Aerodynamic Database Requirements for the Detailed Design of Tactical Aircraft: Implications for the Expanded Application of CFD

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ABSTRACT

The implications of a compressed design cycle relying heavily on CFD in the design of a tactical fighter aircraft are explored. The number of test points required for design is estimated along with the cost for generating simulations for these test points using current methods. Standard CFD approaches currently employed in design and analysis are used as the basis for this estimate. Given the cost of meeting the data requirements with CFD, data requirements which can be satisfied cost effectively with wind tunnel testing are identified, as are parts of the parameter space where CFD can provide large cost savings and schedule compression. Areas where research is needed to enable a compressed, CFD-based design cycle are discussed.

1.0 BACKGROUND

Over the past several decades, the duration of tactical aircraft development programs has extended dramatically. The F-16 contract was awarded in 1975, and initial operating capability (IOC) was achieved four years later. In contrast, the F-35 contract was awarded in 2001 and IOC required 14 years or more for each of the three variants. Figure 1 shows the increase in time required for both first flight and IOC for US tactical fighter programs from 1960. This trend has been recognized as a major problem for competitiveness and cost. This is an era of rapid technical change and competition. Extended development periods risk production of aircraft with obsolete capabilities by the time the product reaches IOC.

The US Department of Defense recognizes this challenge and has recently publicized the need for greatly compressed development cycles. In 2019, Dr. Will Roper, then the Assistant Secretary of the Air Force for Acquisition, Technology and Logistics, stated, “Based on what industry thinks they can do and what my team will tell me, we will need to set a cadence of how fast we think we build a new airplane from scratch. Right now, my estimate is five years. I may be wrong, I’m hoping we can get faster than that.” Dr. Roper cited the opportunities for digital engineering as a key enabling building block to meet this goal.[1] This objective for compressed design cycles and for the use of digital engineering to enable the objective to be met has enormous implications for the way that aerodynamic design and analysis are performed on future tactical aircraft development programs.

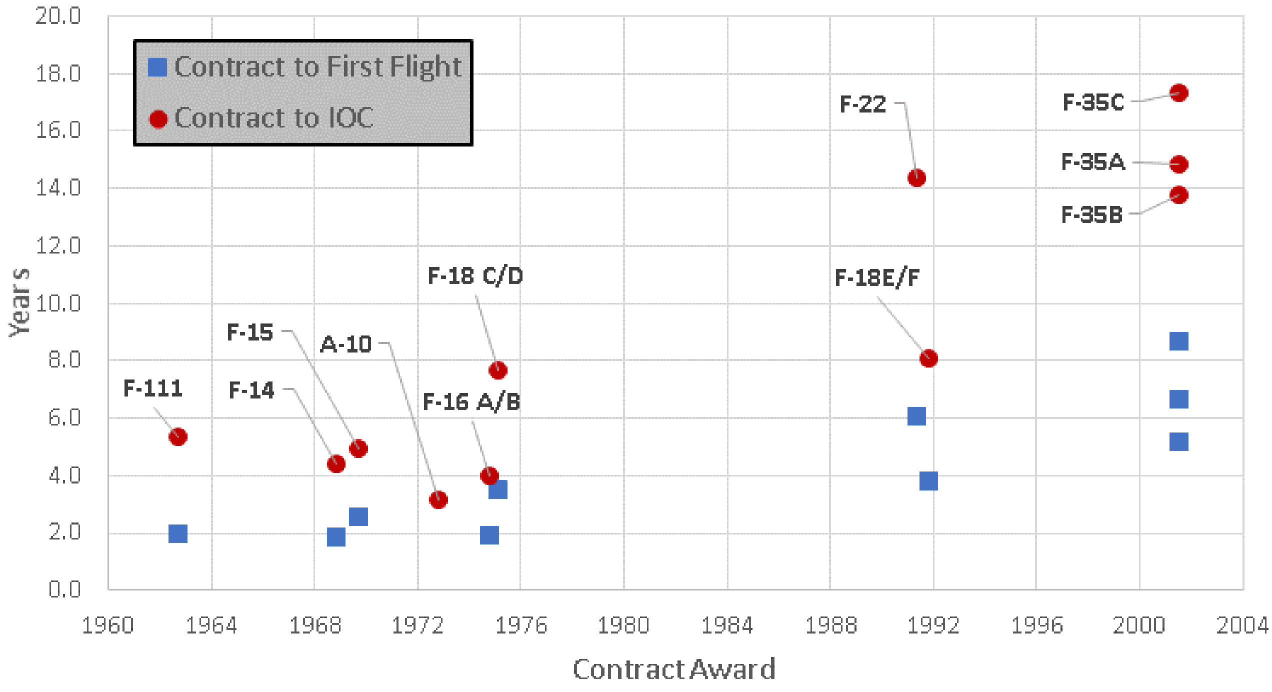
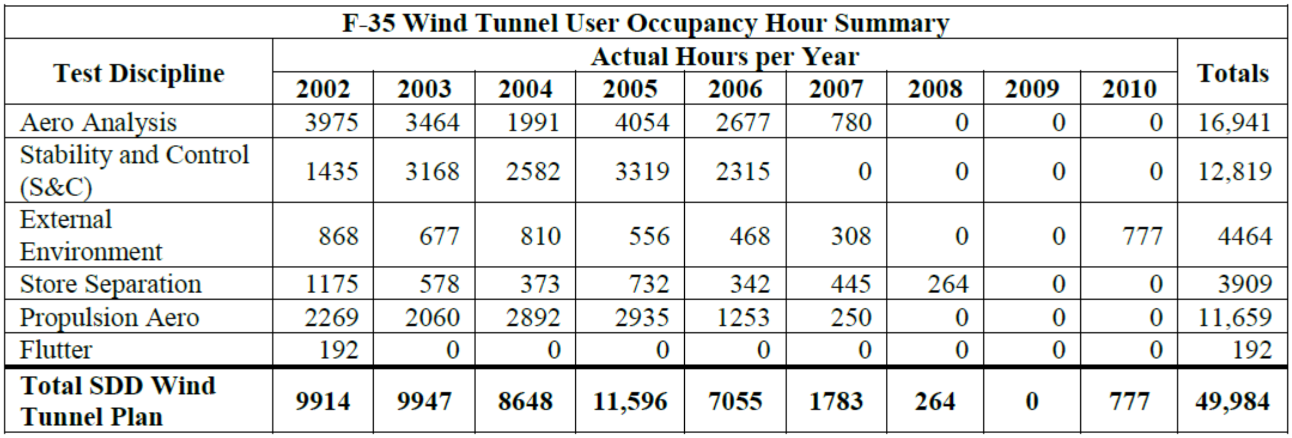


Figure 1 Times to first flight of prototype, and from production contract to Initial Operating Capability for US Tactical Aircraft since 1960

It is important to distinguish the challenges to the expanded application of CFD to fighter aircraft design and analysis as compared to transport aircraft design. The flight envelope for a fighter aircraft is far more extensive than for a transport. The fighter design envelope includes low speed, transonic, sonic and supersonic regimes with much higher angle of attack and yaw capabilities than a transport. Unlike transport aircraft, where tube and wing configurations have been optimized for transonic flow for over 60 years, each new generation of fighters is significantly different from its predecessors. While the F-16 and F-35 are both single engine, multi-role fighters, the F-16 has a single vertical tail while the F-35 has two canted vertical tails. The F-16 has a single, relatively straight inlet and diffuser with a conventional diverter. In contrast, the F-35 has a bifurcated serpentine inlet duct with a bump diverter. The F-16 has external weapons carriage only, while the F-35 has internal weapons bays. A next generation fighter will undoubtedly have a different configuration and different requirements from fifth generation fighters. As a result of these configuration changes, design methods, and in particular CFD, have a limited heritage of relevant testing and validation for a new generation of fighter aircraft. This greatly increases the need to validate computational tools when they are to be applied to fighter aircraft design.

The newest US tactical fighter aircraft to go into production, the F-35, provides context for the recent state-of-the-art for aerodynamic development. Table 1 summarizes the F-35 wind tunnel development hours.[2] It should be noted that this plan was initiated 20 years ago. CFD was highly capable and was used extensively in the design and development of both the prototype and the production F-35. CFD capabilities have improved significantly in terms of both computing hardware and software over the past 20 years. We would expect a comparable development program starting today to have a larger proportion of CFD and less wind tunnel testing than was used for the F-35 even without a compressed development schedule. Nevertheless, the quantity and nature of the F-35 wind tunnel testing program serves as an inventory of the data required for fighter development. In addition, the inertia of established developmental processes and bureaucracies and the challenges in quantifying the uncertainty in CFD-based design data may constrain the use of CFD to dramatically reduce development cycles unless critical challenges are addressed.

Table 1 Wind Tunnel Hours for F-35 Development



F-35 Wind Tunnel User Occupancy Hour Summary										
Test Discipline	**Actual Hours per Year**									**Totals**
	2002	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	
Aero Analysis	3975	3464	1991	4054	2677	780	0	0	0	16,941
Stability and Control (S&C)	1435	3168	2582	3319	2315	0	0	0	0	12,819
External Environment	868	677	810	556	468	308	0	0	777	4464
Store Separation	1175	578	373	732	342	445	264	0	0	3909
Propulsion Aero	2269	2060	2892	2935	1253	250	0	0	0	11,659
Flutter	192	0	0	0	0	0	0	0	0	192
Total SDD Wind Tunnel Plan	**9914**	**9947**	**8648**	**11,596**	**7055**	**1783**	**264**	**0**	**777**	**49,984**

The accuracy of CFD relative to wind tunnel testing is one significant impediment to the increased application of CFD for development. CFD accuracy is sensitive to physical models of turbulence and transition as well as discretization errors arising from insufficient mesh resolution. Driving the uncertainty to acceptable levels can dramatically increase the cost and span time required for a CFD simulation through increased mesh resolution and application of more computationally intensive modeling methods. The span time required for CFD analysis may also prove to be a challenge. From Table 1, we can see that the wind tunnel testing component of the 15 year F-35 development effort was 6 years, or 40% of the duration of the development program. Other activities require significant span time, and require largely completed aerodynamic analysis prior to their initiation. These activities include structural design and analysis, tooling and procurement. If we assume that all aspects of aircraft development are compressed by a factor of 2/3, a five year development effort would require aerodynamic and S&C analysis to be completed in two years. Given the number of test points required, this could prove challenging to achieve with CFD. It would be equally, or more challenging, to achieve with a test-based program.

2.0 OBJECTIVE AND APPROACH

In this paper we estimate the computational effort in terms of CPU core hours to design a fighter aircraft. To obtain this estimate, we assess the aerodynamic and stability and control data points required for tactical fighter aircraft development. For each test point we consider the flight conditions, control surface configuration, and design need error tolerance, to assign a CFD complexity category. These categories are the basis of a quantitative estimate of the computational resources and a qualitative description of CFD methods appropriate for simulations in this category. This enables us to make a very rough estimate of the computational requirements for a tactical fighter development program and an order of magnitude estimate of the cost of computer hardware required to satisfy the requirements. This estimate assumes that individual CFD simulations are run for each test point. We also assume that a CPU-based high performance computer with a standard high speed interconnect between nodes is employed. There are a variety of potential schemes and approaches that could be employed to reduce the CFD application cost. These include application of GPU enabled HPC and CFD software, advanced algorithms, and methods for extracting design data for multiple test points from an unsteady simulation. We do not make quantitative estimates of the computational savings that could be achieved with these alternate approaches in this paper. However, these advanced CFD approaches could be assigned a factor representing cost and computational savings, and that factor applied to the estimates in this paper.

This work provides some perspective on the challenges if we want to obtain all design data using CFD. Based on computational cost and schedule requirements, we suggest areas where wind tunnel testing would have the greatest cost and schedule benefits in the course of a compressed development effort. We highlight areas where CFD provides unique and powerful analysis capability that could improve the development process. Finally, we highlight areas where CFD research and development efforts should be focused to enable a dramatically compressed design cycle.

3.0 CFD CAPABILITIES REQUIRED FOR DESIGN

To assess CFD requirements, we define three categories of CFD analysis, A, B and C. Each category comprises simulations of comparable levels of computational complexity and intensity. By estimating the number of simulations required for each complexity category, we can better assess the magnitude of the computational effort.

A. This category contains points where $\alpha < 10°$, $\beta < 10°$, and control surface deflections < 10°. Test points needed for conceptual design, cruise point predictions of lift and estimates of drag and pitching moment are within this category. Data used for design cycle iterations where reasonably accurate estimates of incremental lift, drag and moment variation due are needed to assess incremental design changes are in this category. Since the accuracy requirements for loads prediction are usually relatively relaxed, most loads data falls in this category. Test points in this category can be predicted by applying steady-state, Reynolds averaged Navier-Stokes (RANS) methods on grids with modest levels of resolution (10-30M finite volume cells). These methods are computationally efficient.

B. This category contains points where $10° < \alpha < 20°$, $\beta < 10°$, and where control surface deflections are between 10° and 20°. This category is appropriate for production configurations with gaps, ECS inlets and exhaust, realistic nozzles, and nozzle jet effects. Data points in this category require a highly resolved RANS simulation, often with between 30M and 300M mesh points. Advanced turbulence models may be required. In some cases, a time accurate, scale resolving simulation on a modest mesh < 100M mesh points may be required. A substantial validation effort may be required as part of the application of CFD methods in this regime.

C. This category is for points where $\alpha > 20°$ or $\beta > 10°$. Cases with highly deflected control surfaces are included. These are challenging flight conditions with significant flow separation, vortex interactions, vortex burst phenomena, shock induced separation, shock/vortex interactions, and other complex flow phenomena. Many test points in this category need accurate moments for development of control laws. Unsteady flow effects linked to maneuver conditions might be required. Approximate predictions might be possible with a highly resolved RANS simulation, but in most cases a scale resolving simulation with either hybrid/RANS large eddy simulation (LES) or wall modelled large eddy simulation (WMLES) is required.

The CFD methods required for each category have characteristics that drive the computational requirements. More details on the methods required for each category follow.

A. Most data points in this category can be captured with reasonable accuracy with a RANS solution. For angles of attack below 5°, a standard two equation turbulence model with a Bousinesq stress-strain relationship is often sufficient. In transonic and supersonic flight conditions there are not usually regions with large shock induced separations. Meshes with approximately 10M mesh points can capture some of the data points at the low complexity end of this category. Wall functions may be acceptable, at least over some parts of the configuration. At the upper end of this range, vortices have lifted off of the surface, and surface oil flows have become highly complex, as shown in Figure 2.[3] The boundary layer flows are highly three dimensional. Capturing the vortices accurately may require an algebraic stress model. or rotation and curvature correction, such as the SA-RC model.[4] Flow conditions with strong shocks or vortices that have lifted off from the surface will require larger meshes with 30-50M mesh points. Solutions in this category may require 1,000 to 8,000 core hours to complete. For the purposes of estimates on requirements for this work, we will assume 3,000 core hours per data point.

B. Many data points in this category can be captured with a highly resolved RANS analysis with an advanced turbulence model. Accurate predictions of drag and pitching moment will require refined meshes that capture relatively small geometric features such as antenna or gaps in control surfaces, nozzles, and other features. Near wall mesh resolution inside the viscous sublayer without wall functions is almost certainly required. A highly refined mesh with 30M to 300M mesh points, potentially with adaptive refinement, may be necessary for acceptable accuracy and fidelity. Accurate turbulence models capturing rotational effects in vortices are required in RANS simulations. Hybrid RANS/LES methods have been demonstrated to capture vortical flows well, at the cost of requiring a time accurate simulation. WMLES is also potentially applicable to cases in this regime. Solutions with modest mesh sizes of approximately 50M may be sufficient for scale resolving simulations for flows in this category. Simulations in this category may require 10,000 to 40,000 core hours. For the purposes of estimating computational requirements for this work, we will assume 20,000 core hours per data point.

C. Capturing test points in this category usually requires a time accurate analysis due to large regions of flow separation, complex vortical flows, and the need to generate accurate inputs for control law development. Historically data in this regime is gathered almost exclusively with wind tunnel measurements. WMLES and Hybrid RANS/LES are the methods of choice in this category. Relatively long time duration simulations may be required to obtain valid statistical averages, increasing computational requirements. Mesh requirements vary widely, and like category B could be between 30M and 300M mesh point. Where separation arises from a smooth surface, a highly resolved surface mesh may be required. Simulations in this category consume 20,000 to 100,000 core hours. For the purposes of estimating computational requirements for this work, we will assume 50,000 core hours per data point.

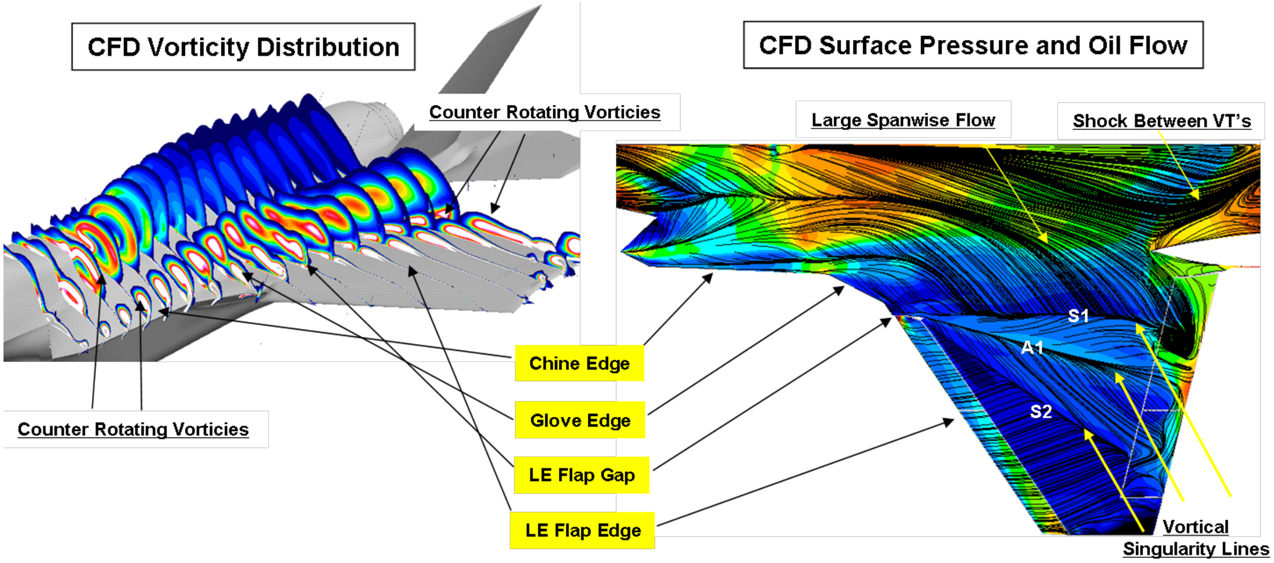


Figure 2 Vortex Pattern, contours of pressure coefficient and simulated oil flow for F-35 at a transonic flight condition.[3]

4.0 DATA REQUIREMENTS FOR THE DEVELOPMENT OF TACTICAL AIRCRAFT

Challenging requirements and the complexities of highly integrated air vehicles have driven the need for increasing amounts of high fidelity aerodynamic data obtained in ever quicker cycles as configurations mature. In previous programs, aerodynamic modeling has often been less than perfect leading to "fly-fix-fly" scenarios, which drove up costs. Desired aircraft attributes were not always achieved. Improvements in predictive capability provide a means to improve pre-flight aerodynamic models, which significantly increases the likelihood that the desired aircraft attributes are achieved during flight test. One of the guiding philosophies of the F-35 program was to develop aerodynamic models with enough fidelity and accuracy to enable the reduction of flight test points; a flight test hour is significantly more expensive than an hour of wind tunnel testing. It is within this context that nearly 50,000 User Occupancy Hours (UOH) of wind tunnel testing were used to support the development of three F-35 aircraft variants, each with unique outer-mold-lines and requirements. The payoff for this strategy was realized as "the number of dedicated (performance) test points flown for any one variant was roughly half the number used for previous fighter aircraft."[5] The need to develop three unique configurations as well as the Short Take-Off and Vertical Landing (STOVL) requirement significantly increased the UOH required to achieve the desired predictive modeling fidelity. An exact accounting would be difficult to achieve, but it is reasonable to assume that a single variant, non-STOVL program could have achieved the same level of evaluation and optimization with roughly 50% of the F-35 total - 25,000 UOH.

Many types of wind tunnel tests are required for the development of a tactical aircraft. Aero-performance and stability and control both require their own version of force and moment tests. Stability and control often requires additional specialized testing including rotary balance, spin, and free-to-roll testing. Wind tunnel tests focussed on airframe and captive store loads are needed for structural design. Propulsion requires wind tunnel testing for inlet performance and engine/inlet compatibility as well as tests to determine the impact of jet-effects. Many of these test types require separate test facilities and models to cover the full Mach range of the aircraft (low-speed, transonic, and supersonic). Current aircraft designs are highly integrated. A design change in an unrelated engineering field can drive a need to update aerodynamic models, requiring additional tests. The scale of data and timelines required to update the aerodynamic models to then be fed back through additional design cycles is one of the reasons why development timelines have grown to 15 years.

Industry is now being challenged to reduce development timelines, presumably without stepping back from the hard fought gains in predictive aerodynamic capability. The expanded use of CFD can help to reduce the reliance on large numbers of wind tunnel tests. The scope and breadth of this topic is large. To make the scope tractable, we focus on transonic force and moment testing that supports aero-performance and stability and control data needs. Together, this testing made up roughly 30% of all non-STOVL F-35 wind tunnel hours.

Given the tri-variant nature of the F-35 program and the large variation in complexity and scope found in each of the wind tunnel tests, no single test matrix provides a good understanding of program data. To better facilitate this discussion, example test matrices have been created. The use of example matrices allows for a more detailed discussion of data requirements without getting bogged in the idiosyncrasies of the F-35 program and the specific time relevant details inherent in a specific test. The size and scope of the example test matrices are reasonable approximations of the F-35 testing program. They mimic database testing and are constructed of relatively square families of control surface deflections, Mach, alpha, and beta. Database testing results in large matrices, but this is counterbalanced by the absence of multiple aircraft configurations for trade-studies as well as a lack of external stores; both of which can be highly configuration and program specific. For example, a test matrix used at the beginning of the program may be a third of the size of this example, but may be applied to three different configurations, resulting in the same number of data points.

4.1 Example Transonic Aero-Performance Test Matrix

Aero-performance data is typically used to create three degree-of-freedom (3DOF) aerodynamic databases that are used to calculate aircraft performance. During development, these calculations are compared and tracked against requirements. Typical requirements include range, acceleration, turn rates, take-off and landing distances, and maximum Mach. During the course of the program this data is acquired multiple times to determine impacts of configuration changes driven by other engineering teams or to improve performance. Calculated performance often runs close to requirements. Sensitivities to aerodynamic coefficients typically drive desired accuracy to levels that are difficult to attain. For this reason, great care is taken to reduce sources of uncertainty during aero-performance wind tunnel testing. Every model, balance, and wind tunnel facility has different levels of measured data uncertainty. Typically, the goal is to limit uncertainty levels to between 5 and 7 drag counts. Important aspects of this testing include obtaining high resolution in the independent variables like control surface deflections, Mach, and alpha. Leading- and trailing-edge flap deflections used in the example test matrix are shown in Table 2. All runs are alpha pitch-pause sweeps at 0 beta. Minimum alpha is set at -6° and max alpha is a function of Mach number. Data is taken in 0.50° increments from -6° up to +10° alpha to accurately capture drag polar shapes. Increments in alpha are increased to 1.0° for 10° to max alpha for the given Mach number. Mach numbers and the associated max alpha in the test matrix are also shown in Table 2. A set of seven horizontal tail deflections are obtained at 0° Leading-Edge Flap (LEF) for each unique Trailing-Edge Flap (TEF) deflection. The described example aero-performance test matrix results in 119 individual configurations and 71,094 unique data points. Based on rough estimates, this test matrix would require approximately 320 UOH. Test costs are highly variable and sensitive to a number of factors that are beyond the scope of this paper. To allow some understanding of the cost associated with running this example test matrix in a large transonic wind tunnel we use an estimate of $12,000 /UOH, resulting in a cost of approximately $3.8M.

Table 2 Representative Aerodynamics and Performance Test Database Parameter Space

	Alpha	
MACH	min	max
0.40	-6	42
0.60	-6	42
0.80	-6	42
0.85	-6	42
0.90	-6	42
0.95	-6	35
1.05	-6	35
1.20	-6	24
1.40	-6	20
1.60	-6	20
1.80	-6	20
2.00	-6	20

LEF/TEF Combinations	
LEF	TEF
-2.5	-10.0
0.0	-5.0
2.5	0.0
5.0	2.5
7.5	5.0
10.0	7.5
13.0	10.0
16.0	
20.0	
30.0	
35.0	

Conditions for Horizontal Tail Control Power		
LEF	TEF	HT Deflections
0.0	-10.0	-20, -10, -5, 0, 5, 10, 20
0.0	-5.0	-20, -10, -5, 0, 5, 10, 20
0.0	0.0	-20, -10, -5, 0, 5, 10, 20
0.0	2.5	-20, -10, -5, 0, 5, 10, 20
0.0	5.0	-20, -10, -5, 0, 5, 10, 20
0.0	7.5	-20, -10, -5, 0, 5, 10, 20
0.0	10.0	-20, -10, -5, 0, 5, 10, 20

This aero-performance wind tunnel matrix allows for a detailed examination of the CFD runs required to replace a wind tunnel test in a future development program. Before an accounting of the number and types of CFD solutions is made, a difference in approach between wind tunnel testing and CFD should be addressed. Wind tunnel test matrices are heavily optimized to increase efficiency and reduce costs. The small time frame required to complete an alpha sweep often results in a full sweep for most configurations. Though data for a 0° LEF configuration at alpha > 20° is not particularly useful, it is often not worth the added complexity to optimize the limits of an alpha sweep for every configuration and Mach being tested. This is not the case when running CFD, where further optimization has a significant impact. Control surface schedules are created and modified during the development program and this activity requires data with some range in alpha for all given control surfaces. To account for this, the number of unique data points has been reduced by limiting the alpha range of each LEF configuration to +/-10° from the LEF deflection. For example, the alpha range for a 10° LEF configuration is reduced from the -6° to 42° range tested in the wind tunnel (65 data points) to a more reasonable range of 0° to 20° (31 data points). When this change is made, the required CFD data points are reduced from 71,094 to 48,120. Despite the large reduction, a large number CFD solutions is required to replace a single wind tunnel test entry. Applying the CFD categories of solution difficulty from Section 3, the number of CFD solutions in each category is shown in Table 3. Roughly 60% of the CFD solutions needed to support aero-performance data requirements fall within the easiest of the three defined categories.

Table 3 Distribution of Aerodynamics and Performance Runs by CFD Category

	No. Of Solutions	%
Total CFD:	48,120	100%
Category A:	28,120	58%
Category B:	9,990	21%
Category C:	10,010	21%

4.2 Transonic Stability and Control Test Matrix

Stability and control data is typically used to create six degree-of-freedom (6DOF) aerodynamic databases that allow the development of flight control laws and to assess handling qualities. The accuracy and fidelity of the data is, in part, driven by the control law design. The importance of accurate aerodynamic modeling is increased when the flight control system incorporates Nonlinear Dynamic Inversion (NDI). “At its core, the NDI controller contains a model of the aerodynamics of the aircraft (including propulsion-aerodynamics) and a model of the aerodynamic and propulsion effectors. In order to minimize performance errors resulting directly from poor modeling, it was important to have a very detailed onboard model of the F-35 across the full operating envelope, and to account for discrete configuration changes and interactions between control surfaces. Parts of the flight envelope where aerodynamic characteristics can change rapidly (e.g. the transonic flight regime) require higher-fidelity modeling, with denser Mach and alpha breakpoints”.[6] The resulting aerodynamic databases contain large numbers of test points. “The current onboard models contain approximately 3 million data points. The original models were derived from wind tunnel testing.”[6] This testing provides base airframe aerodynamics along with control surface effectiveness and interactions. It is particularly important to document nonlinearities in all aerodynamic coefficients across the entire flight envelope. Data requirements lead to very large test matrices that require reductions in fidelity to be reasonable. The example test matrix was constructed by creating a set of baseline runs with a range of LEF with all other control surfaces set to zero. The matrix continues with data to support one-sided control power increments, one control surface at a time (TEF, HT, and rudder). These increments are obtained with a subset of two LEF deflections. The last section of the test matrix gives control surface interactions between TEF/HT and HT/rudder. Control surface deflections shown in Table 4 are all one-sided (not symmetric). All runs are alpha sweeps with data taken at 1° increments between a min and max alpha that are both a function of Mach. Mach numbers and their associated min and max alpha settings are also shown in Table 4. All alpha sweeps are completed at a range of betas between -10° to +10° at 2.5° increments. The example stability and control test matrix results in 56 individual configurations and 232,848 unique data points. Based on rough estimates, this test matrix would require approximately 465 UOH. Using the very approximate figure of $12,000 /UOH, this test would cost $5.6M.

Table 4 Representative Stability and Control Test Database Parameter Space

BASE Table			
LEF	TEF (L)	HT (L)	RUD (L)
0	0	0	0
10	0	0	0
20	0	0	0
35	0	0	0

	Alpha	
MACH	min	max
0.40	-10	40
0.60	-10	40
0.80	-10	40
0.85	-10	40
0.90	-10	40
0.95	-10	30
1.05	-5	30
1.20	-5	20
1.40	-5	20
1.60	-5	20
1.80	-5	20
2.00	-5	20

TEF Control Power	
LEF	TEF (L)
10	-30
35	-30
10	-20
35	-20
10	-10
35	-10
10	10
35	10
10	20
35	20
10	30
35	30

HT Control Power	
LEF	HT (L)
10	-30
35	-30
10	-20
35	-20
10	-10
35	-10
10	10
35	10
10	20
35	20
10	30
35	30

RUD Control Power	
LEF	RUD (L)
10	-30
35	-30
10	-20
35	-20
10	-10
35	-10
10	10
35	10
10	20
35	20
10	30
35	30

TEF / HT Interaction Table		
LEF	TEF (L)	HT (L)
10	-30	-30
35	-30	-30
10	-30	30
35	-30	30
10	30	-30
35	30	-30
10	30	30
35	30	30

HT / RUD Interaction Table		
LEF	HT (L)	RUD (L)
10	-30	-30
35	-30	-30
10	-30	30
35	-30	30
10	30	-30
35	30	-30
10	30	30
35	30	30

Applying the same analysis used on the aero-performance matrix to the stability and control test matrix yields some different results. Optimizing the alpha ranges for each configuration and Mach provides a large reduction in unique data points, down from 232,848 to 95,418. Despite the large reduction, almost twice as many solutions are required to meet stability and control needs than aero-performance needs for a single test entry. Furthermore, when applying the three CFD category definitions, only 11% of the required solutions fall into the easiest category. The full breakdown is shown in Table 5.

Table 5 Distribution of Stability and Control Runs by CFD Category

	No. Of Solutions	%
Total CFD:	95,418	100%
Category A:	10,584	11%
Category B:	19,980	21%
Category C:	64,854	68%

5.0 CFD VERSUS TESTING ON FUTURE PROGRAMS

The role of CFD in development programs will continue to grow and evolve over the coming decades. Increases in computational capabilities and reductions in the cost of computing will facilitate the expansion in the use of CFD and reductions in testing. A challenge in this analysis is that the proportions of CFD and testing in the design process is a moving target. In this section we highlight opportunities and challenges to increased use of CFD in a tactical aircraft development effort.

5.1 Advanced analysis capabilities enabled by CFD

Expanded use of CFD brings with it advantages in capabilities that are difficult to obtain in a test. These advantages include rapid consideration of geometric variations in a timely fashion, multidisciplinary analysis, multiple uses of simulations, ability to simulate flight conditions and configurations accurately. These capabilities result in a reduction in the number of test points required when CFD is used instead of testing.

While expanded use of CFD poses challenges due to solution uncertainty, there are significant advantages to the application of CFD in place of sub-scale testing in the design process. CFD can be applied at full scale Reynolds numbers, where test results require sometimes complex adjustments to account for Reynolds number effects. CFD simulations can be conducted in free air, even in maneuver conditions, where wind tunnel testing has to be corrected for stings, struts, wind tunnel walls and in some cases instrumentation interference. In the traditional design process, aerodynamic, S&C and propulsion databases are developed independently. Sophisticated bookkeeping is required to merge the results of different tests with different models. This combination of increments necessarily includes simplifications that miss higher order interactions. A single simulations with a detailed CFD mesh can account for inlet spillage, jet effects, loads, aerodynamics and S&C. While a CFD-based design process might continue to use simplified models to account for individual functional disciplines, simulations with comprehensive models integrating effects implicitly improve efficiency and accuracy.

A CFD-based process also enables multidisciplinary analysis. A coupled aerodynamic structural model can be used to account for static and dynamic aero-elastic effects. This capability can increase the accuracy of aerodynamic and S&C analysis. Unsteady maneuvers can be simulated. Dynamic stability characteristics can be evaluated with relative ease with computations, while dynamic testing can be costly. Pitch, roll and yaw damping can be directly evaluated for a flight configuration. All of these capabilities can bring critical design characteristics forward in a program, helping to avoid costly problems that can cause unexpected schedule delays.

5.2 Challenges to the expanded application of CFD

Experts in the development of CFD codes recognize that physical models of turbulence, transition and combustion can introduce significant errors into a CFD simulation.[7] They also recognize the challenges involved in obtaining a grid resolved CFD solution for a complex configuration. There is a risk that program management and personnel generating CFD results may not appreciate the error bands for CFD analysis. In contrast, the sources of error for wind tunnel testing are well understood. The errors associated with turbulence modeling and numerical resolution are not a factor. Wind tunnel testing can be costly, with the process of model design, fabrication and testing requiring a considerable span time to complete. However, once a model is complete, an enormous amount of data can be collected rapidly. Once a configuration is mature, aerodynamic and S&C data can be obtained at a difficult, high angle of attack flight condition in a few seconds. In contrast, a CFD simulation at that condition might require hours or days to complete.

For flight conditions where a small scale model can gather useful data in low speed conditions, testing can be very cost effective. Rapid prototyping can enable rapid model generation. CFD costs are not insignificant, as we will see in Section 6. A cost-effective, reduced span development effort should not reflexively mandate a fully digital design process if the objective is to obtain the best design as quickly and cost effectively as possible.

6.0 HPC REQUIREMENTS AND COST FOR EXPANDED USE OF CFD

In this section we make a very rough estimate of the computational requirements for the transonic force and moment portion of a tactical aircraft development program that relies exclusively on CFD. The starting point for this estimate is the number of test points required based on traditional aerodynamic and S&C wind tunnel testing. The number of test points is adjusted to account for efficiencies in CFD and in a program with expanded digital engineering. Using the analysis of Section 4, we can calculate the total CFD core hours required to simulate the test matrix. Representative current core hour costs enable us to make a rough estimate of hardware costs for a CFD-based design effort. These estimates assume that CFD is accurate enough to meet program needs. That assumption may not be justified, and is discussed in Sections 3 and 7. Despite the approximations in these calculations, they provide a basis for sizing program assets and for weighing the cost and schedule trade-offs between testing and CFD for database generation.

6.1 Estimated aero-performance and S&C CFD requirements

As stated previously, a non-STOVL, single variant fighter program would likely achieve the same quality of predictive aerodynamics as the F-35 with 25,000 UOH. The force and moment testing for aero-performance and S&C for F-35 were 11% and 19% respectively of the total non-STOVL F-35 wind tunnel hours. Applying these percentages to the estimated UOH required for a single variant, non-STOVL program (25,000) results in 2,750 and 4,750 UOH for aero-performance and S&C respectively. Given the sizes of the example test matrices in section 4, the single variant, non-STOVL program would run eight aero performance tests (2,750 / 320) and 10 S&C tests (4,750 / 465).

If the aero and S&C design cycles are compressed from six down to two years, we assume that a program using digital engineering will be able to achieve the same compression in iterative design cycles. Applying the same compression to the estimated UOH calculated above for aero-performance and S&C testing of a single variant, non-STOVL aircraft results in 917 (2,750 / 3) and 1,583 (4,750 / 3) UOH, respectively. Assuming the same example matrices defined in section 4 are used, aero-performance could test three times (917 / 320) and S&C could test about 4 times (1,583 / 465). If these tests were to be replaced by CFD, the solutions required, broken up by category, are shown in Table 6 below.

Table 6 Estimate of for Aero Performance and S&C Test Points Required for a compressed, CFD based development program.

CFD Solutions Required	Aero-Performance Solutions x 3	S&C Solutions x 4	Aero-Performance + S&C
Category A:	84,360	42,336	127,000
Category B:	29,970	79,920	110,000
Category C:	30,030	259,416	289,000
Total:	144,360	381,672	526,000

The number of core hours required are obtained from the breakdown in test points by category shown in Section 4. The number of core hours required for each category are given in Section 3. With these inputs we can estimate a total number of core hours required to execute the aero-performance and S&C force and moment portion of a program with CFD. Table 7 summarizes the core hour requirements.

Table 7 Estimate of core hours required for Aero Performance and S&C for a compressed, CFD based development program.

	Aero-Performance + S&C Solns	Core Hours / Solution	Core Hours Required
Category A:	127,000	3,000	380,000,000
Category B:	110,000	20,000	2,200,000,000
Category C:	289,000	50,000	14,500,000,000
Total:	526,000		17,000,000,000

Given the number of core hours, we estimate the number of cores required to execute this two year effort. We assume that the core hour requirements are met by filling the cores completely with CFD runs 7 days a week, 24 hours a day. While this is optimistic, hardware downtime for a major HPC center is usually under 5%. The assumption of an even spread CFD work over the two year period is certainly optimistic but acceptable for the gross estimates we are making. Table 8 summarizes the number of cores required. The S&C testing contributes significantly to the number of category C CFD solutions required. Table 8 clearly shows that category C solutions drive the large number of cores needed.

Table 8 Estimate of computer cores required for aero-performance and S&C for a CFD based, two year effort.

	Core Hours Required	Cores for 2 yr effort (8,760 hrs/yr)
Category A:	380,000,000	22,000
Category B:	2,200,000,000	126,000
Category C:	14,500,000,000	827,000
Total:	17,000,000,000	975,000

6.2 Estimated Program Computer Costs

Finally, we estimate the total cost of the hardware for this two year period. We estimate that the current core hour cost is $0.035.[8] This is the cost of not-for profit systems. The market price for on-demand cloud based computing is much higher, and not relevant to program with a large need over a two year period. Table 9 summarizes our rough estimate of hardware costs for a CFD-based design effort. The calculated cost is significantly higher than the estimate of $34M in wind tunnel costs to obtain the same dataset. However, projecting to the future, computing costs should be expected to decline rapidly. While we may have departed from Moore’s law, significant reductions in CPU costs over the next decade are expected.[9] Since computational speeds per core are advancing more slowly than is the core count per node, the core count requirements should have relevance to estimates of HPC size and cost in the future.

Table 9 Estimate of computer costs for Aero Performance and S&C for a CFD based, development program

	Core Hours Required	Estimated Cost ($0.035/hr)
Category A:	380,000,000	$13,000,000
Category B:	2,200,000,000	$77,000,000
Category C:	14,500,000,000	$508,000,000
Total:	17,000,000,000	$598,000,000

There are numerous capability advancements that could modify these estimates. We will highlight two areas of advancement that could significantly reduce the hardware requirements. The cost estimate for unsteady simulations given in Section 3 is based on the application of hybrid RANS/LES methods such as Detached Eddy Simulation (DES). Wall modelled LES methods could significantly reduce the computational requirements for unsteady simulations. A recent study of flow in a serpentine duct comparing hybrid RANS/LES to WMLES demonstrated an order of magnitude reduction in computational requirements with WMLES.[10] This is largely because WMLES enables coarser mesh resolution near the wall since it employs a kind of wall function. In contrast hybrid RANS methods such as DES typically require a mesh that resolves the viscous sublayer. The greater mesh resolution for the hybrid method results in both more mesh points and a smaller time step for the time accurate iterations. Neither WMLES or hybrid methods fully meet current requirements for a predictive method that can replace wind tunnel testing. WMLES is less mature, and requires more development and validation than hybrid methods. However, maturation of WMLES would significantly reduce hardware requirements.

A second area of reduction of computational requirements is through the use of GPU-based flow solvers. The general purpose flow solver Fun3D has been ported to GPUs. This was a significant effort to ensure a performance increase. GPU enabled flow solvers would reduce turnaround dramatically for large CFD jobs.[11] GPUs can also reduce the cost per simulation. Currently the cost of GPU enabled nodes is much higher than CPU nodes. Flow solvers optimized for GPUs can provide a 50% or greater cost reduction vs CPUs. The further forward we project the HPC cost estimate, the more likely it is that these efficiencies will be realized.

7.0 LIMITATIONS OF CFD ACCURACY AND R&D NEEDS

When current CFD methods are applied to separated flows, they are not accurate enough to stand on their own in the development process. Rizzi and Luckring give a detailed review of the capabilities of CFD methods for the prediction of separated flow.[9] The review highlights the challenges in predicting flow separation, vortices, vortex burst, and shock-vortex interactions with current methods. Use of CFD for cases in categories B and C require validation of CFD tools and processes for a similar configuration and flight condition. Uncertainty quantification is a critical component of expanded use of CFD. Improving the accuracy of physical models implemented in CFD codes is essential to the expanded use of CFD. A clear understanding of the limitations of methods is essential as well.

The computational effort forecast in this study assumes some form of time-accurate, scale resolving simulation over much of the flight envelope. While these methods generally give better predictions of separated flows than RANS, their immaturity and continuing limitations are obstacles to expanded use. Hybrid RANS/LES methods are sensitive to the switching function between RANS and LES regions. The switching function is sensitive to mesh resolution. This presents a new dimension of complexity to mesh resolution studies. These methods are also challenged in regions of smooth body separation. At a boundary between an upstream RANS region and a downstream LES region no resolved turbulence convects into the LES regions, leading to errors. While methods to address this have been demonstrated in simple problems, they are not generally used in production CFD.

Good results have been demonstrated with WMLES for high lift configurations and other complex separated flows. While less susceptible to the RANS/LES boundary issues and switching function sensitivity of hybrid methods, the wall model itself is not mature. Many different wall models have been proposed, and there is no standard approach. When applied to attached flows with strong adverse or favorable pressure gradients and 3-D boundary layers, these methods can yield results with significant variability.

There could be significant benefit from collaborative workshops with multiple rounds of assessment of different methods and results over several years for configurations that address the unique phenomena of tactical aircraft. The AIAA drag prediction and high lift workshops have served that purpose for the maturation of methods for transport aircraft. Several NATO sponsored efforts have approached this level of activity, but more are needed to benchmark methods and to provide a basis for uncertainty quantification of CFD results.

8.0 OPPORTUNITIES AND CHALLENGES FOR THE EXPANDED USE OF CFD

CFD capability has drastically improved in the more than 20 years since the F-35 development program began. Given the challenge to development timelines and the importance of maintaining accurate predictive models, it makes sense to explore how improvements in CFD might be leveraged to meet these goals. The use of realistic wind tunnel run logs, as has been done in this paper, provides an understanding of the opportunities and challenges to the expanded use of CFD. The analysis also provides insight into areas where additional work would be most impactful. This section will discuss areas where the expanded use of CFD is likely to provide significant benefit as well as areas that will likely still require wind tunnel testing.

8.1 Areas of Opportunity for Significant Expansion of CFD

8.1.1 Transonic Aero-Performance Force and Moment Testing

Many of the requirements tied to this type of testing exist at 1-G conditions (cruise, accel, max Mach, etc), though there are important maneuver requirements at higher lift states. Compared to S&C, aero-performance requires fewer solutions. Most of them (60%) are in CFD category A, which require fewer core hours per solution. The three CFD-based aero-performance cycles represent just 13% of the estimated cost in Section 6. The benefits CFD brings in these areas are important; rapid MDO, use of flight geometry, no wind tunnel corrections, and flight Reynolds numbers. The forces and moments obtained in S&C testing often have larger uncertainties in drag due to model scale, balance capacity, and aft-body distortion, but could still be used to validate or enhance the 3DOF aero-performance database. The expanded use of CFD along with a slightly expanded scope of S&C testing may result in large reductions in aero-performance wind tunnel test entries. Before this strategy is adopted, a good understanding of CFD uncertainty relative to program requirements and wind tunnel capability should be obtained. Cost and schedule trade-offs should also be considered in the choice between CFD and wind tunnel testing.

8.1.2 Airframe and captive store loads

Most or all of the solutions obtained in support of the transonic aero-performance force and moment testing can be used to obtain high fidelity airframe loads data. Depending on the confidence of surface pressure data in the more difficult CFD categories, significant reductions in airframe loads wind tunnel testing may be possible. Use of Pressure Sensitive Paint (PSP) on the stability and control force and moment model may be an efficient way of obtaining additional surface pressure data if needed.

8.1.3 Air data

Most or all of the solutions obtained in support of the transonic aero-performance force and moment testing can also be used to obtain data to support the air data system. Additional CFD can be run to obtain inlet mass flow ratio effects or that requirement may be moved over to inlet testing.

8.1.3 Weapons separation

The expanded use of CFD in the area of weapons separation has already been shown to reduce wind tunnel testing requirements. Though viscous solutions offer more accuracy, validation studies have shown that reasonable agreement with wind tunnel data may be possible with panel methods at low-speed conditions and with Euler solutions at transonic conditions.[12]

8.1.4 Jet-effects

The complexity of jet exhaust effects on external aerodynamics makes obtaining this data difficult for both CFD and wind tunnel testing. If the increments are large or important enough, it may make sense to use both testing and CFD to meet data requirements as the two often complement each other in this area. Conversely, if program requirements allow and sufficient validation data are available, it may be acceptable to use CFD to obtain jet-effects data instead of wind tunnel testing. The use of CFD in this area may drastically reduce the complex force accounting associated with data obtained from jet-effects wind tunnel testing. CFD allows for full aircraft configurations to be run without including the complex force accounting required for jet-effects wind tunnel models. This is a significant advantage for CFD, but it can also pose a problem when trying to combine data from both wind tunnel and CFD sources into the same database. Care must be taken not to mix data across force accounting systems in databases. If data sources are combined, consistency requirements may complicate CFD-based force accounting for jet effects.

8.1.5 Inlet-effects

The CFD based aero-performance force and moment data set can serve as the baseline for this data. Obtaining additional solutions with varying inlet mass flows would not significantly add to complexity or difficulty. Furthermore, data point requirements to capture inlet-effects are relatively small for fixed inlet geometries.

8.1.6 Additional Work Needed to Realize CFD Expansion Opportunities

Some relevant CFD validation exists on tactical aircraft configurations, but more is needed to provide confidence in obtaining absolute level coefficient data. The analyst should have confidence in their mesh resolution and choices of turbulence models and discretization settings to generate solutions for a variety of configurations at various points in the flight envelope. A good understanding of CFD uncertainty relative to program requirements and wind tunnel capability is needed. Finally, increased throughput is needed to allow for the marked increase in CFD solutions that would be required. Smart databasing techniques to reduce the solutions needed and automation to increase the rate at which converged solutions are generated may play significant rolls.

8.2 Areas in Which Continued Wind Tunnel Testing is Likely

8.2.1 Low-Speed Force and Moment Testing for Aero-Performance and Stability & Control

The objectives of low-speed testing are generally focused on take-off, approach, and high alpha conditions. Approach conditions are generally in the 10 to 15° alpha region and can involve large beta angles to support crosswind analysis. Control surface deflections of import are often well beyond 10°. Useful take-off data can be obtained at lower angles, but still usually involve large control surface deflections. The majority of conditions useful for approach and take-off analysis would be in CFD category B. By definition, high-alpha conditions represent critically complex flowfields and would be in CFD category C. To be sure, CFD can be used to generate some low-speed data, but given the majority of data point requirements are within categories B and C, solutions will be expensive and time consuming. Conversely, low-speed testing tends to be cheaper and facilities have greater availability than high speed facilities. The value proposition provided by low-speed testing of both large and small scales is likely not to be eclipsed until CFD can deliver accurate solutions covering large numbers of configurations and conditions with complex unsteady flowfields involving large scale separations in relatively short time periods at a low cost.

8.2.2 Inlet Testing

Inlet testing is used to evaluate inlet compatibility and to measure pressure recovery for use in performance calculations. Testing generally involves large matrices of Mach, alpha, beta, engine airflow, and forebody configurations including protuberances. Variable geometry, bleed, and/or bypass systems can significantly increase test point requirements as well. Data requirements include both steady state and time accurate pressure measurements at the Aerodynamic Interface Plane (AIP) at a minimum. CFD predictions of steady state pressure recovery with acceptable accuracy can often be obtained. However, dynamic data requirements are unlikely to result in reductions in wind tunnel testing. Conditions of interest for dynamic distortion are almost by definition difficult for CFD to predict accurately. These conditions are typically at elevated alpha and beta, potentially including incipient smooth surface separations. CFD is a powerful design tool; it is able to show good qualitative agreement with wind tunnel test data. For some cases, CFD can give good quantitative agreement with peak dynamic distortion test data. [13] CFD has already reduced the reliance on wind tunnel testing of inlet configurations by allowing designers to hone in on a smaller set of configurations to test. However, large scale reductions in inlet wind tunnel testing will require the ability to generate thousands of unsteady simulations with acceptable levels of accuracy. Modeling bleed systems and predicting buzz onset are additional challenges.

8.2.3 Transonic Stability & Control Force and Moment Testing

As discussed earlier, data requirements for stability and control involve a large number of data points. Most of those data points (89%) fall in the two most difficult CFD categories, requiring more time and attention to complete. The difficulty inherent in the CFD solutions multiply the already difficult situation caused by the number of points required. The difficulty of the CFD required also adds significant uncertainty to the data; something that can add to development time lines instead of reducing them. If given a set of wind tunnel or flight data, CFD can often be made to match reasonably well by refining grids, altering discretization settings, changing turbulence models, etc. Once these settings have been fine tuned to provide the desired level of agreement, it may be appropriate to continue running CFD with the same settings to capture configuration changes incrementally. However, this acts to further increase the number of data points needed to meet requirements; one set of points to refine and match with previous wind tunnel testing and another set to capture configuration changes moving forward. For CFD to reduce reliance on wind tunnel testing for stability and control, confidence in results for a majority of the data points - in an absolute sense - must be high. An understanding of the mesh and modeling requirements must be known when setting up the problem or inferred after an initial solution is obtained. Confidence in simulation accuracy must be backed up by a library of validation cases covering multiple relevant configurations and conditions. Finally, methods to reduce the number of data points required and to increase solution throughput should be pursued. Reductions in required data points may be achieved with improvements in control law design, smarter methods of database creation, or both. Increases in CFD solution throughput might be achieved with more capable computational hardware, faster computational methods, and increased levels of automation in running, job tracking, and post processing.

9.0 SUMMARY

There is a need to compress the design process for tactical aircraft. Expanded application of CFD can help to enable this compression. We have shown that large databases must be generated over a large parameter space covering a wide range of flow conditions, angles of attack and control surface deflections throughout the design process. The majority of the test points within this parameter space are difficult to simulate accurately with steady-state Navier-Stokes methods. While unsteady, scale resolving modeling approaches are more accurate in flight regimes with significant regions of flow separation, they are computationally expensive and the accuracy of these methods are not well enough established to meet many design requirements without extensive validation. We have outlined flight regimes where CFD provides the greatest payoffs relative to wind tunnel testing, and those where testing may prove advantageous in the near future. To fully realize the potential of CFD there should be significant development in CFD methods and validation. Failure to do this will limit the potential for reduced testing, improved design optimization, reduced costs, and compressed design cycles that could be achieved with CFD.

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