Aerothermodynamics At NASA – Langley Research Center

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INTRODUCTION

The Aerothermodynamics Branch at NASA – Langley Research Center is tasked with developing, assessing and applying aerothermodynamic technologies to enable the development of hypersonic aircraft, launch vehicles, and planetary/earth entry systems. To accomplish this mission, the Branch capitalizes on the synergism between the experimental and computational facilities/tools which reside in the branch and a staff that can draw on five decades of experience in aerothermodynamics.

The Aerothermodynamics Branch is staffed by 30 scientists/engineers. The staff, of which two-thirds are less than 40 years old, is split evenly between experimentalists and computationalists. Approximately 90 percent of the staff work on space transportation systems while the remainder work on planetary missions. The Branch manages 5 hypersonic wind tunnels which are staffed by 14 technicians, numerous high end work stations and a SGI Origin 2000 system. The Branch also utilizes other test facilities located at Langley as well as other national and international test sites. Large scale computational requirements are met by access to Agency resources.

AEROTHERMODYNAMIC PROCESS

Aerothermodynamics is a blend of aerodynamic forces and moments, pressure/shear loading, heating and fluid dynamics across the speed range. This information is obtained from ground based experiments, engineering/computational analysis and flight test results and becomes the basis for the aerothermodynamic process.

The aerothermodynamic process is the road map that defines the steps necessary to turn mission requirements into a flight vehicle. A systems analysis, based on mission requirements, will define an initial concept. The configuration is then screened using parametric ground-based testing to determine whether or not the vehicle is flyable (aerodynamics) and survivable (aeroheating) throughout the reference trajectory. If the vehicle passes this test, then the flight characteristics of the vehicle are optimized using detailed ground based testing and CFD codes. Ultimately, the outer mold lines are frozen.

At this point, hight fidelity testing and "benchmark" CFD codes are used to develop a flight data book and establish aerodynamic/aeroheating flight margins.

This process has been developed and refined through Langley's involvement in the design and analysis of hypersonic vehicles beginning with the X-15 and currently the NASA family of X planes. During that time, the Branch has dealt with blunt to very slender vehicles such as the high energy Jovian entry vehicle, Galileo, the Shuttle Orbiter, DOD missile programs, Mars micro probes, NASP, Hyper X and the X-33.

ANALYSIS TOOLS

Up until the mid 1980's, aerothermodynamic analysis was based on engineering tools, data obtained from ground based facilities and a very limited amount of flight data. At this time, Computational Fluid Dynamics (CFD) began to contribute to the knowledge base, primarily as a tool to characterize real-gas effects at flight conditions. As CFD has matured, it has taken on an increasingly larger role in the analysis of hypersonic vehicles. Currently, for a given vehicle, CFD accounts for approximately 25% of the aerothermal data base. In another decade that percentage should double due to increased computer speed/size, radical improvements in surface modeling/grid generation and improved solution techniques. However, ground based facilities will always be a major contributor to the aerothermodynamic data base due to their ability to quickly generate large amounts of data.

Ground Based Testing

The Aerothermodynamic Facilities Complex[1] (AFC) represents all of NASA's experimental aerothermodynamic testing capability via conventional-type (as opposed to impulse-type) hypersonic blowdown-to-vacuum wind tunnels. The five facilities of the AFC provide a Mach number range from 6 to 20 using three different test gases. The 20-Inch Mach 6 Air Tunnel can provide unit Reynolds numbers from 0.5 to 8 million per foot in perfect air (i.e. $\gamma = 1.4$ in the freestream and within the model shocklayer) via reservoir stagnation pressures from 30 to 500 psia at a temperature of approximately 950 °R. The 15-Inch Mach 6 Hi Temp Tunnel provides essentially the same Reynolds number in air, but at an increased total temperature capability (to 1500 °R). The 20 –Inch Mach 6 CF_4 Tunnel simulates real-gas effects at Mach 15 – 20 by using a gas three times heavier than air which provides a relatively low value of γ within the shocklayer of the model; thereby simulating the low γ aspect of a dissociated gas. . The 31-Inch Mach 10 Tunnel can provide unit Reynolds numbers of .5 to 2 million per foot at reservoir stagnation pressures of 350 to 1450 psia at a temperature of 1850 °R. The 22-Inch Mach 15/20 He Tunnel provides a high Mach number test capability using an unheated gas as helium can be expanded from ambient temperature to Mach 26 without liquification. Over the past decade, these facilities have been upgraded to improve data quality and to implement a common instrumentation and data acquisition system among the facilities.

Standard measurement and visualization techniques, strain gauge balances to obtain aerodynamics, oil-flow for surface streamlines, thin film resistance gauges for discreet surface temperature/heat flux measurements, electronically scanned pressure models and

schlieren are available. In addition, Langley has developed phosphor thermography[2] technology to obtain global surface heat transfer measurements. Work is continuing to enhance the quality of the experimental data by implementing rapid model fabrication[3] and 3-dimensional optical scanning[4] QA processes to reduce time from design to test as well as improved measurement and data analysis techniques. Model coatings[5] capable of providing simultaneous global temperature and pressure distributions will undergo tunnel testing by the end of this year. In addition, a technique[6] designed to rapidly extrapolate ground based heating data to flight surface temperatures has shown great promise.

CFD and Grid Generation

Grid Generation: One of the major impediments to the timely inclusion of CFD analysis in the design process has been the long lead time required to generate grids. The Aerothermodynamics Branch has made a large investment in the development of a state-of-the-art, robust grid generation process based on commercial and in-house developed software for both structured[7] and unstructured[8] grid generation. Given a surface definition, block decomposed, viscous, structured grids can be generated in 1-5 days depending on the complexity of the configuration while parametric geometry changes and regriding can take as little as ½ day. Currently, the Branch's unstructured grid generation is based on the FELISA[9] system and limited to grids for inviscid flow. A viscous capability based on the VGRID[10] software is being developed. In general, the unstructured grid generation is less cumbersome than the structured grid generation and it is much easier to handle parametric geometry changes. It is still time consuming due to required initial preprocessing of the surface geometry. Limited grid adaptation for structured grids is imbedded in the flow solver with some additional refinement capability available through the grid generation tools while unstructured grid adaptation resides in the grid generator.

Computational Tools: The Branch has several codes at its disposal. Some are designed for specific tasks or flow regimes while others are general in nature.

The Langley Approximate Three-dimensional Convective Heating[11] (LATCH) and Solution of the Axisymmetric Boundary Layer Equations[11] (SABLE) are engineering codes designed to quickly assess a vehicle's thermal environment. LATCH can rapidly compute the approximate heating along inviscid surface streamlines on complex three-dimensional vehicles based on the axisymmetric analog for 3D boundary layers. The SABLE code computes axisymmetric and two-dimensional boundary layer flows on reentry vehicles and can be interfaced with the LATCH code to compute approximate 3D boundary layer solutions along streamlines on complex vehicles. Each of these codes has a turbulent option and can handle perfect gas, CF_4 and equilibrium air chemistry flows. In each code, edge conditions are obtained from an existing 3D inviscid flowfield solution. LATCH can work with solutions on both structured and unstructured grids while SABLE is currently restricted to working with structured grids. Both of these codes can compute the global heating in a matter of minutes on a SGI R10000 work station.

The FELISA[9] code is an inviscid flow solver for unstructured grids that is multigrid accelerated for subsonic/ supersonic flows, TVD upwinded for hypersonic flows and can

handle perfect gas, CF_4 and equilibrium air chemistry flows. The code is used extensively for parametric aerodynamic analysis and trade studies and to generate input solutions for the LATCH code. The Langley Aerothermodynamic Upwind Relaxation Algorithm[12] (LAURA) code also has an inviscid option for structured grid computations.

The LAURA code is the "benchmark" flow solver used by the Branch. It is a finite-volume code based on Roe's averaging and TVD limiters. It has options for chemical and thermal nonequilibrium flow in Earth and Mars atmospheres, laminar or turbulent flow and finite catalytic wall models. This code has been extensively validated against ground based and flight data and has been the workhorse CFD code in the development of Mars entry vehicles and the NASA's current family of X planes. The commercially available GASP code was also used in parts of the X33 and X34 programs.

The Viscous Shock Layer[13] (VSL) code provides the Branch with a tool to quickly assess high energy entry flows over axisymmetric bodies using detailed thermodynamic and chemistry models and accounting for surface ablation, radiation and shock slip.

The Direct Simulation Monte Carlo[14] (DSMC) method is based on the statistical simulation of molecules as they collide with themselves and a vehicle moving through a fluid. DSMC is used to simulate flows under highly rarified conditions where conventional continuum methods such as Navier-Stokes analysis are not valid. The applications can range from RCS jet interactions to on orbit contamination studies.

With the exception of the VSL code, all of the flow solvers used by the Branch have a vector and MPI implementation. The codes are routinely run on C-90 and SGI Origin 2000 mainframes as well as single and clustered workstations. The Branch is also investigating a shared memory multi-level parallel implementation of the LAURA code on a 256 processor Origin 2000.

CFD is still a maturing technology which offers many opportunities for large productivity gains. The Aerothermodynamics Branch is looking to the following areas to elevate the quality and timeliness of CFD in the aerothermodynamic design process. The grid generation process can still be improved. In particular, by tying the grid generator directly to the configuration's CAD representation. This can improve the structured grid generation process, but the big impact is on the time required to generate an unstructured grid, which can be reduced by an order of magnitude, and at the same time improve the quality of the surface grid. The Branch has a prototype for such a system working and will continue the development of this software. To take advantage of this enhanced unstructured grid generation capability, the Branch is building a new "benchmark" flow solver based on unstructured grids the will maintain all of the functionality of the current LAURA code and include grid adaptation based on error estimates from the adjoint equations. In addition, the Branch will continue to search for improved engineering prediction technology that will speed the analysis process over the hypersonic portion of a trajectory and the rapid integration of flight thermal environments with TPS sizing programs.

FLIGHT DATA

Hypersonic flight data is very scarce, but it represents a unique opportunity to benchmark prediction techniques, both experimental and computational, against flight values. Historically, the Branch has utilized all available flight data in this manner. For example, confidence in the Branch's analysis tools being used in today's X plane programs is directly linked to Shuttle Orbiter flight data which is almost 20 years old. There will soon be new opportunities for benchmarking against flight data as the X planes begin to fly. These vehicles represent new configurations and TPS systems relative to vehicles that have flown in the past. Also, on board measurements should be of a higher quality than those available in the past and there is also a potential to get global surface temperatures from ground based measurements. As with the Orbiter flight data, this new set of data will drive significant improvements in both experimental and computational aerothermodynamic analysis tools.

FUTURE PROGRAMS

With the emphasis on space transportation systems and reduction in the cost of access to space, aerothermodynamics is in the critical path of NASA's high profile programs. While the X-33/X-34 programs are nearing flight status, The X-37, 2nd generation RLV(Lockheed Martin) and 3rd generation space transportation system programs are being initiated. An exciting growth area for aerothermodynamics is the renewed interest in high energy planetary entry probes such as the Mars Sample Return, Comet Sample Return and Human Exploration and Development of Space (HEDS) programs.

SUMMARY

The Aerothermodynamics Branch has developed a well defined process for aerothermodynamic analysis and design based on five decades of experience. As NASA's lead Center for aerothermodynamics, the Branch has the personnel, experimental facilities and computational tools to effectively carry out its mission while continuously upgrading its analysis capabilities. NASA's current focus on access to space activities will keep aerothermodynamics in the critical path of these programs. However, renewed interest in high energy planetary entry missions is a growth area for this discipline.

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