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ABSTRACT

Computational fluid dynamics (CFD) tools have been used extensively in the analysis and development of the X-43A Hyper-X Research Vehicle (HXRV). A significant element of this analysis is the prediction of integrated vehicle aero-propulsive performance, which includes an integration of aerodynamic and propulsion flow fields. This paper describes analysis tools used and the methodology for obtaining pre-flight predictions of longitudinal performance increments. The use of higher-fidelity methods to examine flow-field characteristics and scramjet flowpath component performance is also discussed. Limited comparisons with available ground test data are shown to illustrate the approach used to calibrate methods and assess solution accuracy. Inviscid calculations to evaluate lateral-directional stability characteristics are discussed. The methodology behind 3D tip-to-tail calculations is described and the impact of 3D exhaust plume expansion in the aftbody region is illustrated. Finally, future technology development needs in the area of hypersonic propulsion-airframe integration analysis are discussed.

INTRODUCTION

Hypersonic airbreathing vehicle configurations are characterized by highly-integrated propulsion flowpath and airframe systems. A significant challenge in the development of this class of vehicle is an assessment of propulsion-airframe flow field interactions and the integrated aero-propulsive performance of candidate systems. Advanced experimental, analytical and computational tools are being developed to aid in the design of configurations that exploit propulsion-airframe interactions to maximize performance and enhance stability and control characteristics. Presently, capabilities for testing complete engine flowpath/ airframe configurations that model all of the pertinent interactions affecting integrated vehicle performance are limited. Predictive methodologies, including computational fluid dynamics (CFD) and other analysis tools, must encompass a wide range of modeling capabilities to capture all of the relevant flow physics of the complete scramjet flowpath as well as the external airframe. This analysis is normally accomplished using a multi-level approach, increasing in complexity and fidelity as the design is matured. The preliminary analysis phase may employ different tools for the various flowpath components, which necessitates the development of force accounting systems appropriate for specific configurations. CFD is also a valuable tool used to interpret aerodynamic and propulsion ground test data.

One objective of the Hyper-X program is to develop and mature the technologies required for hypersonic airbreathing flight.[1] Three flight tests of the Hyper-X Research Vehicle (HXRV), or X-43A, are currently scheduled to obtain in-flight performance data on a scramjet-powered hypersonic configuration. The first two of these flight tests will be at Mach 7 test conditions with a third flight at Mach 10. The development of the Mach 7 X-43A required a pre-flight assessment of longitudinal and lateral-directional aero-propulsive characteristics near the target flight test condition.[2] The development of this pre-flight data base was accomplished through extensive aerodynamic wind-tunnel testing[3] and a combination of 3D inviscid airframe calculations and cowl-to-tail scramjet cycle analyses to generate longitudinal performance increments between mission sequences. These increments were measured directly and validated through tests of the Hyper-X flight engine (HXFE) and vehicle flowpath simulator (VFS) in the NASA Langley 8-Foot High Temperature Tunnel (8-Ft. HTT).[4] Predictions were refined with tip-to-tail Navier-Stokes calculations, which also provided information on

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scramjet exhaust plume expansion in the aftbody region. A qualitative assessment of lateral-directional stability characteristics was made through a series of tip-to-tail inviscid calculations, including a simulation of the powered scramjet flight test condition. CFD predictions were also used to address other aspects of vehicle performance and flight test development, including boundary layer trip design and assessment[5], thermal and structural loads and scramjet flowpath component performance.

The Hyper-X program represents the first opportunity to correlate analytical and CFD predictions with ground-test and flight-test data on an airframe-integrated scramjet configuration. Comparisons with available ground test and flight data will be used to calibrate tools and physical models. Since the CFD and experimental test techniques used in the Hyper-X program represent the state of the art in hypersonic propulsion-airframe integration (PAI) research, an examination of these methods also provides insight into future technology development needs for the next phase of hypersonic vehicle development.

This paper presents an overview of the methods used in the analysis and pre-flight development of the Mach 7 X-43A vehicle. A discussion of CFD codes and other analysis tools is included with their respective capabilities and limitations. The appropriateness of various physical modeling approximations and their effect on performance predictions is discussed. The methodology for integration of tools for various flowpath components is discussed with limited results and comparisons to available data. Finally, a discussion of future challenges for hypersonic propulsion/airframe integration and predictive methodologies for integrated vehicle performance is presented.

MISSION DESCRIPTION AND ANALYSIS REQUIREMENTS

The nominal Hyper-X flight trajectory is illustrated in figure 1. The flight profile begins with the captive carry flight of the Hyper-X Launch Vehicle (HXLV) under the wing of a B-52 aircraft. The HXLV consists of the X-43A mounted to the first stage of a Pegasus® booster rocket, manufactured by Orbital Sciences Corporation, with a vehicle-to-booster adapter. Following air-launch of the HXLV from the B-52, the vehicle is boosted to the appropriate flight test condition and, at burnout, the X-43A separates from the booster. Upon stabilization, the cowl door, which remains closed throughout the boost phase to block the inlet entrance and protect the internal engine components from high heat loads during boost, opens to establish flow through the engine. Following a few seconds of unpowered operation, hydrogen fuel is introduced and the powered portion of the scramjet test is conducted, lasting approximately seven seconds. A series of parameter identification (PID) maneuvers are then conducted and the cowl door closes as the vehicle begins a controlled descent prior to mission termination, while conducting additional PID maneuvers to measure lower Mach number aerodynamic stability and control characteristics. This flight profile necessitates the

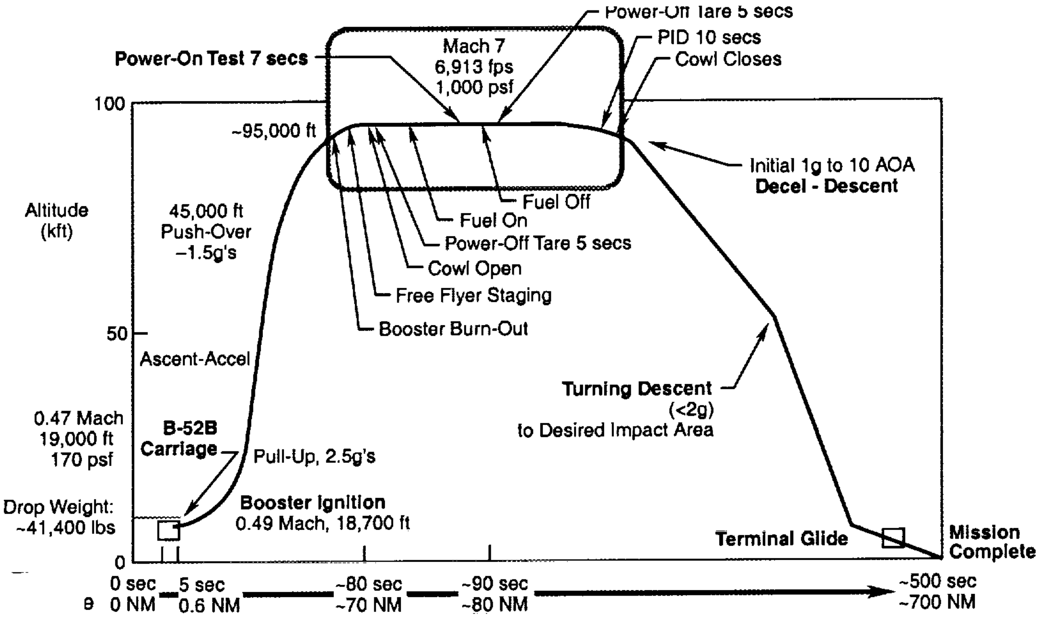

Figure 1. Hyper-X Flight Trajectory.

analysis of three distinct mission phases: cowl-closed unpowered, cowl-open unpowered and cowl-open powered. Much of the analysis for aero-propulsive performance is built upon the prediction of force and moment increments between the various mission points. The term "inlet-open increment" is used to refer to the difference in force and moment quantities between the cowl-open unpowered and cowl-closed points and the term "power-on increment" is used to refer to the difference between the inlet-open powered and unpowered phases of the flight.

A complete nose-to-tail analysis of the X-43A at the conditions of interest requires a wide range of flow modeling capabilities. A summary of the relevant flow physics and prediction requirements is shown in figure 2. At hypersonic Mach numbers, high temperature gas effects become important. For the Mach 7 Hyper-X flight conditions, it is sufficient to model the flow field as a mixture of thermally-perfect gases, where thermodynamic quantities vary as a function of temperature using curve fits for the appropriate species. Composite species models may be used to approximate the composition as a single species to reduce computational overhead. Surface pressure and skin friction predictions are generally required on all external surfaces to resolve vehicle forces and moments and to provide structural loadings on vehicle components. Heat transfer predictions may also be required to assess thermal loads. This implies the need for appropriate turbulence models and knowledge of the boundary layer state. Accurate computations of forebody flow fields, characterized by shocks, shock-boundary layer interactions and potentially separated flow regions, are required to compute mass capture at the cowl lip station. The inlet flow field is characterized by shock-boundary layer interactions, flow separation in unfavorable pressure gradients, high leading edge thermal loads and corner flow regions. Accurate computation of the inlet/isolator region is necessary to provide equivalent 1D properties to evaluate component performance. Computation of the combustor flow field requires modeling fuel injection and complex mixing phenomena as well as finite rate chemical reactions. Downstream of the combustor, the high-temperature scramjet exhaust flow field must be modeled by approximating the species constituents of the combustion process. This powered exhaust plume expands in the aftbody region and may interact with vehicle aerodynamic or control surfaces, especially at deflected wing settings or when the vehicle is at non-zero angles of attack or sideslip. The determination of integrated vehicle performance requires analysis of both internal and external flow fields and an appropriate accounting of the interactions between the two. Another objective of the Hyper-X analysis is to determine the extent to which these flow features must be modeled in order to generate quantities of interest with engineering-level accuracy.

ANALYSIS TOOLS

The primary CFD tool used for the pre-flight performance analysis of the X-43A is the General Aerodynamic Simulation Program (GASP), a product of AeroSoft, Inc.[6] GASP is a multi-block, structured-grid, upwind-based, Navier-Stokes flow solver. Mixtures of thermally-perfect gases are modeled using polynomial curve fits for thermodynamic properties.[7] GASP can model frozen, equilibrium or finite-rate chemistry with models for hydrogen-air combustion. The Baldwin-Lomax algebraic turbulence model with the Goldberg backflow correction has been widely applied for turbulent flows.[8] Various two-equation eddy-viscosity

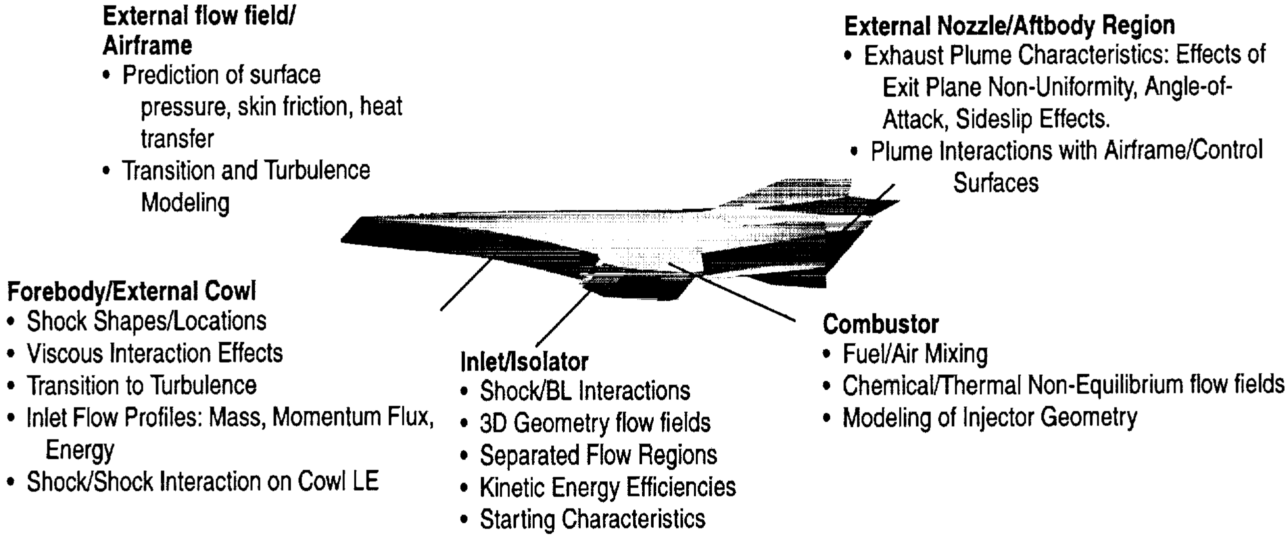

Figure 2. X-43A Flow Physics and Flow Modeling Requirements.

formulations are also available in GASP and have been used for various applications. Convergence acceleration options include a V-cycle multi-grid algorithm, mesh sequencing and local time stepping. A large calibration data base is available for GASP for hypersonic configurations and scramjet flow fields. Predictions for surface pressure, flow-field quantities and integrated forces and moments have compared well to available experimental data at unpowered and simulated powered conditions in previous studies.[9-13]

Another CFD tool used in the Hyper-X scramjet flowpath design and analysis is the Viscous Upwind Algorithm for Complex Flow Analysis (VULCAN).[14] VULCAN is a Navier-Stokes solver capable of solving turbulent reacting and non-reacting flows. Physical modeling capabilities include a variety of one-equation and two-equation turbulence models, compressibility models, finite-rate chemistry and turbulence-chemistry interaction effects. A variety of numerical schemes to reduce computational cost are also available, including wall functions for two-equation turbulence models, multi-grid methods for elliptic and space-marching schemes, mesh sequencing and conditioning of governing equations to reduce numerical stiffness. Recent enhancements to the code include parallel capabilities through the use of message-passing interface (MPI) routines.

Two additional tools are used for analysis of the internal propulsion flowpath. The first is the supersonic hydrogen injection program (SHIP).[15,16] SHIP uses the SIMPLE (semi-implicit method for pressure-linked equations) method to solve the parabolized, mass-averaged equations for conservation of mass, momentum, total energy, total fuel and turbulence fields in a variable area domain of rectangular cross section. The second tool used for flowpath analysis is the SRGULL code.[17] SRGULL is comprised of a two-dimensional/axisymmetric Euler flow solver (SEAGULL), which is used to solve the forebody, inlet and external nozzle regions of the lower surface flowpath, and a one-dimensional chemical equilibrium cycle analysis code (SCRAM), which is used to approximate the combustor flow field. SRGULL also includes an integral boundary layer method (HUD) to provide a viscous component to the forces and moments and has a one-dimensional isolator model used to predict the onset location of pressure rise ahead of the fuel injectors associated with heat addition due to combustion. Several scaling factors, based on previous studies and ground test data, are included to account for such factors as mass spillage, inlet kinetic energy efficiency, base pressure, combustion efficiency and nozzle thrust multiplier to account for three-dimensional effects.

PRE-FLIGHT ANALYSIS METHODOLOGY

Longitudinal Performance Increments

The development of the X-43A pre-flight aero-propulsive performance data base includes an analysis of the post-separation point through the powered flight experiment. Although not the focus of this paper, the data base also supports the ascent, stage separation and post-experiment descent phases of the mission as well. Three mission points are analyzed: cowl-closed, cowl-open unpowered and cowl-open powered. A large body of wind-tunnel data exists for the cowl-closed configuration. Because of model scale and facility limitations, it is not possible to simulate the flow-through engine or to model powered effects in available aerothermodynamic facilities. Therefore, CFD predictions were used to determine the inlet-open and power-on performance increments. These increments were then applied to the experimental data base to develop predictions for longitudinal performance in each of the three mission phases. The increments were computed using GASP to obtain 3D inviscid flow solutions for the X-43A airframe and SRGULL computations for the propulsive flowpath surfaces of cowl-open configurations from the cowl leading edge station to the vehicle trailing edge (inlet/isolator, combustor, internal and external nozzle). Figure 3 illustrates the force accounting system used in this methodology.

The inviscid calculations were obtained using a space marching technique with the exception of the blunt nose of the vehicle. Sidewall, cowl and wing leading edges are treated as aerodynamically sharp. The use of the inviscid approximation reduces computational time and allows multiple points to be analyzed. Solutions were obtained for the flight-scale X-43A over a matrix of points that included variations of Mach number and angle of

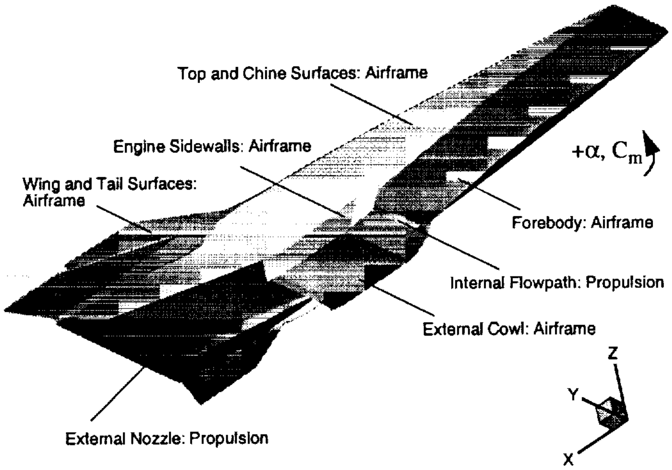

Figure 3. X-43A Force Accounting Methodology.

attack around the Mach 7 test point. A qualitative depiction of the computed performance increments is shown in figure 4. The predictions indicate a decrease in normal and axial force as well as a nose-down pitching moment increment when the cowl door is opened due to higher surface pressure on the external nozzle and a relief from the high pressure on the forward-facing cowl door. A decrease in axial force as well as a nose-down pitching moment increment is predicted for the power-on increment due to the pressurization of the external nozzle surface from the powered scramjet exhaust plume.

Viscous Predictions

Viscous predictions of the cowl-closed configuration were also obtained at various conditions to examine trends due to Reynolds number effects. Computations with GASP were obtained for a model-scale configuration at ground test conditions and for a full-scale configuration at representative flight conditions. The GASP calculations are performed by space marching most of the body, with the exception of the blunt nose region and the wake region aft of the cowl trailing edge in the aftbody and the vehicle base. The Baldwin-Lomax algebraic model is used as the turbulence model in these calculations.

Viscous forebody and flowpath computations were also used to examine various aspects of vehicle and component performance. PNS forebody calculations were used to predict inlet mass capture for the vehicle and subscale flowpath models. The Baldwin-Lomax turbulence model was generally used with the transition location fixed based on estimations of the effectiveness of boundary layer transition strips on the forebody. Limited experimental pressure data from ground tests show good agreement with surface pressure predictions. A series of viscous forebody computations at various angles of attack and sideslip angles at Mach 6 wind tunnel conditions was used to provide a correlation with surface pressure data used to calibrate an experimental flush-air data sensors (FADS) system for measurement of Mach number and angle of attack.[18] Figure 5 shows a qualitative comparison of predicted and measured pressures at one cross-sectional station. Reasonable agreement was obtained considering that the computations do not model the boundary layer trip geometry. Viscous calculations of the inlet/isolator region have been used to provide correlations with surface pressure and schlieren data from various engine flowpath tests. These computations have also been used to compute equivalent 1D properties to evaluate scramjet component performance.

Computations have also been performed to obtain thermal loads on both the cowl-closed and cowl-open configurations. Navier-Stokes solutions have been used to evaluate turbulent heating amplification, corner flow effects and shock-shock interaction effects on heat flux predictions in the cowl leading edge and sidewall regions. Figure 6 shows the surface grid topology in the sidewall/cowl leading region used for a Navier-Stokes calculation to obtain heat loads in this region for the

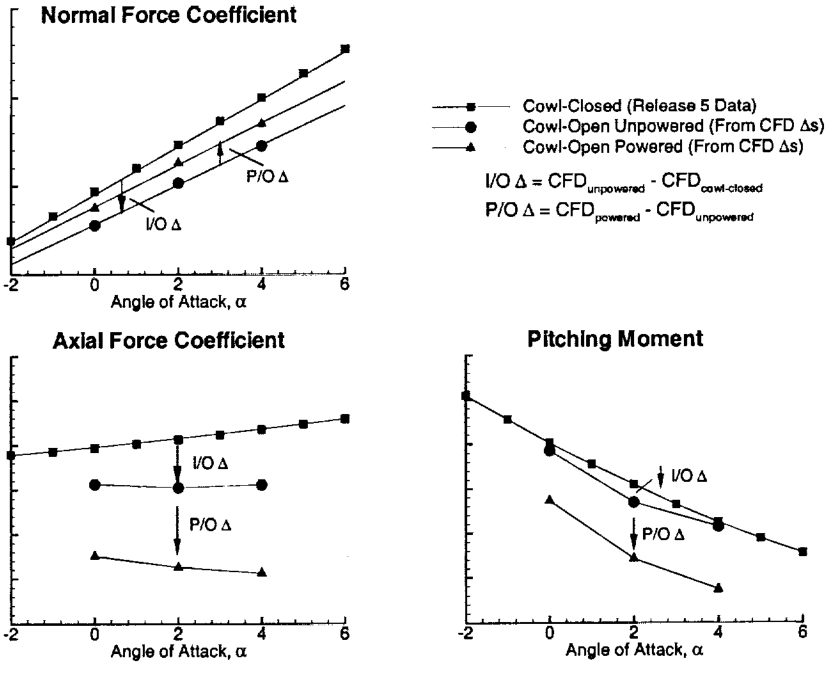

Figure 4. CFD Prediction of X-43A longitudinal performance increments at Mach 7.

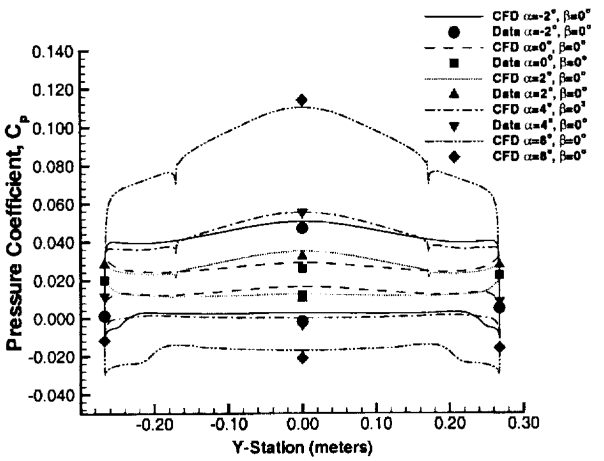

Figure 5. Comparisons of wind-tunnel surface pressure measurements and CFD predictions at forebody station.

cowl-closed configuration.

Code Calibration and Accuracy Assessment

Code calibration and accuracy assessment is accomplished through appropriate comparisons of CFD predictions with available experimental data. Figure 7 shows a qualitative comparison of force and moment predictions from 3D GASP inviscid and viscous computations of the X-43A cowl-closed configuration with subscale wind tunnel data at Mach 6. The results from a viscous computation shown in the figure were obtained at the same Reynolds number and model scale as the data. There is an obvious discrepancy with the inviscid CFD axial force prediction. The agreement is much better for the viscous computation. Normal force coefficient is also slightly overpredicted and smaller nose-up pitching moment values are predicted than are indicated by the data base comparisons. There is little significant difference between the inviscid and viscous computations in normal force or pitch at 0^{o} angle of attack. The discrepancies between the data and CFD predictions are most likely the result of a combination of uncertainties in corrections made to the data and physical modeling approximations in the calculations. The data shown in figure 7 have been corrected for sting interference effects, base pressurization and other facility and testing procedure effects. Assumptions regarding the boundary layer and the lack of modeling of the forebody boundary layer trips may also contribute to the uncertainty of CFD predictions. Despite these approximations in physical modeling and considering the uncertainties in the data, the agreement is considered good. Comparisons of forebody and aftbody surface pressure predictions with HXFE/VFS full-scale data obtained in the 8-Ft. HTT also show good agreement. Additionally, inviscid surface pressure predictions do not differ substantially from viscous predictions for external airframe surfaces, suggesting that the inviscid approximation is sufficient to obtain pressure loads on these surfaces.

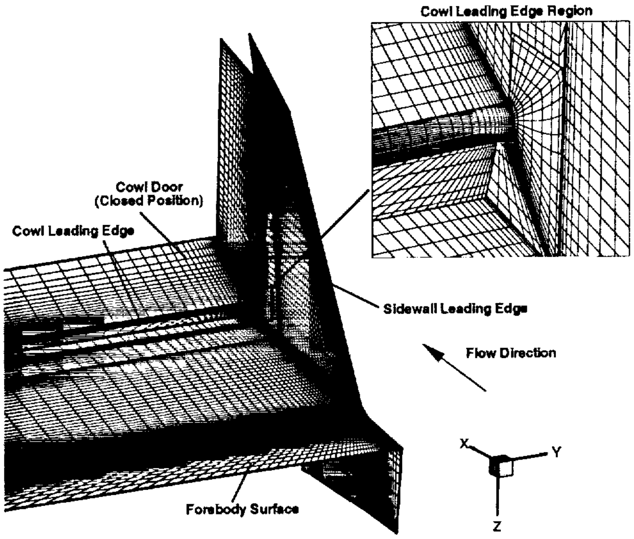

Figure 6. Mach 7 cowl-closed viscous grid used for heat transfer prediction.

Verification of predicted force and moment coefficients from SRGULL is accomplished primarily through comparisons of SRGULL surface pressure and force and moment predictions with higher-fidelity CFD solutions for comparable component efficiencies as well as appropriate comparisons between predictions and data. Experimental measurements from various scramjet flowpath tests in Langley scramjet test facilities have shown good agreement in terms of axial force and surface pressure predictions. Reasonable agreement with surface pressures have also been obtained in the inlet/isolator and nozzle regions. Reasonable correlations of pitching moment have also been obtained.

The only experimental verification of the CFD-computed longitudinal force and moment data base predictions for the cowl-open configurations were obtained from tests of the HXFE/VFS model in the 8-Ft. HTT.[3] The 8-Ft. HTT is a propulsion test facility that uses methane-air combustion and oxygen replenishment to generate a test gas with total enthalpy and Mach number equivalent to flight conditions.[19] The VFS is a full-scale model with that duplicates the flowpath and chine surfaces of the X-43A, but does not model other components. A sketch of the VFS model mounted in the test section is shown in figure 8. The primary objective of these tests was to verify the propulsion thrust performance, fuel sequencing, and operability of all engine-related subsystems. Force and moment data for each of the three post-separation mission points (cowl-closed, cowl-open unpowered and cowl-open powered) near the scramjet test point were also obtained. The VFS

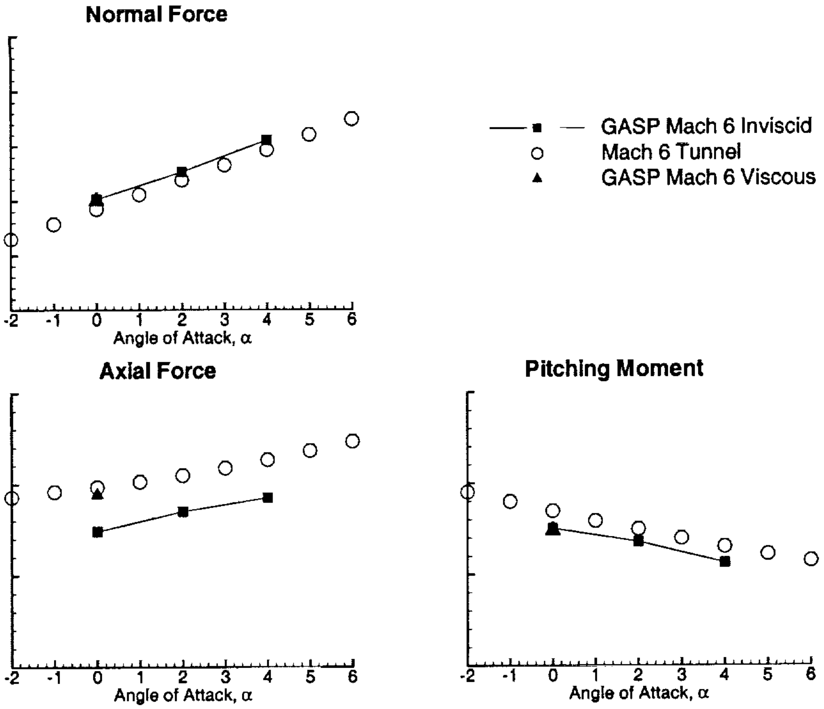

Figure 7. X-43A cowl-closed predictions vs. subscale experimental data base at Mach 6.

configuration models all of the salient features of the flowpath surface affected by these transitions, including 3D expansion of the scramjet exhaust plume over the aftbody surface. Because of the differences in geometry and test gas composition, only the cowl-opening and power-on increments obtained in the test can be utilized. In general, these data show good agreement with the predicted increments.[3] The magnitude of axial and normal force as well as pitching moment increments are comparable and the measurements confirm a small nose-down pitching moment resulting from the cowl-opening sequence. Furthermore, detailed comparisons of surface pressure distributions from these tests and viscous and inviscid CFD predictions as well as cowl-to-tail scramjet flowpath cycle predictions show that the 8-Ft. HTT test conditions are a good simulation of flight parameters. The comparisons show that the pre-flight database prediction methodology is sufficient to provide an accurate prediction of total force and moment increments. However, higher fidelity Navier-Stokes solutions are required to resolve detailed physics of the flowpath.

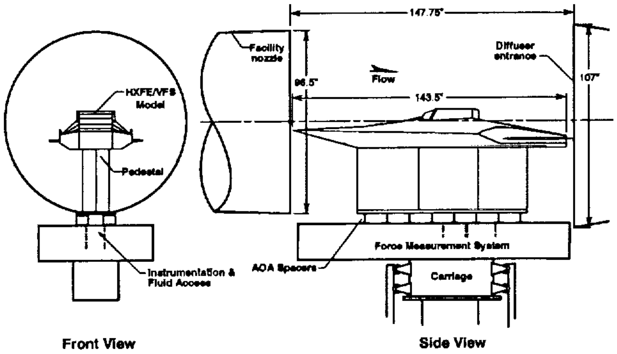

Figure 8. HXFE/VFS model installed in the 8-Ft. HTT.

Lateral-Directional Stability Characteristics

Computations were obtained on the X-43A at the same three mission points analyzed previously in order to evaluate the effect of the cowl-opening and fuel-on sequences on lateral-directional stability.[20] No experimental force and moment data is available for the cowl-open configurations at non-zero sideslip angles. Computational cost and gridding requirements are prohibitively large for 3D viscous computations at non-zero sideslip. 3D inviscid computations were obtained for the cowl-closed, cowl-open unpowered and cowl-open powered conditions at Mach 7, 2° angle-of-attack, and 0° and 3° sideslip. The unpowered computations were obtained using GASP, including the internal flowpath without the geometry of the fuel injectors in the combustor. The powered computations were obtained using a 1D cycle analysis method for the combustor. Several lateral stations were computed for the combustor analysis in order to approximate some lateral variation in flow field properties at the 3° sideslip condition. Figure 9 shows predicted values for side force, yawing moment and rolling moment derivatives computed from the 0° and 3° predictions. The CFD analysis predicts that the cowl-opening and power-on sequences of the flight have

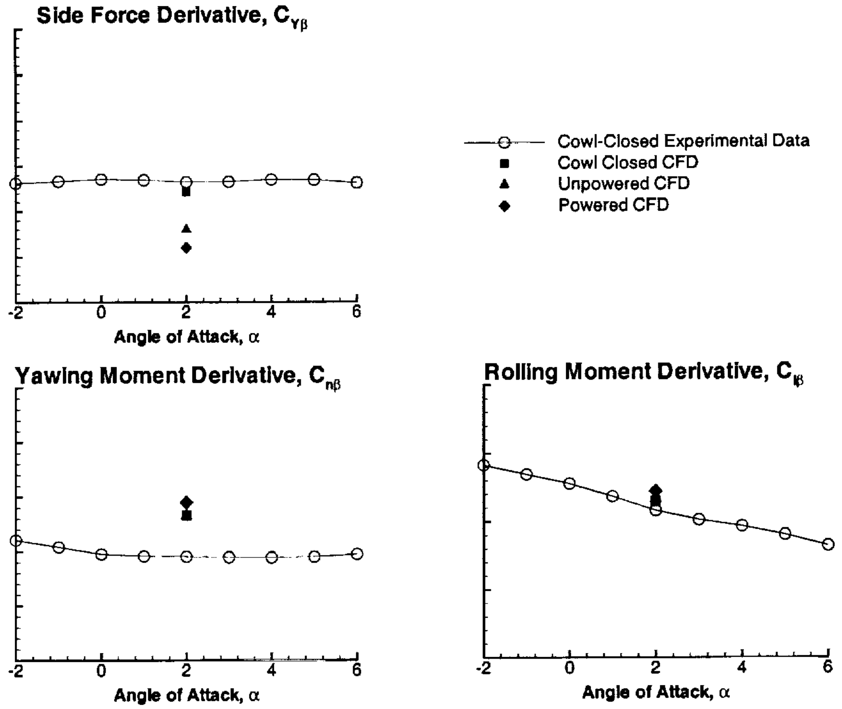

Figure 9. Inviscid CFD Predictions of X-43A Lateral-Directional Stability Derivatives at Mach 7.

little significant direct effect on the lateral-directional stability. There is, however, a significant indirect effect of the powered flight condition on airframe stability and control as a result of the horizontal wing deflection required to trim the resultant propulsive-induced pitching moment. An analysis of the aftbody flow field solution also indicates some impingement of the powered scramjet exhaust plume on the horizontal wing surface of the vehicle at the 3° sideslip, 2° angle of attack condition. No analysis was done to evaluate control surface effectiveness under powered conditions or to evaluate exhaust plume interaction effects at non-zero sideslip with deflected wing surfaces.

Tip-to-Tail Simulations

A viscous tip-to-tail calculation, including a simulation of powered effects, was used to provide the most detailed prediction of performance possible at the target flight test point of Mach 7, 2° angle-of-attack.[21] This calculation was accomplished using GASP to simulate both external and internal flow fields, including modeling the powered scramjet exhaust effects. A 1D cycle analysis was still used to approximate the combustor flow field due to the complexity of modeling the geometry of this region as well as the physical modeling requirements and computational cost to compute turbulent reacting flow fields in the combustor. A summary of the methodology is shown in figure 10. External flow fields are typically computed by solving the PNS equations except in the regions of the nose and cowl leading edge where bluntness effects are important. The scramjet exhaust plume is modeled as a single-species thermally-perfect gas. An analysis of the aftbody flowfield from this calculation shows that the exhaust plume expands beyond the boundaries of the external nozzle "propulsion" surface as defined in figure 3, creating uncertainty in the force accounting assumptions used previously to couple propulsion flowpath and airframe CFD predictions. This effect is illustrated in figure 11, which shows density contours of the exhaust plume at several cross-sections along the aftbody. A comparison of total integrated forces and moments from this calculation with those developed from applying the CFD-computed performance increments to experimental cowl-closed data base values shows only small

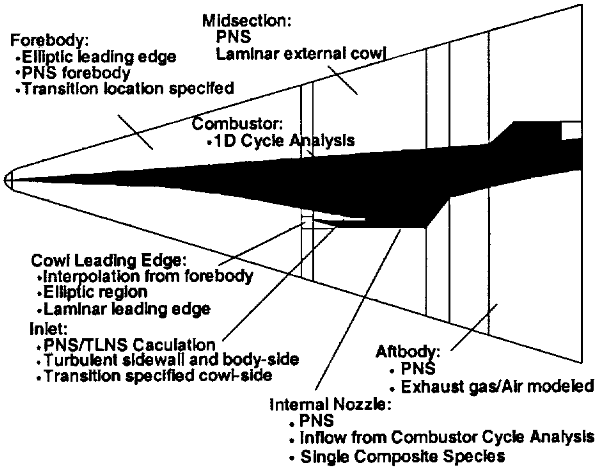

Figure 10. 3D Tip-to-Tail Solution Methodology.

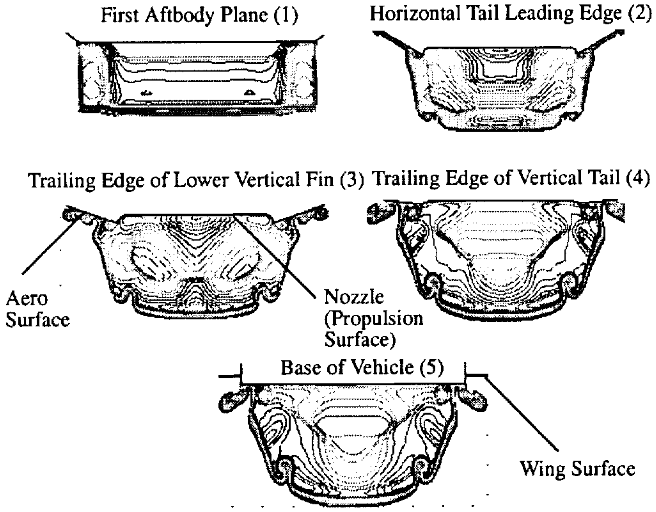

Figure 11. Density Contours Showing 3D Exhaust Plume Expansion.

differences in predicted axial force and pitching moment, indicating that this "spillage" effect is small at the nominal Hyper-X scramjet flight test condition.

FUTURE HYPERSONIC PAI ANALYSIS

The X-43A pre-flight database methodology, utilizing inviscid airframe CFD computations and scramjet flowpath cycle analyses, was successful in predicting pre-flight basic longitudinal performance increments based on a comparison with available experimental data from HXFE/VFS testing. However, an assessment of the methodology illustrates areas of uncertainty and highlights opportunities for technology development. The inviscid approximation, which was necessary to reduce computational time and memory requirements and enable multiple 3D airframe calculations at parametric conditions, necessitates the use of approximate methods to determine viscous drag forces. The uncertainty in this prediction contributes to the overall uncertainty in trim performance and net thrust predictions at the powered scramjet test point. Interactions of the powered scramjet exhaust plume with airframe and control surfaces are not fully captured in the data base approach. The 3D tip-to-tail analysis illustrated the three-dimensional exhaust plume expansion in the aftbody region, which makes it difficult to define a force accounting system that separates propulsive and aerodynamic forces. Furthermore, the methodology used for the X-43A is highly configuration dependent and applicable only to a point design. Future hypersonic airbreathing systems will require analysis across a broad trajectory. Predictions, as well as data, for angle of attack or sideslip effects on plume expansion characteristics are lacking. No direct measurements were available for the cowl-open configurations to evaluate lateral-directional stability, control surface effectiveness or associated trim drag penalties under powered conditions. Pre-flight predictions were based on unpowered cowl-closed wind-tunnel data and the effect of any plume interaction was neglected in these models. Additional data on these effects is needed in the development of future systems.

A continued maturation of hypersonic airbreathing vehicle technologies is dependent on the development of advanced experimental and computational techniques to fully examine PAI characteristics of candidate designs and to exploit airframe-propulsive interactions to maximize performance. Higher fidelity analysis methods are required earlier in the design and development process to fully evaluate trim performance. This implies a need to implement algorithmic and hardware improvements that improve the efficiency of Navier-Stokes codes to reduce computation times and enable studies over a wide range of conditions within reasonable time frames. Implementation of parallel methods offer improvements in run-time efficiency. Other algorithmic advances, such as multi-grid methods, dynamic grid adaptation and other convergence acceleration techniques, may provide improvements. Advanced grid strategies, such as overset or unstructured grids, may be appropriate for 3D vehicle calculations and other complex geometries. Continuing advances in physical modeling capabilities will also improve the fidelity of predictions, including advanced turbulence models, transition prediction, turbulence-chemistry interactions, finite-rate chemistry models (particularly for hydrocarbon fuels) and modeling of multi-phase flows. Validation of models will be enhanced by correlations of CFD predictions, ground test data and flight data for the X-43A. Continued maturation of these tools will progress towards the goal of solving full 3D tip-to-tail flowpaths with reacting flow chemistry in reasonable computation times as well as 3D vehicle analyses over a wider range of conditions.

SUMMARY

Computational Fluid Dynamics (CFD) and other analytical tools have been used in the development and pre-flight analysis of the Mach 7 X-43A vehicle. Integrated aero-propulsion performance was predicted using 3D inviscid airframe computations and engineering cycle analysis tools. Longitudinal performance increments compare well with measured increments from integrated flowpath tests of the Hyper-X flight engine (HXFE). Surface pressure predictions compare well with limited ground test data. CFD was also used to qualitatively assess lateral-directional stability characteristics. Viscous computations were used to evaluate scramjet flowpath component performance and other phenomena. A 3D viscous tip-to-tail simulation was performed which shows detailed flow field characteristics of the vehicle at the target scramjet flight test condition. An assessment of analysis methods may be used to highlight future technology development needs for hypersonic airbreathing vehicles.

REFERENCES

1. Freeman, Delma C. Jr.; Reubush, David E.; McClinton, Charles R.; Rausch, Vincent J. and Crawford, J. Larry: The NASA Hyper-X Program, Presented at the 48th International Astronautical Conference, October 1997.

2. Engelund, Walter C.; Holland, Scott D.; Cockrell, Charles E. Jr. and Bittner, Robert D.: Aerodynamic Database Development for the Hyper-X Airframe Integrated Scramjet Propulsion Experiment. AIAA 2000-4006, August 2000.

3. Huebner, Lawrence D.; Rock, Kenneth E.; Witte, David W.; Ruf, Edward G. and Andrews, Earl H. Jr.: Hyper-X Engine Testing in the NASA Langley 8-Foot High Temperature Tunnel. AIAA 2000-3605, July 2000.

4. Holland, Scott; Woods, William and Engelund, Walter C. Hyper-X Research Vehicle Experimental Test Program Overview. AIAA 2000-4011, August 2000.

5. Berry, Scott; Auslender, Aaron H. and Dilley, Arthur D.: Hypersonic Boundary Layer Trip Development for Hyper-X. AIAA 2000-4012, August 2000.

6. Godfrey, Andrew G.: General Aerodynamic Simulation Program Version 3.0 User's Manual. Aerosoft, Inc., May 1996

7. Svehle, R.A. and McBride, B.J.: Fortran IV Computer Program for Calculation of Thermodynamic and Transport Properties of Complex Chemical Systems. NASA TN D-7056, 1973.

8. Goldberg, U.C.: Separated Flow Treatment with a New Turbulence Model. AIAA Journal, vol. 24, no. 10, pp. 1711-1713, 1986.

9. Huebner, Lawrence D. and Tatum, Kenneth E.: Computational and Experimental Aftbody flow fields for Hypersonic Airbreathing Configurations with Scramjet Exhaust Flows. AIAA 91-1709, June 1991.

10. Huebner, Lawrence D. and Tatum, Kenneth E.: CFD Code Calibration and Inlet-Fairing Effects on a 3D Hypersonic Powered-Simulation Model. AIAA 93-3041, July 1993.

11. Tatum, Kenneth E.; Witte, David W.; Monta, William J. and Walters, Robert W.: Analysis of Generic Scramjet External Nozzle Flowfields Employing Simulant Gases. AIAA 90-5242, December 1990.

12. Srinivasan, Shiva; Bittner, Robert D. and Bobskill, Glenn J.: Summary of the GASP Code Application and Evaluation Effort for Scramjet Combustor Flowfields. AIAA 93-1973, June 1993.

13. Loomis, Mark P.; Venkatapathy, Ethiraj; Papadopoulos, Periklis; Davies, Carol B.; Berry, Scott; Horvath, Tom and Campbell, Charles.: Aeroheating and Aerodynamic CFD Validation and Prediction for the X-38 Program. AIAA 97-2478, June 1997.

14. White, Jeffrey A. and Morrison, Joe H.: A Pseudo-Temporal Multi-Grid Relaxation Scheme for Solving the Parabolized Navier-Stokes Equations. AIAA 99-3360, July 1999.

15. Markotos, N.C.; Spalding, D.B. and Tatchell, D.G.: Combustion of Hydrogen Injected into a Supersonic Airstream (The SHIP Computer Program). NASA CR-2802, April 1977.

16. Ferlemann, Paul G.: Improvements to the SHIP Computer Code and Predictions of Vorticity Enhanced Turbulent Supersonic Mixing. Master of Science Thesis, George Washington University, Washington, D.C., August 1993.

17. Pinckney, S. Zane.: Program SRGULL: An Advanced Engineering Model For the Prediction of Airframe-Integrated Subsonic/Supersonic Hydrogen Combustion Ramjet Cycle Performance. NASA TM 1120, January 1991

18. White, J. T.: X-43A Real Time Angle-of-Attack Estimation Scheme Utilizing Flush Airdata Sensing (FADS) System Inputs. AIAA 2000-4013, August 2000.

19. Huebner, Lawrence D.; Rock, Kenneth E.; Voland, Randall T. and Wieting, Allan R.: Calibration of the Langley 8-Foot High Temperature Tunnel for Hypersonic Propulsion Airbreathing Testing, AIAA Paper 96-2197, June 1996.

20. Frendi, Abdelkader: On the CFD Support for the Hyper-X Aerodynamic Database, AIAA 99-0885, January 1999.

23. McClinton, Charles R.; Voland, Randy; Holland, Scott D.; Engelund, Walter C.; White, J. T. and Pahle, Joe W.: Wind Tunnel Testing, Flight Scaling and Flight Validation with Hyper-X, AIAA 98-2866, June 1998.