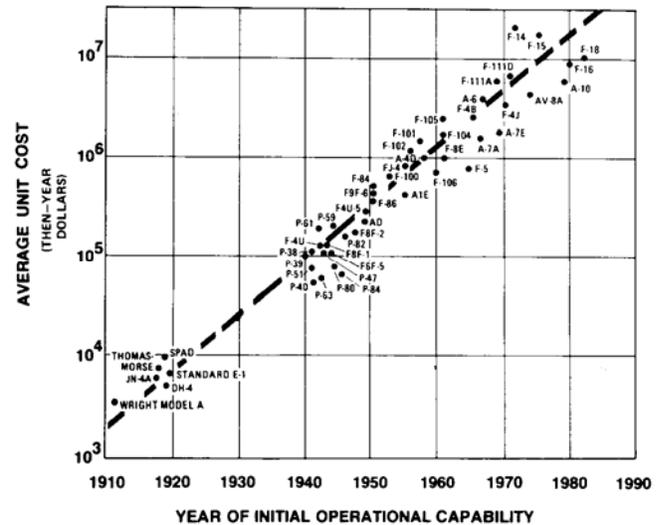
Figure 1: Tactical Aircraft Cost Escalation

2.0   AFFORDABILITY AND AIRPLANE DESIGN

Airplane design is an iterative decision-making activity aimed at creating plans for converting resources, preferably optimally, into a flight vehicle that meets customer's need (paraphrasing Woodson [2]). For most of the 20th century, the "higher, faster, farther" paradigm dominated customer thinking. Aircraft industry responded with increasingly complex and costly airplanes to meet customer demands. To be sure, affordability was *always* a key consideration but cost escalations could be "justified" as the price for technological superiority.

During the 1980s, military leadership in the U.S. began to push for technological superiority at *affordable cost* rather than at *any cost*. During the post-Cold war era of the '90s, this shift in thinking became an accepted policy. But what is the right metric of *affordability*? Paul Kaminski, the-then US Undersecretary of Defense (Acquisition & Technology), provided an answer in a speech on 27 January 1995 at the Industrial College of the Armed Forces: "*As we purchase new and modified systems, we will stress reduction of overall life cycle cost—not just the initial acquisition cost.*" This answer leads one to conclude that lowering life cycle cost (LCC) is a key customer requirement that aircraft industry ignores at its own peril.

Devising effective ways of reducing LCC requires a comprehensive understanding of its key components. But obtaining *truly accurate* cost estimates is extremely difficult if not impossible [3]. There is, however, a

general consensus that the total LCC is about equally split between the operation & support (O&S) functions and the design, test and production functions. As shown in Figure 2, the design & test and production functions—the principal responsibility of the industrial sector—can be further divided into production (or manufacturing) costs of approximately 30 percent of the LCC, and the design & test costs of about 20 percent.

It may appear at first glance that LCC reduction is best accomplished by reducing production and O&S costs which make up nearly 80 percent of the program LCC. In contrast, costs incurred in the design and test activities are only about 20 percent. However, a more careful examination indicates that design and test activities have *a disproportionately large impact* on life cycle costs. As shown in Figure 3, a large portion of the LCC—between 70 and 80 percent—is committed during the design & test phase! Therefore, an effective strategy for LCC reductions must employ airplane design practices that are best suited to reducing the committed life cycle costs.
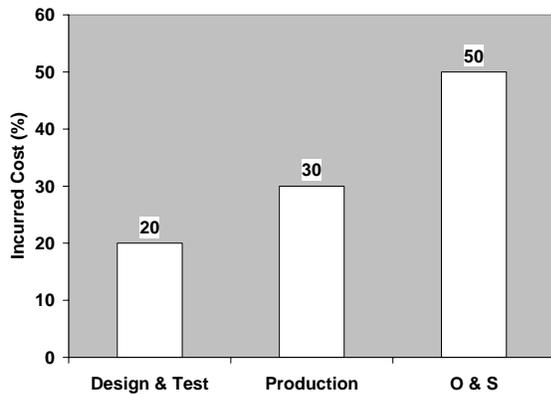
Figure 2: Incurred Costs as a Percentage of LCC
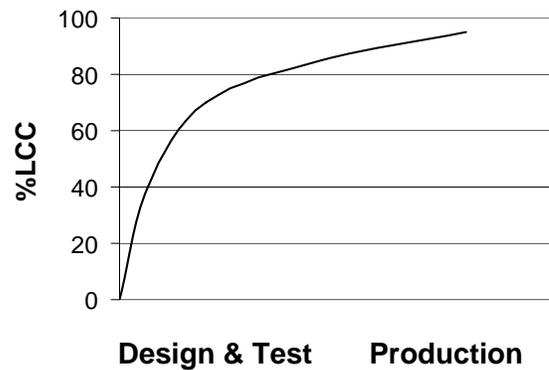
Figure 3: Committed Costs as a Percentage of LCC

2.1 Reflections on Airplane Design Practices

In this section, we first examine traditional design practices and their deficiencies for effectively reducing LCC. We then outline an approach based on the integrated product and process development (IPPD) concept to rectify these deficiencies.

2.1.1 Traditional Design Practices

The very early years of aircraft development were dominated by a *fly-fix-fly* paradigm. However it quickly gave way to the *test-build-fly* paradigm, thanks to the rapid advances in aeronautical sciences and the resulting increase in aeronautical engineering knowledge base. The test-build-fly approach relied on analysis and ground tests to generate data for design needs. As customers demanded ever higher levels of performance, aircraft became ever more complex. It took a larger number of engineers with many different functional specialties to produce data to support design needs.

Over time the functional specialists got organized into separate departments each having its own "language" and "standards." With ever expanding size and increasing specialization of the functional departments, effective communication and coordination became increasingly more difficult. This was true for interactions among the departments as well as between the departments and the design organization. "Throw it over the

wall" became the norm. To further compound the problem, the design organization got segregated from manufacturing, marketing, and support organizations. In this "stovepipe" structure, the design organization became more focused on its perceived priority of designing aircraft with high levels of performance and less so on production or O&S costs. As a result, LCC was a *fall out* of the design effort—not something consciously managed by the design organization.

The process that evolved for designing ever more capable—and complex—airplanes is called the traditional design process in this paper. This process is typically carried out in three stages: conceptual, preliminary and detail. A brief overview of each stage is presented in Appendix A; more details can be found in Reference 4. In each stage the myriad of activities can be broadly placed into two categories: synthesis and analysis. Synthesis covers defining, refining, and altering concepts and configurations; analysis encompasses methods, tools and expertise to produce data and its use in evaluating competing concepts and configurations. All disciplines such as aerodynamics, structures, flight control, etc. individually conduct comprehensive and extensive evaluations of the candidate concepts and configurations. The tools used in the early stages are typically much less sophisticated than the ones used in the later stages. Many times, data from different disciplines create conflicting demands on the direction in which a design should be altered. Then, additional time and resources are spent for reconciling the differences. A simple example is that of wing design. The best set of geometric parameters obtained from purely aerodynamic considerations may have to be changed if structural analyses indicate that the wing is heavier than the target weight. Multiple iterations between aerodynamics and structures disciplines may be necessary to achieve an acceptable solution.

2.1.2   Key Deficiencies of Traditional Design Process

Although excellent aircraft have been developed using the traditional design practices, these practices suffer from two key deficiencies, long cycle time of design iterations and inherent risk of missing cost, schedule or performance targets.

2.1.2.1   *Long Cycle Time of Design Iterations*

A typical design effort starts out with the customer providing top-level requirements. Program Office and Systems Engineering then develop design guidelines, and the Design organization creates concepts, evaluates them with the help of specialists from different disciplines, and selects a preferred configuration.

Once the "lines are frozen," the process is complete from the Design perspective but the design has not necessarily reached closure. When the production organization investigates the most economical way of manufacturing the design, and the support organization scrutinizes it from a maintenance perspective, they usually suggest design changes that restart a whole chain of events involving almost all disciplines. Typically, several iterations between the design and manufacturing organizations may be required to reach closure. The cycle time for a complete iteration is typically quite long—weeks and months not days. The long cycle times can be traced to the sequential nature of the traditional design process.

For modern airplanes with high degree of complexity, completing a design iteration using the sequential process can take a very long time indeed. As a result, the number of iterations that can be conducted to explore a wider spectrum of alternatives within Program schedule and cost is severely limited. Relatively few configurations can be explored in detail before one must close out the effort. Chances are therefore small for successfully developing an "optimal" configuration to meet customer needs and expectations.

2.1.2.2   *Inherent Risk of Missing Cost, Schedule or Performance Targets*

In a traditional design process, the amount of time and resources allocated to the early stages of design are relatively small. Most of the decisions are, therefore, based on data from relatively crude and simplistic analyses and tests. Manufacturing, operation and support functions are incorporated into decision making in a rather superficial way. However, *decisions made in the early stages essentially define the fundamental architecture of the airplane* and largely dictate how it will have to be manufactured, operated and supported.

As the design effort progresses, more decisions are made which build upon, and interlock with, the earlier decisions. Each successive decision makes the previous ones less and less accessible to change, because the cost of delay and expense of reversing the built-in and built-upon decisions become prohibitive [5]. Even though knowledge about designs increases with time as more and more data from tests and analyses come in, designers rapidly lose freedom to make changes in roughly inverse proportion to the knowledge about the design. Designers are constantly faced with a rather poor choice: either modify the design to achieve superior performance at the expense of cost increases and schedule delays or compromise the performance to meet cost and schedule targets.

2.1.3   IPPD Concept to Rectify Deficiencies

Once the deficiencies of the traditional design process are recognized, it is not difficult to devise solutions; the real challenge is in selecting and implementing the "right" ones! In the mid-eighties, the design engineering community introduced Concurrent Engineering (CE) as a means of rectifying the deficiencies of the traditional design practices. CE is not a single tool but a collection of tools and ideologies that must be customized for different situations. At the heart of CE is the concept of integrated product and process development (IPPD).

2.1.3.1   *Attributes of IPPD Concept*

The IPPD concept may be characterized by the following attributes:

- Closer relationship with the customer and constant communication to better understand customer requirements.
- Integrated Product Teams (IPTs) for a more complete understanding of requirements; a broader and more balanced discussion of issues and alternatives; and simultaneous design of product and processes.
- Design for X (DFX) methodologies, where X includes manufacturability, producibility, maintainability, testability, reliability, safety, quality, cost, etc., to develop proper guidelines to improve product design.
- Integrated design and analysis tools using a digital product model to capture and refine product and process design data.
- Integrated design automation tools to streamline the design process and assure understanding of design intent.
- Extensive use of physics-based analysis methods and simulation tools for improved product performance with fewer design/build/test iterations.

IPPD is characterized by integration of all aspects of product development including design, marketing, manufacturing, and support. It relies on considering all requirements and constraints from the start rather than altering a design in its later stages to facilitate manufacturing or accommodate product support needs. Proper trade-offs can therefore be made in *early stages of design* and the need for design changes later on is considerably reduced. This should results in improved quality and increased productivity of the entire

development process.

The IPPD concept is not as radical as it sounds. At the most basic level, it mimics the earlier days of airplane development characterized by close interaction and effective communication between (and within) the design, analysis, test and manufacturing organizations made possible by the relatively small groups of people involved. IPPD is a modern-day approach to foster closer interaction and to enable effective communication among a much larger number of personnel supporting a design project. It exploits advances in information technology and computer-aided engineering methods to achieve that.

2.1.3.2   *Design in the IPPD Context*

In the IPPD context, design is viewed as an *integrated multidisciplinary process* supported by fast, accurate and cost-effective means of generating data for each contributing discipline. Such an integrated process must not be construed as an "automated design process." It cannot substitute for human creativity and unique synthesis ability. What an integrated process can do well is to shorten cycle time for design iterations and accelerate design closure. It can expeditiously provide design teams with data needed to make more informed decisions *early* and thereby alleviate the most serious shortcomings of the traditional design process. Design teams can then devote more time and effort to considering a broader set of options with attendant improvements in quality and productivity. The integrated process does not in any significant way differ from the traditional process in what activities are actually carried out, the significant difference is *how*.

The IPPD design approach is contrasted with the traditional design approach in Figure 4. The IPPD approach requires additional effort in the early stages of the design process, but the integration of product and process design should result in a more producible product that better meets customer needs, a quicker and smoother transition to manufacturing, and a lower life cycle cost [5, 6].

A design process that encapsulates the IPPD design approach is called simulation based design (SBD) in this paper. SBD offers considerable promise in overcoming the deficiencies of the traditional design practices as discussed in more detail in the next section.
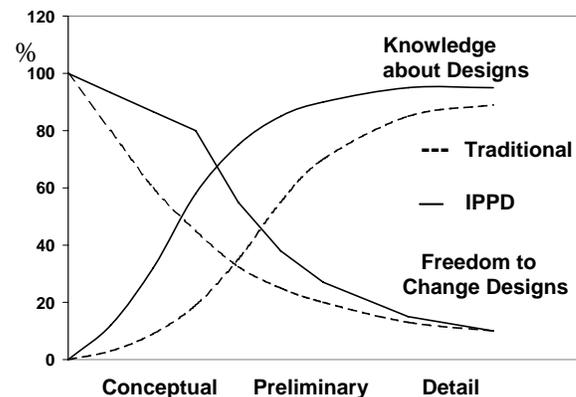
Figure 4: Knowledge about Designs and Freedom to Change Designs in Traditional and IPPD Design Practices

3.0   SIMULATION BASED DESIGN

A simulation based design effort employs integrated multi-disciplinary models, computational simulations and simulators to guide the development of a virtual prototype (VP) with a degree of functional realism comparable to a physical prototype. A traditional design effort typically produces physical prototypes to validate the functional characteristics of the design. In the SBD environment, one can concurrently address engineering design concerns of the design team, production concerns of the manufacturing team, logistical concerns of the maintainer, and training concerns of the operator—and thereby rectify the deficiencies of the traditional design practices.

Once a virtual prototype is finalized, it can serve many needs. For example, VP can be used in a synthetic

environment (that mimics the actual environment, e.g., air for airplanes) to assess system capabilities. When a system is fielded, VP can be used for training and indoctrination which can offer significant savings in time and resources by reducing or eliminating physical experimentation while overcoming safety, environmental and security constraints associated with live testing.

3.1 Enabling Computational Methods

SBD relies on computational methods as the *primary* means of generating all data required to make design decisions. Computer-aided design (CAD), computer-aided manufacturing (CAM) and computer-aided engineering (CAE) methods are the three classes of enabling methods: CAD for creating, altering and defining configuration geometry; CAM for simulating fabrication, tooling and assembly; CAE methods to evaluate quality, performance and reliability of the entire configuration as well as its constituent components.

It is important to note that SBD did not drive the development of computational methods. They have been steadily evolving since the 1950s motivated primarily by the desire to exploit advances in digital computers to increase the efficiency and productivity of engineering activities. For example, CAD evolved to supplant the slow and inefficient manual drafting process, computational fluid dynamics (CFD) to complement theoretical and experimental means of generating aerodynamic data, and computational structural mechanics (CSM) for structural data. However, the methods have been largely applied in a segregated manner. Each engineering group typically maintains its own geometric models and data formats. When interacting with other groups, much extra effort is required to reconcile geometric-model and data incompatibilities. As a consequence, the design process itself suffers from potential for errors and delays.

SBD requires the computer-aided methods to be used in an integrated manner and thereby alleviates the potential of errors and delays. A product definition database (PDD) serves as the "glue" as shown schematically in Figure 5. PDD maintains all design information in a digital format. The key challenge is to ensure that data supplied by the various teams conform to the database standards. Each team should be able to extract the necessary information from PDD to perform their tasks. In addition, effective communication and collaboration mechanisms are needed for the different teams to function in an integrated manner. The PDD must not only support the needs of the design community, but also be useable for modelling and simulation (M&S) activities of other communities including acquisition, logistics, and operations to support the entire virtual prototyping environment—a very tall order indeed but one that is being successfully tackled by a number of vendors such as Dassault Systemes with CATIA V5.
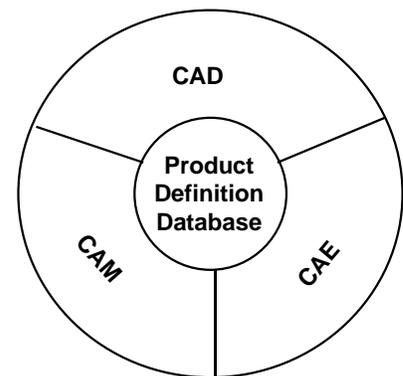
**Figure 5: CAD/ CAM/ CAE
Integration through Product
Definition Database for SBD**

It is worth pointing out that CAD, CAM and CAE methods relate to a description of the configuration concept; they are *not* suited for transforming customer requirements to abstract functional descriptions and then to a configuration description. The process of concept creation that occurs in the earliest conceptual design stage is quite often vague, and not well understood. How an engineer generates good design concepts remains a mystery that researchers from engineering, computer and cognitive sciences need to work together to unravel.

3.2   Expectations of Computational Methods

With the recognition of the potential benefits of the integrated approach outlined above comes the realization that CAD, CAM and CAE methods must adapt to a different set of requirements to best serve the needs of SBD. Design teams' expectations are highlighted in the following subsections. The material is liberally drawn from References 4 thru 7.

3.2.1   CAD Methods

In order to enhance communication of design intent to everyone involved through more realistic visualization, and to provide a more effective mechanism to represent how parts fit together to make assemblies, CAD methods must provide the capability of constructing complete three-dimensional solid models including geometry, topology and tolerances. The solid model representations are easy to understand and interpret. Also, a rigorous representation of each part's boundaries is required to avoid ambiguities of traditional representations. Using solid models and simulation tools, designers can model accessibility of components and assemblies, and thereby incorporate maintenance and support considerations into designs. Feature-based representation and parametric design are essential to further enhance and augment the utility of the solid models.

Specification of features, such as holes, slots, cut-outs, fillets, ribs, etc., can simplify the creation of designs. The design comprises a basic shape and a hierarchy of features and associated attributes. Feature attributes include dimensions, parameters and tolerances. In addition, other information such as cost, process requirements, producibility restrictions, can be associated with individual features. This capability can provide producibility and cost data directly to the designer while the product is being designed. It also helps designers to think in terms of manufacturing cost and quality implications and not just geometry. The feature-based design information in turn helps process planning and computer-aided manufacturing.

Parametric design allows a standard geometry to be specified just once for an approved group of parts. With one or more dimensions or characteristics established as variable parameters, multiple parts or assemblies can be generated by varying these parameters while maintaining overall geometric relationships. Designs can be modified with a minimum of time and effort which supports the overall objectives of the SBD process.

3.2.2   CAM Methods

For SBD to be successful, design information must extend beyond geometric information and parts lists. It must also include the design or specification of manufacturing processes including (i) layout of production equipment, (ii) process plans with the given production processes, (iii) parts and subassembly programming (e.g., Numerically Controlled machining), and (iv) tool and fixture design. Considerable progress is being made in the development of CAM software tools for accurate representation of complex processes. Their capabilities include process planning, dimension and tolerance analysis, schedule simulation, assembly simulation, factory simulation, ergonomic simulation, and feature-based costing. One example of the manufacturing simulation for the Joint Strike Fighter program is shown in Figure 6.
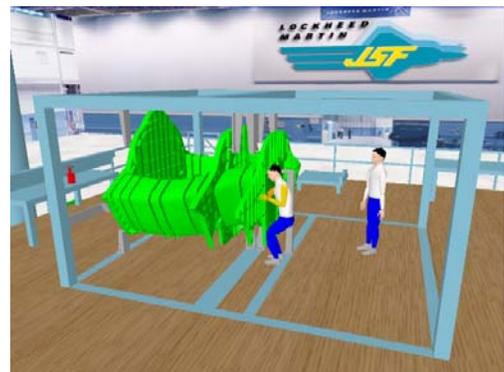
Figure 6: Joint Strike Fighter Manufacturing Simulation

Integrating the CAM methods with CAD part geometry and features permits simulation of the resulting production system before the system is actually installed. In such an integrated environment, when the product design data is released, process design data is also simultaneously released. This ensures that when a new part is introduced or a design change is made, the electronic information includes the correct process plans, tool requirements, and parts programs for the latest configuration and process capability. With integrated CAM and CAD methods, geometry and process information can be passed directly to production process equipment.

3.2.3   CAE Methods

Computer-aided engineering methods provide designers with essential information needed to assess the functional characteristics of the design and for simulating its performance, thus minimizing the need to build and test physical prototypes. For example, CFD methods can provide aerodynamic force and moment data for estimating airplane performance and handling qualities. Similarly, finite element methods can support structural design by providing valuable information about loads and stresses.

The use of CAE methods in design is not new. The advent of digital computers in the 1950s motivated their development. A few visionaries saw the inherent potential of computers for more effectively treating problems of increasing complexity associated with the development of ever more capable airplanes. For example, MacNeal [8] offered the following rationale in his 1956 report for developing a computational method for structural optimization: *"The reason for considering automatic structural design optimization at this time is the desire to take advantage of the capabilities of modern, high-speed computers. It is hoped that such an application will result in a saving of time and money and, at the same time, in more nearly optimum structural design."* Mazelsky and O'Connell [9] were also motivated by the same desire at about the same time but their focus was on aircraft dynamic load problems such as flutter, gust, landing and taxi loads that needed to be considered to a higher degree of sophistication for airplanes with higher speeds and thinner wings that were being considered. The evolution of CFD can also be traced to the desire to exploit the increasing power of computers to estimate aerodynamic characteristics of complex configurations for which wind tunnel use was expensive and time consuming and the theoretical and analytical approaches were inadequate [10].

In the years to come, the role of CAE methods will expand further. Coupled CAE methods offer the only *practical* means of simulating multidisciplinary interactions that are a cornerstone of the SBD process. For example, combining CFD and computational structural mechanics (CSM) methods provides an effective means of exploring issues related to aircraft flexibility, which is difficult and very expensive to do using physical prototypes. In addition, combining CAE methods with numerical optimization techniques affords a powerful means of computationally defining and/or refining geometric shapes to produce desired characteristics while satisfying a prescribed set of constraints.

3.3   Measure of Merit of Computational Methods

The true measure of merit of a computational method is its effectiveness in meeting designer's desires and expectations. Assessing the effectiveness is greatly facilitated by expressing it as a product of two factors as proposed by Miranda [11]:

$$Effectiveness = Quality \ x \ Acceptance$$

Here the "Quality" factor refers to the credibility and realism of predicted data, and the "Acceptance" factor to timeliness and cost of generating data. Clearly computational methods that rapidly and inexpensively produce credible data offer the maximum effectiveness. Maximizing "Effectiveness" by *simultaneously* increasing

both "Quality" and "Acceptance" ought to be the principal goal of the scientific and engineering community engaged in the development of computational methods.

A comprehensive discussion of the effectiveness of all types and classes of computational methods that enable SBD is beyond the scope of this paper (and certainly beyond the capabilities of the author!). Instead the remainder of the paper focuses on one class of methods, namely, CFD. The choice of CFD is motivated by two key considerations. First, CFD plays a pivotal role in any SBD effort. Second, CFD serves as a good surrogate for a wide variety of computational methods. Even a cursory look at current CFD methods suggests several aspects that cut across computational methods in other disciplines. For example, CFD methods are based on a hierarchy of approximations to the underlying physics and they employ a broad spectrum of mathematical and numerical formulations—much like what one sees in other disciplines. Therefore many of the observations we make about CFD in this paper do readily extend to computational methods in other disciplines as well.

4.0   CFD FOR SBD

CFD is an indispensable tool for SBD. There are two rather obvious reasons. First, CFD can provide aerodynamic data such as forces and moments and stability & control parameters required to make accurate assessment of airplane performance. This assessment is essential to ensure that the configuration would be able to successfully carry out the intended mission. Second, CFD provides critical input data for many other CAE methods to carry out their own analyses. For example, airframe structural analysis requires steady and unsteady loads that CFD can provide. Flight control system design requires airplane response to control commands; CFD provides incremental forces and moments. In addition CFD can provide on- and off-body data for an improved understanding of the flow features surrounding an airplane which offers valuable guidance for modifying the configurations.

Note that wind tunnels have traditionally provided the types of design data that SBD demands of CFD. However, wind tunnels are not well suited to meeting the demands and tempo of a SBD process. Evaluating a large number of design variations (dozens not a few) in a short period of time (hours or days not weeks and months) is expected in a SBD effort. Also, it is crucial that every successive design incorporate the learning from the preceding designs. CFD holds an edge over wind tunnels in meeting this expectation. The time and cost of building a large number of wind tunnel models and conducting a large number of tests are prohibitive in comparison to using CFD.

It is interesting to note that the time and cost advantages of CFD over wind tunnels were recognized rather early and led to irrational exuberance in the mid-seventies—well before SBD came along. In their celebrated article in 1975, Chapman et al [12] predicted that *"...within a decade computers should begin to supplant wind tunnels in the aerodynamic design and testing process..."* In addition they forecasted that *"To displace wind tunnels as the principal source of flow simulations for aircraft design....the required computer capability would be available in the mid-1980s."* However, it did not take long for rational sobriety to take hold! In spite of dramatic improvements in CFD capabilities over the past four decades as summarized in Section 4.1, CFD has not supplanted wind tunnels. Although CFD has made noteworthy inroads, wind tunnels continue to be the primary means of generating data to meet aircraft design needs. But a way must be found to exploit CFD's advantages in order to realize the full potential benefits of SBD as discussed in Section 4.2.

Before moving on to Section 4.1, it is important to note that there is one design activity, namely, shape optimization, for which CFD is uniquely suited whereas theoretical and experimental methods are totally

inadequate. In designing a new airplane or modifying an existing one, it is clearly important to have good estimates of configuration aerodynamic characteristics. However, it is significantly more valuable if an optimum shape can be determined for desired aerodynamic characteristics. The traditional cut-and-try approach—relying on the results of analyses and aerodynamic expertise to guide shape redesign—cannot provide an optimum shape. Combining CFD methods with a numerical optimizer is the only means of generating optimum shapes. The optimization approach requires computation of derivatives of an objective function with respect to the design variables. There are many different ways it can be done using CFD whereas it is totally impractical using wind tunnels. Methods for computing the derivatives include finite differences [13], automatic differentiation [14], and adjoint systems [15]. Interdisciplinary considerations can be brought to bear on shape optimization through the specifications of constraints.

4.1 CFD Capabilities

A wide variety of CFD methods are available to support aircraft design needs. The methods can be broadly categorized into four levels as shown in Figure 1. This categorization is principally based on level of sophistication of physics modeling, mathematical formulations, and the timeframe of introduction of the methods to aircraft design

It has long been known that Level IV codes, based on the Navier-Stokes (N-S) equations, can simulate nearly all flow phenomena of interest for which the continuum assumption is valid. (The Boltzmann equations based on the kinetic theory of gases are needed to model molecular flows; the related numerical methods will not be covered here.) However, adequate computer power and efficient numerical algorithms were not available until the 1990s. This forced researchers to

Figure 8: Evolution of Four Levels of CFD Methods

explore alternatives based on inviscid approximations to the N-S equations; the first three levels correspond to codes based on a hierarchy of inviscid approximations—with concomitant limitations on their range of applicability as shown in Figure 9. Basic features of each level of CFD methods and their capabilities are highlighted in the following subsections.

4.1.1 Linear Potential Methods (Level I)

The linear potential methods are based on the Prandtl-Glauert or Laplace equations which form the lowest level inviscid approximation to the N-S equations. Most of the codes employ the boundary integral approach. The governing partial differential equations (PDEs) along with the boundary conditions are cast in a surface-integral form using Green's theorem. The solution is constructed by discretizing the geometry into small elements and assigning a singularity (sources, doublets, or vortex filaments) to each element. The singularity strengths are determined by satisfying the no-normal-flow condition at a control point on each element. Depending upon the approximations used in surface discretization (mean
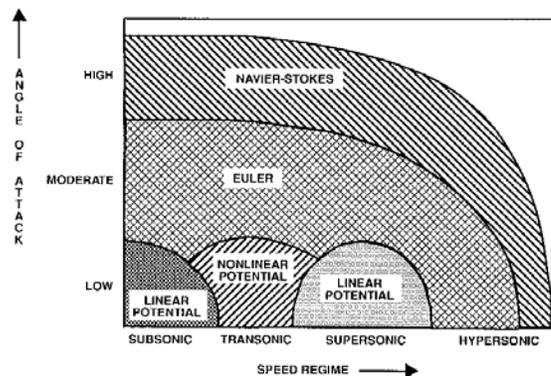
Figure 9: Regions of Applicability of Four Levels of CFD Methods in a Notional Design Space

surface or actual surface) and the type and functional form of singularities (constant source, constant doublet, linear doublet, etc.), codes with different characteristics [11] can be developed.

The simplest codes, widely known as vortex-lattice methods, employ mean-surface representation of geometry and vortex filaments as singularities. The VORLAX code [16] is a representative example. When the actual surface geometry is discretized, the methods are commonly called panel methods. Low-order singularity distributions, constant on each element, have been employed in QUADPAN [17] and higher-order ones, linear or quadratic, in PANAIR [18].

The simplicity of the physical and mathematical formulation of the linear potential codes inherently restricts their validity to purely subsonic and supersonic attached flows. In spite of these restrictions, the codes are quite extensively used in design efforts due to their ease of use, computational efficiency, and relatively high level of confidence built upon years of use. An experienced user can set up a computational model in a matter of hours even for relatively complex configurations like a complete aircraft. Figure 10 shows a QUADPAN model of the P-3 Orion aircraft with a rotodome for airborne early warning and control [19]. This model was used to evaluate the mutual interference effects of the rotodome and the baseline vehicle.

The computational times for Level I codes range from a few seconds on supercomputers to a few minutes on workstations. However, user expertise and experience are crucial to ensuring proper interpretation of the solutions. The vortex-lattice methods and panel methods generally provide good estimates of forces, moments and distributed airloads for steady flight conditions. The data form the basis for performance and weight estimations in the early stages of design. Some of the codes also offer a design option that can be used to determine geometric characteristics (like twist and camber of a wing) for a prescribed set of aerodynamic

Figure 10: P-3C AEW&C QUADPAN Model

parameters. To meet the aerodynamic data needs of the aeroelastic and flutter disciplines, versions of the doublet-lattice method [20] are the codes of choice.

The linear potential codes were first introduced into the aircraft design environment in the late 1960s and the entire class of codes reached a high level of maturity in the early '80s. With the possible exception of the oscillatory aerodynamic codes [21, 22], very little effort is presently going into research and development of this level of codes.

4.1.2   Nonlinear Potential (Level II)

The nonlinear potential methods are based on either transonic small perturbation (TSP) equations or full-potential equations (FPE). Their ability to model transonic flows with shocks is the most significant benefit over the Level I codes. However, this benefit comes at the expense of added complexity stemming from the need to resort to a field approach to solve the nonlinear PDEs. The field approach requires that a region surrounding a given configuration be divided into small elementary volumes; it is no longer sufficient to just divide the surface.

Considerable progress was made in the 1970s towards the development of practical transonic-flow analysis methods [23]. The progress had its genesis in the landmark paper of Murman and Cole [24]. The TSP code of

Boppe [25] and the FLO-series of FPE codes of Jameson and Caughey [26] were in widespread use by the late 1970s. In practice, TSP codes are easier to use than FPE codes, especially for complex geometries, because of the differences in the boundary condition treatment. The TSP approach permits a simplified treatment based on the application of the no-normal-flow condition at a mean surface. In contrast, the FPE approach requires application at the actual surface. Consequently, Cartesian field-grid systems suffice for the TSP codes whereas the FPE codes need boundary-conforming grids. Cartesian grids are considerably easier to set up compared to the boundary-conforming grids. Of course, the TSP codes suffer from limitations on the class of geometries and flow conditions that they can model accurately—a direct result of their simplified boundary-condition treatment.

The promise and excitement of the newly-found ability of computing transonic flows were so strong in the '70s that even wing design procedures [27] were developed while the analysis methods were still evolving. Since transonic flows are particularly susceptible to viscous effects associated with shock/boundary-layer interaction, considerable research was done in coupling inviscid TSP and FPE codes with boundary-layer codes. Aeroelastic analysis capabilities based on the TSP formulation [28] were also developed.

Although the Level II codes provided the much needed capability of modeling transonic flows, they were not as effective as the Level I codes. A variety of factors contributed to this situation. For example, the level of grid generation technology was not mature enough to support routine application of the FPE methods to anything more complicated than a wing or a wing-body. Applications of the codes confirmed, as one might have suspected, that solution accuracy deteriorated for flows containing strong shock waves or large regions of vorticity (e.g., leading-edge vortices). Usefulness of the codes was therefore severely limited, especially for fighter design since the performance of a typical fighter aircraft is greatly influenced by the leading-edge vortices.

In the author's opinion, nonlinear potential codes were basically taken over by the rapid pace of advances in Euler codes in the early eighties. The TRANAIR code [29] was an exception to this trend. TRANAIR adopts an unconventional hybrid approach combining the flexibility of panel methods to handle complex geometries with the ability of FPE formulations implemented on Cartesian grids to handle nonlinearities of transonic flows.

4.1.3   Euler (Level III)

The Euler equations, which form the basis of the Level III codes, represent the highest-level inviscid approximation to the N-S equations. The Euler codes are applicable throughout the subsonic to hypersonic flight regime. This, combined with their demonstrated ability to automatically capture rotational flow regions (such as wakes shed behind wings and vortices emanating from sharp leading edges of fighter-type wings), requiring no explicit a priori definition of such regions, renders them significantly more useful than the Level I or II codes. However, the enhanced capability comes at the expense of additional computational cost of solving at least four and generally five coupled first-order PDEs instead of one second-order PDE.

Two factors at the dawn of the eighties convinced most researchers to shift their focus to Euler equations: (i) projected growth in computer power and (ii) development of more efficient numerical algorithms to solve the Euler equations [30, 31]. In addition, the accelerated pace of boundary-conforming grid generation technology along with the introduction of the finite-volume concept to decouple flow solvers from grid mappings held considerable promise for realizing CFDer's dream of routinely analyzing complete aircraft geometries. A synopsis of the impressive progress made is presented here; details can be found in many publications

including References 10 and 32.

Three distinct development paths can be identified for Euler codes. During the early part of the eighties, most researchers focused their energies on structured-grid methods with emphasis on patched multiblock [33] or overset grids [34] to handle complex geometries. One example is presented here to illustrate the capabilities of a typical patched multiblock Euler code, TEAM, to support F-22 design needs. (More details about the code itself can be found in Reference 10, Chapter 18.) This example involves full aircraft airloads prediction [35]. Nearly 370 analyses were done covering six Mach numbers, several angles of attack and a few yaw angles. Effects of leading- and trailing-edge flap deflections, horizontal tail deflections and rudder deflections were simulated using the surface transpiration concept [36]. A correlation of computed and measured surface pressures is shown in Figure 11.

The development path shifted towards unstructured-grid methods from the mid-eighties onwards. The shift was prompted by the realization that unstructured grids [37] afforded greater flexibility in handling complex geometries and promised to "automate" the grid-generation process. Cartesian-grid methods [38, 39] that evolved in the early nineties offered yet another attractive alternative because they essentially dispensed with the difficulties of grid generation leading to considerable reductions in time and manual labor. As far as flow solvers are concerned, structured- and unstructured-grid methods as well as Cartesian-grid methods can provide steady-state solutions on full aircraft configurations in a matter of hours using today's high-performance computers.

**Figure 11: F-22 Surface
Pressure Correlation for
Transonic Flight Condition of
0.9 Mach Number and 8o Angle
of Attack**

Two other aspects of Euler codes development deserve mention here. First, shock-capturing rather than shock-fitting has become the preferred approach; both upwind and central-difference with adaptive-dissipation schemes have enjoyed a great deal of success. Second, most codes solve the time-dependent form of Euler equations even for modeling steady flows. Convergence acceleration techniques, such as local time stepping and multigrid, are employed to obtain time-asymptotic steady-state solutions in a computationally efficient manner. Both explicit and implicit time-marching schemes have been effectively utilized. Due to the use of time-dependent equations, extending the codes to model unsteady flows is relatively straightforward. An example presented here involves prediction of time history of hammershock overpressure in the F-22 inlet duct at a supersonic flight condition [40]. Figure 12 shows a snapshot of duct pressures and the Mach field around the forebody. The ability to compute unsteady flows has been exploited to develop dynamic aeroelastic analysis methods [41]. Inverse design [42] and aerodynamic design optimization [15] methodologies based on Euler codes are also noteworthy.

**Figure 12: F-22 Inlet Hammershock
Overpressure Prediction**

Whereas Euler codes are superior to nonlinear potential (Level II) codes in modeling strong shocks, the solutions do not necessarily simulate the transonic flows more accurately because they cannot model shock/boundary-layer interaction effects. Some researchers have combined Euler codes with boundary-layer codes to correct this deficiency. The Euler codes do have an edge over potential-flow methods in capturing leading-edge vortices. But the location and strength of the primary vortices may not be accurate in cases where the secondary and/or tertiary vortices exert considerable influence [43]. Also, the codes cannot provide an estimate of total drag (including skin-friction) or model flow separation from smooth surfaces. It is, therefore, not surprising that the development of N-S codes has been aggressively pursued in parallel.

4.1.4   Navier-Stokes (Level IV)

Navier-Stokes codes have a great deal in common with Euler codes. In practice, a single code usually serves the need of solving both Euler and N-S equations. This follows directly from the similarities between the two sets of equations. Elimination of diffusion terms readily converts the N-S equations to the Euler equations as they both share a common set of convective terms. However, the practical implications of this seemingly minor difference are enormous. In order to accurately resolve the diffusion terms, highly clustered grids are required close to solid surfaces (as well as in other regions where viscous stresses are large).

With appropriate grid clustering, one can use the N-S equations to simulate laminar flows in a relatively straightforward fashion. But using these equations to *directly* simulate even simple turbulent flows stretches the current supercomputers to their limits [44]. At present, the Reynolds-averaged Navier-Stokes (RANS) equations are used almost exclusively to simulate turbulent flows on aircraft configurations. For a large majority of problems, the thin-layer approximation to the RANS equations is employed to reduce the problem to a manageable size. But these simplifications impose a heavy toll; we now require a turbulence model! A variety of turbulence models are available ranging from relatively simple algebraic models to more sophisticated Reynolds-stress models. The models have been applied to produce impressive results. Two representative examples are included here.

Example 1: Goble and Hooker [45] computed lift and drag forces as well as surface pressures on the P-3C aircraft using the NASA TetrUSS unstructured-grid code. This effort was undertaken in support of the P-3C Service Life Extension Porgram. A sample solution is shown in Figure 13. Although CFD data correlated well in general with wind-tunnel and flight data, discrepancies were attributed to turbulence modeling. Spalart-Allmaras turbulence model coupled with a wall-function model to reduce grid clustering requirements was used for this effort.

Example 2: Wooden and Azevedo [46] use a structured-grid CFD method, Falcon, for refining JSF outer mold lines. Figure 14 shows a typical surface pressure coefficient (C_p) distribution used for identifying drag reduction targets. Such solutions were generated using a

Figure 13: P-3C Solution with Propeller Effects

multi-block structured-grid code with a 177-block grid having a total of 27 million grid points. The two-equation k-kl turbulence model of Smith [47] is used in their calculations.

4.1.5   Summary

The preceding discussion highlights the tremendous advancement in CFD capabilities that has been made to date. Of course, many more examples can be cited to demonstrate how CFD can be applied to simulate flow about complex configurations. The multitude of applications has helped us learn to exploit the complementary aspects of CFD and wind tunnels.

Based on CFD applications to F-22 design during the early 1990s, Bangert et al [35] pointed out that the design team relied heavily on wind-tunnel data due to the limitations of CFD codes in modeling viscous effects, especially when applied to full aircraft geometries and the full speed, altitude, and maneuver flight envelope. This is not too surprising due to the then level of maturity of the RANS methods. More than 40,000 hours of wind-tunnel

Figure 14: JSF Cp Distributions

testing was done to support the F-22 development. Nearly a decade later, the development team of the Joint Strike Fighter (JSF) aircraft [47] also relied on extensive wind-tunnel testing for generating aerodynamic performance data to meet Key Performance Parameters and Performance Specifications related to Mission Performance. Since 2002 a total of more than 48,000 wind tunnel test hours on the Lightening II have been completed at eighteen facilities around the world.

The continued heavy reliance on wind tunnels is clearly incompatible with the SBD vision of relying on computational methods as the *primary* means of generating all design data (see Section 3.1). Meeting the demands of SBD for future aircraft design will require dramatic improvements in CFD effectiveness as discussed in the next section.

4.2   Maximizing CFD Effectiveness for SBD

For maximum CFD effectiveness in meeting SBD needs, we must simultaneously maximize both "Quality" and "Acceptance" factors as outlined in Section 3.3. In this section we highlight some of the associated hurdles and challenges.

4.2.1   Accuracy

The ultimate value of CFD simulations depends entirely on the credibility of the predicted solutions for the intended use. As pointed out by Mehta [48], a solution lacks credibility unless its uncertainty is known, but the simulation uncertainty is ubiquitous. It is difficult to improve the credibility of the simulations without knowing the model uncertainty. The intended use of a simulation identifies which errors should be tracked and quantified and also determines the acceptable level of accuracy. That is, a simulation may be credible for one use but not another, even though the simulation accuracy is the same.

When looked at from the SBD perspective, the Level IV CFD methods—the ones based on high fidelity physics—are the most relevant. They are expected to provide credible predictions for the widest possible applications of interest. However, assessing the accuracy of computed viscous solutions remains an overarching challenge. The two components of solution accuracy, numerical and physical, are discussed next.

4.2.1.1   Numerical Accuracy

A solution may be considered numerically accurate if it shows little or no sensitivity to changes in grids as well as numerical parameters related to the algorithm. (It is assumed that the code in question has been verified as to the adequacy of its numerical formulation in solving the governing equations.) Figure 15, extracted from Reference 49, shows an example of the surface pressure sensitivity to numerical parameters, in this case the flux-limiter compression factors used in the Falcon upwind scheme. Note that the multiple symbols denote run-to-run variations in the wind-tunnel test measurements—an important consideration in using data from one single run to assess the credibility of computed solutions.
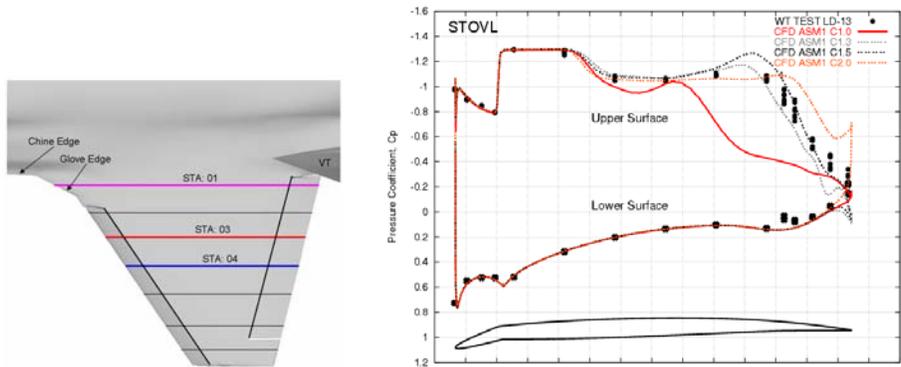
Figure 15: Sensitivity of JSF surface pressures to flux limiters

Cunningham et al. [50] conducted low speed wind-tunnel tests and unsteady CFD analyses of the F-22 configuration to identify important characteristics of the buffeting loads on the fins and evaluation of various aerodynamic modifications to alleviate these loads. Figure 16 shows a CFD pressure distribution and structure of the vortex breakdown. The grey envelopes illustrate the 3-D boundaries of the flow reversal surfaces. Inside of these surfaces, the velocity field is generally flowing forward relative to the airplane. The first set of CFD runs had a relatively coarse grid arrangement on the vertical fins for conservation of computational resources and reduced run times. However, the computed unsteady CFD pressure distributions exhibited discrepancies with test data, and the computed RMS pressure levels were very low. When a finer grid was used for the vertical fin to more accurately represent a small rounded leading edge, computed RMS levels were very much in line with the measured wind tunnel data.
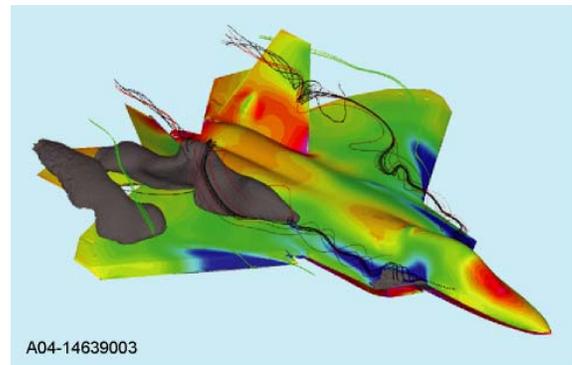
Figure 16: F-22 Unsteady CFD Flow Simulation

At present, systematic parametric studies are about the only means of estimating the effects of grid resolution and numerical parameters such as dissipation and dispersion. Schedule and cost constraints of a typical design effort do not permit extensive investigations to determine "optimal" grids and numerical parameters. *What we need is built-in means of quantifying the level of accuracy*. Estimation of numerical error is admittedly a difficult problem but a solution is urgently needed if CFD is to deliver on its promise for SBD.

4.2.1.2   Physical Accuracy

Even if a code produces a numerically accurate solution, it is not trivial to determine how well the solution

stacks up against reality—a measure of its physical accuracy. To date, the CFD community has advocated and conducted extensive "validation" exercises to generate computed vs. experimental data correlations, and used them to substantiate claimed levels of physical accuracy of their codes. However, the exercises have contributed more to the proliferation of databases than to increasing the knowledge base. *Extensive correlations on geometries and flow conditions that differ substantially from those being considered by the design teams are of little value.* This situation is particularly relevant to military aircraft projects since new designs are generally quite different from the older ones (for which correlations might exist).

The traditional approach to code validation is fraught with other difficulties as well. How many test cases, what combination of flow conditions for each test case, and what turbulence models must we consider before a code can be declared fully validated? A matrix of runs using any reasonable set of test cases and flow conditions quickly grows into a monumental task. Even if we assume that adequate resources as well as high-quality measured data—with known error bounds—are available for carrying out such a task, we run against the tide of technology dynamics. The rapid pace of advances in hardware, numerical algorithms, and in transition and turbulence modeling fosters an environment where codes are never quite "finished." Sometimes the changes are nominal, many times not. Any rational cost/benefit assessment of a plan that allocates huge amount of resources to validating a code that might be superseded the next day by a "new and improved" method does not support the traditional validation approach.

When RANS equations are solved to simulate aerodynamic problems in aircraft design where viscous effects dominate, the accuracy and reliability of the solutions continue to suffer from the inadequacies of turbulence models. One example is included here to illustrate the sensitivity of flow solution to turbulence models. In Figure 17, extracted from Reference 49, vorticity magnitudes on F-35 STOVL configurations are shown for two-equation k-kl model [47] and two variations (ASM1 and ASM2) of an explicit algebraic stress model [51]. These solutions were generated using a patched multiblock structured-grid methods using a 197-block grid with a total of 36 million grid points. Assessing the accuracy of these solutions is a truly monumental challenge indeed.
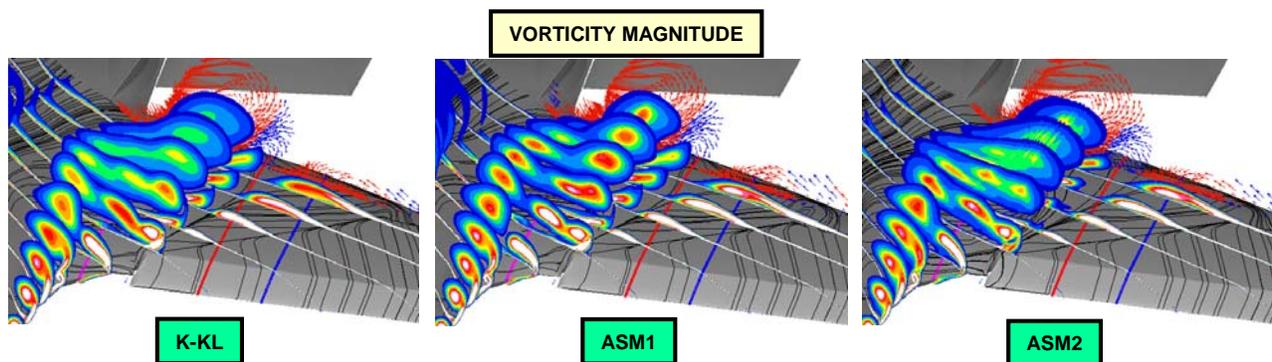
Figure 17: Vortex Flow Sensitivity to Turbulence Models for JSF F-35 STOVL Configuration

Experiences in simulating turbulent flows to date have been rather mixed. There have been many successes in turbulent-flow simulation using simple models and many failures using the more sophisticated ones. Attempts at refining existing models and developing new, improved ones continue unabated. Considerable effort has also been devoted to developing models for laminar to turbulent transition, an area of crucial importance for

accurate viscous flow simulation.

In the author's opinion, the prospects of a simple universal turbulence model are rather bleak; capturing the complex nature of turbulence into a model with a few free parameters is a long shot indeed. One option for CFD practitioners is to rationalize the use of RANS codes—in spite of their limitations—by accepting Bradshaw's observation [52]: *"...we cannot calculate all flows of engineering interest to engineering accuracy. However, the best modern methods allow almost all flows to be calculated to higher accuracy than the best informed guess, which means that the methods are genuinely useful even if they cannot replace experiments."* However, it does not obviate the desire to develop a <u>truly predictive</u> CFD capability so that the full potential benefits of SBD can be realized.

Continuing advances in large eddy simulation (LES) and direct numerical simulation (DNS) offer very attractive options for developing a CFD capability that can be *truly* predictive unlike the RANS methods which will continue to suffer from turbulence and transition model uncertainties. However, even rough order of magnitude estimates of the required computational resources for a full aircraft analysis at flight Reynolds number are staggering as shown in Figure 18. Due to the Re^3 computational work barrier, it appears that DNS will not be practical for several decades. However, LES could become practical in about twenty years if computer memory and speed increase by about four orders of magnitude. Considering the ten-fold increase in speed and memory every 7 years since 1975, it is conceivable that the required computational resources will become available by 2020. It is imperative that more effort be directed at several pacing items such as sub-grid scale modeling; numerical algorithms; boundary conditions; grid generation; and tools for analyzing, visualizing and managing

Figure 18: Computing Resources for Developing a "Truly" Predictive CFD Capability

extremely large amounts of data. Even more importantly, advances are required in wind tunnel measurement techniques to collect data required to assist the development of effective LES and DNS capability.

An assessment of the level of accuracy and associated error bounds of the solutions is even more critical when CFD methods are combined with those from other disciplines to simulate multidisciplinary interactions. Figure 19 shows sensitivity of take-off gross weight (TOGW) of a high-speed civil transport (HSCT) configuration to changes in aerodynamic drag [53]. A two count increase in drag results in a vehicle with nearly 60,000 lbs. higher TOGW. This example clearly illustrates the critical important of quantifying computational uncertainty associated with predicted data—drag for this example at hand. When devising approaches to resolve the issue of computational uncertainty, however, we must remain cognizant of their impact of the proposed approaches on the "Acceptance" factors, i.e., turnaround time and cost, as discussed in the next two subsections.
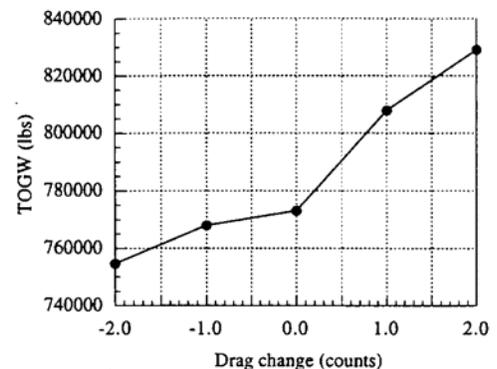
Figure 19: Effect of Drag Estimation Error on TOGW in HSCT Design

4.2.2   Turnaround Time

The time span from the initial go-ahead to the final delivery of data from a CFD analysis is called the turnaround time. It has always been a critical factor in CFD effectiveness for aircraft design. For example, Bangert et al [35] identified *"Minimizing calendar time of CFD analyses"* as the topmost requirement based upon their experiences with CFD applications to F-22 design. In order to meet the SBD tempo, rapid turnaround of CFD applications will be ever more crucial.

There is no single value for turnaround time that one can use as the absolute target. CFD applications vary considerably in scope depending upon the nature of the design problem and customer needs. The turnaround time is strongly influenced by the level of CFD code as mentioned in Section 4.1. Lower-level codes offer rapid turnaround whereas higher-level codes take longer. Due to the limitations of the lower-level codes in modeling many flows of interest (see Section 4.1.1), it is absolutely essential that the turnaround time of the higher-level codes be made comparable to that of the lower-level codes.

A typical CFD application process consists of three steps: (i) geometry acquisition and grid generation; (ii) running the flow solver, and (iii) processing flow solver output to extract the desired aerodynamic data.

4.2.2.1   Geometry Acquisition and Grid Generation

Acquiring geometry from a CAD system and generating a grid on it can be a major bottlenecks. Many times, the output of a CAD system requires "cleaning up" before a suitable grid can be generated on it. The clean up is in the nature of plugging-up gaps and making sure that geometric integrity is preserved in the transfer process. Differences between the surface geometry used by the CFD method and the CAD geometry introduce computational uncertainty that must be addressed.

Considering that the "wetted" surface is a subset of the CAD geometry, a software package that eliminates the need for the non-value-added clean-up activity is invaluable. As far as grid generation is concerned, the process needs to be fully automated with no manual "rework." At present, rework is almost always required to improve grid quality. The quality of the first grid is usually not satisfactory. Either the flow solver fails to converge on it or the grid is unable to resolve key flow features. Rework increases turnaround time, and costs, of configuration analyses. Morrison and Hemsch [54] identified high quality grids as the first step to obtaining a high quality solution. Their conclusion is based on a statistical analysis of several viscous solutions of a wing-body configuration focused on drag prediction.

4.2.2.2   Running the Flow Solver

Reducing the run times of flow solvers has attracted considerable attention in the past. Advances in algorithms and the use of high-performance computers have had a significant impact. At the present time a steady viscous analysis of a full aircraft configuration can be performed in a matter of hours on highly parallel computers. However, even this level of speedup is insufficient. When a large number of runs are to be made on a single model to produce the amount of aerodynamic data required to meet design needs, the total span of time can reach unacceptable proportions. An even more challenging situation arises when the configuration geometry also changes and multiple analyses have to be performed on each variation. This is precisely what SBD demands!

Lack of robustness of flow solvers is another important factor that necessitates making multiple runs to get just one solution. The goal ought to be: *one run, one solution*. Further research in improved algorithms to enhance robustness must be continued. It should also be noted that the higher-level methods have been rather

ineffective to date in supplying unsteady aerodynamics data in a timely and cost-effective fashion; most design projects currently rely on lower-level linear potential methods. Advances in more efficient algorithms for time-dependent analyses are urgently needed.

4.2.2.3   Processing Flow Solution

The third and final step in CFD analysis involves processing flow solution (i.e., flow solver output) to extract engineering data from the flow solver output. Significant advances in visualization software have been made over the past twenty years. Although the available software packages provide the necessary features and capabilities to carry out the process, it continues to be time consuming and labor intensive. As pointed out by Wooden and Azevedo [46], one major issue identified early in their use of CFD for developing JSF F-35 outer mold lines was the difficulty in manipulating large CFD datasets, approximately 1.5 Giga Bytes per solution!

With continuous reductions in grid-generation and flow-solver run times, and increasing use of CFD, much of the knowledge will remain buried in the flow solver output unless even faster and more efficient means of extracting it are developed. Dramatic improvements in man-machine interfaces are needed to accomplish this.

The challenge for the CFD community is clear: develop appropriate technologies and integrate them in a manner that brings the turnaround time for each analysis to a matter of minutes. The list of potential enabling technologies includes streamlined interfaces to CAD systems; standard data-exchange protocols; automated grid generation; highly scalable parallel processing of flow solver software; and intelligent systems for data analysis and management, to name a few.

4.2.3   Cost

Costs associated with CFD application include both labor and computing. At present, labor expenses are mainly connected with pre- and post-processing steps. For higher-level CFD codes, the labor expenses are still beyond the acceptable range. Progress in developing streamlined interfaces between grid-generation methods and CAD systems is crucial to reducing the geometry acquisition/ grid generation times. As a matter of fact, technologies needed to reduce labor hours also contribute significantly to turnaround time reduction.

Computing costs mainly relate to running the flow solver and may include grid generation in some instances. Computers with high processing speeds and large memory are typically needed to produce the desired amount of data on schedule. The IPPD design process will most likely require that the full range of data be generated over a matter of days, not months. Computing expenses to suit this kind of timeframe must not be so large that the total product development cost increases rather than decreases.

Consequently, cost and computational efficiency of the entire hardware and software system are very important considerations for effective CFD use in the future. Strategies for increasing computational efficiency and reducing cost will have to be an integral part of all future plans for CFD development and application.

5.0   CONCLUDING REMARKS

Today's marketplace for military aircraft is quite different from the one we have had for most of the 20th century in one critical aspect. Increased performance at ever increasing costs is no longer acceptable. The goal instead is increased performance at an affordable cost. Also it is expected to be the norm for the foreseeable future. Military aircraft of the future are likely to be equally as complex as the ones in service today, if not

more so. Advances in technology are expected to continue at an accelerated pace. These advances will have to be incorporated into new designs, or used for upgrading the existing airplanes, because the customer demands technological superiority. But it must be accomplished at affordable costs.

Simulation based design offers a promising approach to effectively meet customer needs. SBD requires that quality data be delivered to design teams as early as possible so that more informed decisions can be made in the early stages of design. To meet this SBD requirement, we need to incorporate into the design process fast, accurate and cost-effective means of generating data for each contributing discipline as well as for complex interdisciplinary relationships among design variables. The disciplines include the traditional ones such as aerodynamics, structures, signatures, etc., and the nontraditional ones such as producibility and supportability.

Fast, accurate and affordable methods will increase productivity and reduce the number of expensive tests needed to support design data needs. Advanced computational methods that offer rapid turnaround capability will reduce design cycle time. Design teams can then explore a wider spectrum of alternatives within the schedule and cost constraints of a typical aircraft development effort than is currently feasible. The use of advanced methods may also reduce the number of cycles required for design closure. Design teams will be able to conduct extensive trade-offs needed to guide the evolution of a design in a direction that minimizes life cycle costs. Improved understanding of component interactions will permit design changes to be made early and thereby reduce risk and increase the probability of meeting all customer needs.

High-fidelity physics-based methods will play a crucially important role in the emerging SBD environment. These methods will help design teams expeditiously evaluate the impact of proposed modifications to an airplane as well as to develop new configurations. Significant improvements in the effectiveness of computational methods are, however, needed. Dramatic reductions in both turnaround time and cost are required. The issue of producing credible solutions of acceptable accuracy needs to be tackled head on. At present our ability to assess the credibility of computational estimates is severely hampered by our inability to quantify the associated computational uncertainty. Quantification of computational uncertainty is admittedly a monumental problem but it needs to be urgently addressed. The RTO-AVT-147 Symposium's focus on this issue is timely. Without an effective and practical solution, computational uncertainty will remain an Achilles' heel for realizing the full potential benefits of simulation based design.

6.0   REFERENCES

[1]   Augustine, N.R., "Augustine's Laws," Published by American Institute of Aeronautics and Astronautics, New York, NY, 1983.

[2]   Woodson, T.T., "Introduction to Engineering Design," McGraw-Hill Book Co., 1966.

[3]   Anon., "Sticker Shock: Estimating the Real Cost of Modern Fighter Aircraft," An Occasional Report by defense-aerospace.com, July 12, 2006.

[4]   Raymer, D.P., "Aircraft Design: A Conceptual Approach," AIAA Education Series, Published by AIAA, Washington DC, 1989.

[5]   "Design for Manufacturability," Tool and Manufacturing Engineers Handbook, Volume VI, Published by Society of Manufacturing Engineers, R. Bakerjian (ed.), 1992.

[6] Proceedings of the 1996 National Design Engineering Conference, Chicago, Illinois, March 18-21, 1996.

[7] Raj, P., "Aircraft Design in the 21st Century: Implications for Design Methods (Invited)," AIAA Paper 98-2895, June 1998.

[8] MacNeal, R.H., "Automatic Structural Design Optimization," Report No. SN392, Lockheed Aircraft Corporation, California Division, December 6, 1956.

[9] Mazelsky, B. and O'Connell, R.F., "The Integrated Use of Analog and Digital Computing Machines for Aircraft Dynamic Load Problems," Journal of the Aeronautical Sciences, Vol. 23, No. 8, August 1956.

[10] "Applied Computational Aerodynamics," Edited by P.A. Henne, Progress in Astronautics and Aeronautics, Vol. 125, American Institute of Aeronautics and Astronautics, Washington DC, 1990.

[11] Miranda, L.R., "Application of Computational Aerodynamics to Airplane Design," *AIAA Journal of Aircraft*, Vol. 21, June 1984, pp. 355-370.

[12] Chapman, D.R., Mark, H., and Pirtle, M.W., "Computers vs. Wind Tunnels for Aerodynamic Flow Simulations," AIAA Astronautics & Aeronautics, April 1975.

[13] Reuther, J., van Dam, C.P., and Hicks, R., "Subsonic and Transonic Low-Reynolds-Number Airfoils with Reduced Pitching Moments," AIAA Journal of Aircraft, Volume 29, 1992, pp. 297-298.

[14] Carle, A., Green, L.L., Bischof, C.H. and Newman, P.A., "Application of Automatic Differentiation in CFD," AIAA Paper 94-2197.

[15] Reuther, J., Jameson, A., Alonso, J.J., Rimlinger, M.J., and Saunders, D., "Constrained Multipoint Aerodynamic Shape Optimization Using an Adjoint Formulation and Parallel Computers," AIAA 97-0103, January 1997.

[16] Miranda, L.R., Elliott, R.D., and Baker, W.M., "A Generalized Vortex Lattice Method for Subsonic and Supersonic Flow Applications," NASA-CR 2865, December 1977.

[17] Youngren, H.H., Bouchard, E.E., Coopersmith, R.M., and Miranda, L.R., "Comparison of Panel Method Formulations and Its Influence on the Development of QUADPAN, an Advanced Low-Order Panel Method," *AIAA Paper 83-1827*, July 1983.

[18] Magnus, A.E., Ehlers, F.E., and Epton, M.A., "PANAIR - A Computer Program for Predicting Subsonic or Supersonic Linear Potential Flow About Arbitrary Configurations Using a Higher-Order Panel Method," NASA CR-3251, April 1980.

[19] Johnston, C.E., Youngren, H.H., and Sikora, J.S., "Engineering Applications of an Advanced Low-Order Panel Method," *SAE Paper 851793*, October 1985.

[20] Giesing, J.P., Kalman, T.P., and Rodden, W.P., "Subsonic Steady and Oscillatory Aerodynamics for Multiple Interfering Wings and Bodies," *Journal of Aircraft 9*, Oct. 1972, pp. 693-702.

[21] Chen, P.C., Lee, H.W., and Liu, D.D., "Unsteady Subsonic Aerodynamics for Bodies and Wings with

External Stores Including Wake Effects," *Journal of Aircraft 30*, May 1993, pp. 618-628.

[22] Chen, P.C. and Liu, D.D., "Unsteady Supersonic Computations of Arbitrary Wing-Body Configurations Including External Stores," *Journal of Aircraft 27*, Feb. 1990, pp. 108-116.

[23] "Transonic Aerodynamics," *Progress in Astronautics and Aeronautics*, Vol. 81, American Institute of Aeronautics and Astronautics, Washington DC, 1982, Nixon, D. (ed.)

[24] Murman, E.M. and Cole, J.D., "Calculation of Plane Steady Transonic Flows," *AIAA Journal 9*, January 1971, pp. 114-121.

[25] Boppe, C., "Transonic Flowfield Analysis for Wing Fuselage Configurations," NASA CR 3243, 1980.

[26] Caughey, D.A., and Jameson, A., "Progress in Finite-Volume Calculations for Wing-Fuselage Combinations," *AIAA Journal 18*, Nov. 1980, pp 1281-1288.

[27] Hicks, R.M. and Henne, P.A., "Wing Design by Numerical Optimization," *AIAA Paper 77-1247*, 1977.

[28] Borland, C.J. and Rizetta, D.P., "Transonic Unsteady Aerodynamics for Aeroelastic Applications, Vol. I, Technical Development Summary for XTRANS3S," AFWAL-TR-80-3107, 1982.

[29] Samant, S.S., Bussoletti, J.E., Johnson, F.T., Burkhart, R.H., Everson, B.L., Melvin, R.G., Young, D.P., Erickson, L.L., Madson, M.D., and Woo, A.C., "TRANAIR: A Computer Code for Transonic Analysis of Arbitrary Configuration," *AIAA Paper 87-0034*, January 1987.

[30] Jameson, A., Schmidt, W. and Turkel, E., "Numerical Solution of the Euler Equations by Finite-Volume Methods Using Runge-Kutta Time-Stepping Schemes," *AIAA Paper 81-1259*, June 1981.

[31] Rizzi, A., "Damped Euler Equation Method to Compute Transonic Flow About Wing-Body Combinations," *AIAA Journal 20*, Oct. 1982, pp. 1321-1328.

[32] "Computational Aerodynamics Based on the Euler Equations," AGARD-AG-325, September 1994, Sloof, J.W. and Schmidt, W. (eds.)

[33] Weatherill, N.P., and Forsey, C.R., "Grid Generation and Flow Calculations for Aircraft Geometries," Journal of Aircraft, Vol. 22, No. 10, 1985, pp. 855-860.

[34] Benek, J.A., Buning, P.G., and Steger, J.L., "A 3-D Chimera Grid Embedding Technique," AIAA Paper 85-1523, June 1985.

[35] Bangert, L.H., Johnston, C.E., and Schoop, M.J., "CFD Applications in F-22 Design," *AIAA Paper 93-3055*, July 1993.

[36] Raj, P. and Harris, B.W., "Using Surface Transpiration with an Euler Method for Cost-effective Aerodynamic Analysis," *AIAA Paper 93-3506*, August 1993.

[37] Jameson, A., Baker, T.J., and Weatherill, "Calculation of Inviscid Transonic Flow over a Complete Aircraft," AIAA Paper 86-0103, Jan. 1986.

[38] Tidd, D.M., Strash, D.J., Epstein, B., Luntz, A., Nachshon, A., and Rubin, T., "Application of an Efficient 3-D Multigrid Euler Method (MGAERO) to Complete Aircraft Configurations," *AIAA Paper 91-3236-CP*, 1991.

[39] Karman, S., "SPLITFLOW: A 3D Unstructured Cartesian/Prismatic Grid CFD Code for Complex Geometries," *AIAA Paper 95-0343,* January 1995.

[40] Goble, B.D., King, S., Terry, J. and Schoop, M., "Inlet Hammershock Analysis Using a 3-D Unsteady Euler/Navier-Stokes Code," *AIAA Paper 96-2547*, July 1996.

[41] Guruswamy, G.P., "Unsteady Aerodynamics and Aeroelastic Calculations for Wings Using Euler Equations," *AIAA Journal 28*, 1990, pp. 461-469.

[42] Campbell, R.L. and Smith, L.A., "A Hybrid Algorithm for Transonic Airfoil and Wing Design," *AIAA Paper 87-2552*, 1987.

[43] Raj, P., Kinard, T.A. and Vermeersch, S.A., "Vortical Flow Simulation Using An Unstructured-Grid Euler Method," *ICAS-96-1.4.5*, September 1996.

[44] Moin, P. and Mahesh, K., "Direct numerical simulation: a tool in turbulence research," CTR Manuscript 166, Center for Turbulence Research, Stanford University, Stanford, California, April 1997.

[45] Goble, B.D. and Hooker, J.R., "Validation of an Unstructured Grid Euler/ Navier-Stokes Code on a Full Aircraft with Propellers," *AIAA Paper 2001-1003, Aerospace Sciences Meeting, 2001*

[46] Wooden, P.A., and Azevedo, J.J., "Use of CFD in Developing JSF F-35 Outer Mold Lines," *AIAA-2006-3663, 24th Applied Aerodynamics Conference, 2006.*

[47] Smith, B. R., "The *k-kl* Turbulence Model and Wall Layer Model For Compressible," *AIAA Paper 1999-0365*, June 1999.

[48] Mehta, U.B., "Guide to Credible Computer Simulations of Fluid Flows," Journal of Propulsion and Power, Vol. 12, No. 5, Sep-Oct 1996, pp 940-948.

[49] Wooden, P.A., Smith, B.R. and Azevedo, J.J., "CFD Predictions of Wing Pressure Distributions on the F-35 at Angles-of-Attack for Transonic Maneuvers," *AIAA-2007-4433, 25th Applied Aerodynamics Conference, 2007*

[50] Cunningham, A.M., Jr., Anderson, W.D., Patel, S.R., and Black, C.L., "Lockheed Martin Aeronautics Perspective on Aircraft Buffet Prediction and Analysis," Symposium on Flow-Induced Unsteady Loads and Impact on Military Applications, Applied Vehicle Technology Panel (AVT), NATO, Budapest, Hungary, 25-28 April 2005..

[51] Smith, B. R., "An Explicit Algebraic Stress Model for Simulations of Flows with Streamwise Curvature," *AIAA Paper 2003-3738*, June 2003.

[52] Bradshaw, P., "Turbulent Secondary Flows," *Annual Review of Fluid Mechanics*, 19, 1987, pp. 53-74.

[53] Giunta, A.A., Golividov, O., Knill, D.L., Grossman, B., Haftka, R.T., Mason, W.H., and Watson, L.T.,

"Multidisciplinary Design Optimization of Advanced Aircraft Configurations," MAD Center Report 96-06-01, Virginia Tech, Blacksburg, VA.

[54] Morrison, J.H., and Hemsch, M.J., "Statistical Analysis of CFD Solutions from the Third AIAA Drag Prediction Workshop (Invited)," *AIAA 2007-254, 45th Aerospace Sciences Meeting, January 2007.*

APPENDIX A: TRADITIONAL DESIGN PROCESS

A traditional aircraft design process may be divided into roughly three stages, conceptual, preliminary and detail. Key features of these three stages are outlined in this Appendix.

Conceptual

In this stage, the task is to conceive solution concepts--typically represented by sketches--that can functionally meet the design requirements, such as range, payload, takeoff and landing distances, etc., as dictated by the intended mission. A good sketch includes the approximate wing and tail geometry, fuselage shape, engine location, etc. This information can be used to estimate performance and weight fractions by comparison to previous designs. A "sizing" process uses these estimates to determine required total weight and fuel weight to perform the mission. The "first-order" sizing provides the necessary information to develop an initial layout with more details such as landing gear, inlet ducts, cockpit, major avionics, etc., to ensure that everything fits.

The initial layout is analyzed to refine the first set of estimates of aerodynamics, weights, and installed propulsion characteristics. Performance capabilities are calculated and compared with design requirements. Optimization techniques may be used to determine the lightest or lowest-cost aircraft to meet the mission. The results of these trade-off studies are used to revise the initial layout.

The process is repeated many times, and for several competing concepts depending upon the available resources, in attempts to devise an "optimal" solution. Functional specialists periodically review the design to ensure its soundness from their perspective. For example, flight controls experts may conduct a six-degree-of-freedom simulation to verify the adequacy of the control surfaces. The resulting layout is then ready for preliminary design.

Preliminary

During the preliminary design stage, specialists in many disciplines, such as structures, landing gear, control systems, etc., design and analyze their portion of the aircraft. Testing is initiated in areas such as aerodynamics, propulsion, structures, and stability & control. Appropriate changes are made to the design based upon the results of the analyses and tests.

A key activity at this stage is "lofting" where accurate mathematical models of the outside shape are generated to ensure proper fit between different components. The ultimate objective of the preliminary design effort is to establish enough confidence that the airplane can be built on time and at the estimated cost while meeting all customer requirements. A mockup is usually constructed to support this objective.

Detail

During the detail design stage, actual pieces to be fabricated are precisely defined. For example, the wing box is designed and analyzed as a whole during the preliminary stage. It must now be broken down into individual ribs, spars, and skins, each of which is separately designed and analyzed. In addition, more extensive testing is

performed. Problems not obvious in the previous stages may be uncovered requiring further design iterations. It may be necessary to revise the design layout, or go even one step back to conceive new solution concepts.

Another important activity during this stage is to define the fabrication and assembly processes, starting from the smallest and simplest parts to the full aircraft. Sometimes, changes are suggested so that the design can be manufactured more easily and economically. This may require making design changes with potentially adverse impact on performance and weight. It may even be necessary to make some adjustments to the initial design requirements.

Success ultimately depended upon the quality and timeliness of decisions throughout the design process. The quality and timeliness of decisions in turn depended upon the availability of quality data at the decision-maker's disposal in a timely manner.

Computational Uncertainty: *Achilles' Heel*
of Simulation Based Aircraft Design (Invited)

Paper No. P1

Discusser's Name: A. Cenko

Question: Commercial aircraft manufacturers have been using CFD for wing-pylon-engine integration for many years. Integrating weapons on military aircraft is a simpler problem. Lockheed was very successful in solving a weapon integration problem on the F-35 after it was uncovered in wind tunnel testing. Do you think that weapon integration will ever be used in the preliminary design phase?

Author's Reply: The short answer is yes. And it should be. The key challenges remain how reliable the answers are and how much time and resources are available in the preliminary design phase. Many problems need to be addressed in this phase within limited time and funding. Of course, the more cost-effective and accurate methods are, the more likely they are to be applied in the preliminary design phase.