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NUMERICAL PREDICTION OF SERN PERFORMANCE USING WIND CODE (INVITED)

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ABSTRACT

Computational results are presented for the performance and flow behavior of single-expansion ramp nozzles (SERNs) during overexpanded operation and transonic flight. Three-dimensional Reynolds-Averaged Navier Stokes (RANS) results are obtained for two vehicle configurations, including the NASP Model 5B and ISTAR RBCC (a variant of X-43B) using the WIND code. Numerical predictions for nozzle integrated forces and pitch moments are directly compared to experimental data for the NASP Model 5B, and adequate-to-excellent agreement is found. The sensitivity of SERN performance and separation phenomena to freestream static pressure and Mach number is demonstrated via a matrix of cases for both vehicles. 3-D separation regions are shown to be induced by either lateral (e.g., sidewall) shocks or vertical (e.g., cowl trailing edge) shocks. Finally, the implications of this work to future preliminary design efforts involving SERNs are discussed.

INTRODUCTION

Motivation

One of the challenging aspects of a single-stage-to-orbit spaceplane design (e.g., NASP, X-43) is related to the single-expansion ramp nozzle (SERN) performance. Early on in flight, at low speeds and low altitudes, the nozzle flow is highly overexpanded. Large separation regions tend to form, resulting in reduced axial thrust, which adversely affects the "transonic push." Perhaps more importantly, significant pitch moment can result which impose formidable requirements on the control system (e.g., need for additional control surfaces and/or ballast), which further degrade overall vehicle performance.

There is renewed interest in understanding SERN performance by the Air Force, NASA, and industry for the National Aerospace Initiative (e.g., Hyper-X) and Next Generation Launch Technology (NGLT)

programs, which include rocket-based combined cycle (RBCC) and turbine-based combined cycle (TBCC) propulsion system concepts. Fig. 1 is an artist's rendering of the X-43B, the third and largest of NASA's Hyper-X series flight demonstrators, which is scheduled to fly later this decade.

Literature Review

Previous research has demonstrated the utility and accuracy of Reynolds-Averaged Navier Stokes (RANS) models for assessing the performance of nozzle geometries including: planar, axisymmetric (conventional), plug, and single-expansion ramp (discussed below).

Hamed and Vogiatzis[1] determined that 3-D numerical models are not necessary to get a reasonable estimate of 2-D convergent-divergent nozzle performance. 2-D numerical models results, using the NPARC code, typically came well within ~2% of experiment for the thrust coefficient. They found pronounced 3-D effects only at severely overexpanded conditions. The limiting factor in accuracy is attributed to turbulence modeling and the presence of complex 3-D secondary flow regions. Variation in the upstream flow conditions between experiment and the numerics are also cited as a potential source of error. They also noted that the internal nozzle pressure distribution "shifts" forward slightly as the freestream Mach number is increased from static to 0.2. These aforementioned researchers also completed parametric studies[2] using NPARC, on the effect of turbulence models on 2-D convergent-divergent nozzle pressure distributions. They found two-equation models (i.e., κ-ε and κ-ω) gave the best overall results, for both 2-D and 3-D computational models.

Ostland and Jaran[3] have demonstrated that a 2-D axisymmetric numerical model, using the finite-volume EURANUS code, can achieve good agreement with experiment for the pressure distributions along a conventional truncated-ideal axisymmetric nozzle (i.e.,

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that a physical limiter on the production of turbulent kinetic energy across the shocks was most important for accurate results. Among the four eddy-viscosity, turbulence models used, Menter's Shear Stress Transport (SST) model was deemed to produce the best prediction of free-shock separation onset.

As a portion of a review of the status of flow separation prediction in conventional nozzles (i.e., both free-shock and restricted-shock), Frey and Hagemann[4] examined the results from a finite-volume, unstructured, adaptive, RANS flow solver, which included a modified κ-ε turbulence model. They concluded that numerical results for the SSME and Vulcain engines show good qualitative agreement with experiment. They also suggest that the nozzle contour strongly influences the appearance of the restricted-shock type of separation. Specifically, RSS is found only to occur in thrust-optimized nozzles, and not in truncated ideal or conical nozzles.

Nasuti and Onfri[5] performed an array of RANS simulations for a truncated plug nozzle at realistic flight conditions, using an in-house developed code, which included a Spalart-Allmaras one-equation turbulence model. The thrust performance is shown to dramatically reduce as freestream Mach number increases. They concluded that the interaction with a freestream reduces the external pressure felt by the nozzle exhaust, leading to reduced pressures acting along the thrust-producing surfaces.

The present author could not locate publicly available literature involving numerical simulation of SERNs during overexpanded operation. Note that during the NASP-era there were only limited efforts to apply 3-D RANS methods for nozzle performance evaluation, and only a modest level of success was achieved.

Carboni et al[6] conducted a large-scale experimental investigation of SERN thrust performance. Subscale model tests were conducted in NASA Langley Research Center's (LaRC) 16-ft transonic tunnel and NASA Lewis Research Center's (LeRC) 10 ft x 10 ft supersonic tunnel. They evaluated the thrust performance for a wide range of SERN geometries (i.e., various ramp, cowl, and sidewall configurations) and wide range of operating conditions (i.e., subsonic to hypersonic). Among their many findings, they showed that installed performance at transonic and low supersonic speeds was generally quite poor (net installed thrust efficiencies varied between 65% and 85% along a hypothetical vehicle trajectory). Also, the results indicate a decrease in performance with a decrease in nozzle pressure ratio (NPR), and with increases in freestream Mach number (at constant NPR). Geometric variations were found to create subtle to significant performance effects.

Recently, Andrews et al[7] conducted a detailed investigation of a powered NASP Model 5B using LaRC's 16-ft transonic tunnel. The model was powered via a plenum to simulate realistic overexpanded operating conditions during transonic flight. The SERN pressure distribution was well resolved with pressure transducers. The matrix of runs included variations in plenum supply pressure, freestream Mach number and static pressure, angle-of-attack, sideslip, and power-on/power-off. The role of each parameter on performance has been characterized. Note that public access to this document is currently restricted.

It is the emergence of the NASP Model 5B experimental database that is the impetus for the present numerical investigation.

Research Objectives

The first objective of the current effort is to validate a RANS model, using the WIND code, for prediction of the performance (i.e., integrated loads and pitch moments) of realistic 3-D SERN configurations. More specifically, an estimate of error level, based on direct comparison with experiment, is needed. Only the transonic flight range and overexpanded nozzle conditions are considered.

Another important objective was to characterize the sensitivity of SERN performance to realistic variations in freestream conditions (i.e., pressure (altitude) and Mach number). A related objective is to understand the type(s) of flow separation phenomena observed in the computations and how they are affected by freestream conditions. A final related objective was to estimate the computational resources required to complete an appropriate matrix of simulation results (i.e., to determine whether such a methodology can be implemented as a preliminary design tool).

METHODOLOGY

RANS simulations of transonic flow conditions are conducted for the NASP Model 5B and the ISTAR RBCC (a variant of X-43B).

The NASP 5B model was constructed to enable direct comparison (and validation) of the numerical

predictions with the previously described experimental data recently obtained at LaRC. Note that this vehicle's nozzle can be considered high-expansion ratio since it was configured for very high Mach number flight.

The ISTAR RBCC model was constructed as part of on-going efforts for the X-43B program. Note that this vehicle's nozzle can be considered mid-expansion ratio since it was configured for moderate hypersonic speeds.

Model Geometry

Simplifications to the exact vehicle geometries were made in order to construct the computational models. Fig. 2a illustrates the original, complete NASP 5B as tested in the experiment. Fig. 2b illustrates the simplified version used in the WIND computations. The internal flowlines are not altered, nor are the lower body outer mold lines. The various control surfaces are removed, in addition to other more subtle contour changes. Fig. 3 illustrates only the simplified version of ISTAR RBCC geometry used in the WIND computations, which included the aft half of the vehicle with modification to the wing shape.

The geometries were simplified to reduce grid generation and computational convergence turnaround times, and to improve numerical robustness, while still retaining the critical aerodynamic lines. Note that all computations herein are conducted at angle-of-attack of zero degrees (level flight). This constraint is to minimize the impact of the geometric simplifications (e.g., missing control surfaces) on the flowfield results. Andrews et al[7] have demonstrated a relatively modest influence of angle-of-attack on the NASP 5B flowfield in their power-on experiments.

Grid Resolution

The 3-D grids for both vehicle models were constructed with sequencing and parallel performance in mind. The symmetry plane (i.e., pitch plane) is used to reduce the domain by ½. The NASP 5B and ISTAR RBCC fine grids include approximately 7 and 8 million cells, respectively. The grids are sequenced from coarse to medium to fine, with a factor 8 increase in cells between each level (i.e., x2 along I-, J-, and K- directions). Approximately 90% parallel efficiency on 24-processors was attained in each case (on fine grids). The internal flowpath viscous wall surfaces are resolved with 0.0001 inch initial spacing, which results in a $y+ <$ 3 for the NASP 5B model and $y+ < 1$ for the ISTAR RBCC model, along all internal surfaces. Both are

deemed sufficient for turbulence modeling without wall functions. A grid sensitivity study, described later, demonstrates that a sufficient measure of grid independence is obtained.

Run Matrix

Tables 1a and 1b list the cases simulated for the NASP 5B validation effort and NASP 5B performance sensitivity study, respectively. The freestream Mach and static pressure nozzle pressure ratio (*SNPR*) are provided. The *SNPR* is defined as follows:

$$SNPR = P_{exit}/P_\infty (1)$$

where, P_{exit} = static pressure at cowl trailing edge
P_∞ = freestream static pressure

That is, *SNPR* is a measure of how overexpanded the internal nozzle flow becomes upon reaching the cowl trailing edge, with 1.0 being perfectly expanded. This value is somewhat ambiguous since the pressure can vary along the cowl trailing edge plane; so an average value at the cowl trailing edge was "eyeballed" in the numerics. The angle-of-attack (α) and sideslip (β) are always zero (i.e., level flight).

Table 1a. NASP 5B cases simulated for comparison with experiment

Case	Mach	SNPR
1a	0.70	0.268
1b	0.90	0.272
1c	1.20	0.344
1d	1.20	0.436
1e	1.20	0.486
1f	1.20	0.529

The NASP 5B validation cases are chosen to follow a set of cases identified by Andrews et al[7] as cases of interest. The first three cases represent a possible trajectory, while the next 3 cases complete a short sweep of *SNPR* at Mach 1.2. By choosing these conditions, direct comparisons could be made with the experimental data sets. The NASP 5B sensitivity cases include a modest matrix of additional cases (i.e., 9) in which only freestream pressure and Mach number are varied.

Table 1b. NASP 5B matrix for sensitivity study

	Mach		
SNPR	0.7	0.9	1.2
0.25	x	x	x
0.44	x	x	x
0.67	x	x	x

Table 2 lists the matrix of runs conducted for the ISTAR RBCC performance sensitivity study. Again, this study includes a limited matrix (i.e., 12 cases) in which only freestream pressure and Mach number are varied.

Table 2. ISTAR RBCC matrix for sensitivity study

	Mach		
SNPR	0.7	0.9	1.2
0.40	x	x	x
0.50	x	x	x
0.67	x	x	x
1.00	x	x	x

Numerical Scheme

WIND[8] version 4.0 was chosen for all flow simulations presented herein. WIND is the production flow solver of the NPARC Alliance; a partnership between the NASA Glenn Research Center (GRC), Boeing, and the USAF Arnold Engineering Development Center (AEDC) dedicated to the establishment of a national, applications-oriented flow simulation capability. Although WIND is largely derived from NAST3D,[9] it actually represents a merger of the capabilities of several other solvers. WIND is a node-based, finite-volume, multi-block structured code, which permits mismatched, abutting, and overlapping block boundaries. WIND's grid sequencing, parallel processing, and well-validated turbulence models are all features which were deemed essential. It should be noted that further development of the WIND code is ongoing.

The implemented numerical scheme to solve the 3-D Reynolds-Averaged Navier-Stokes (RANS) equations is true, second-order, spatially accurate (i.e., cell stretching is included in flux extrapolations). The inviscid fluxes were computed with Roe flux-difference splitting plus limiters to ensure monotonicity in the solution (i.e., to satisfy the TVD property). An implicit, 3-D spatial factorization scheme, with local time stepping, was chosen to drive the solutions to steady state. Menter's Shear Stress Transport (SST) model[10]

was chosen to handle fine-scale turbulence effects. SST is a blended combination of κ-ω (near walls) and κ-ε (away from walls). One-dimensional Riemann invariants are implemented to calculate the inflow and outflow conditions for the freestream.

The NASP 5B experiments at LaRC included a high-pressure plenum that is connected to the internal nozzle. Consequently, stagnation conditions (provided by LaRC) are imposed at the plenum exit/nozzle inflow boundary in the numerical model.

The predicted, uniform combustor exit conditions for the X-43B at these flight conditions were provided by the ISTAR design team, and are proprietary. In order to smoothly impose these flow conditions in the numerical model, the flow conditions had to be "expanded" so that the numerical inflow conditions are aligned with slightly diverging duct walls at the inflow plane. This was done without altering the massflow or thrust.

Numerical Procedure

Convergence monitoring is accomplished via integrated load and moment histories. Once the oscillations in these values over several hundred iterations were less than 1%, the solution is deemed well enough converged. These integrated load and moment predictions did not typically approach within 1% error of experimental results; consequently, there was no reason to spend the CPU resources required to obtain much better convergence.

CPU costs for the simulations may be of practical interest for similar SERN evaluation efforts. The NASP 5B model required the approximate CPU times listed in Table 3 to obtain convergence using a 24-processor SGI Origin 3800 arrangement. The number of cycles required was typically around 5000 iterations at each grid level. The CPU costs and number of cycles required are similar for the ISTAR RBCC model.

Table 3. Approximate CPU requirements

NASP5B	Run time (x24 proc)
Coarse grid	30 min
Medium grid	+4 hr
Fine grid	+24 hr

Sufficient grid independence for the integrated load and moment predictions was obtained based on comparisons between the medium and fine grid level solutions for an initial set of NASP 5B results (see discussion in Results section). A similar convergence study for the ISTAR RBCC simulations conducted for initial test cases (not

discussed herein), also demonstrated grid independence. Consequently, only medium grid level results are reported for the matrix of runs conducted for the sensitivity studies.

RESULTS FOR NASP5B

Cases 1a, 1b, and 1c

These three cases were originally identified by LaRC as highly overexpanded cases, representative of the transonic speed regime (i.e., Mach 0.7, 0.9, and 1.2, respectively).

Fig. 4 illustrates a comparison between the WIND and LaRC experimental results for Case 1a (Mach 0.7, $SNPR=0.268$) for the internal pressure distribution along the SERN. The contour plot includes the entire SERN surface starting from the x-location of the cowl trailing edge (TE) on the left side. The experimental contour plot (as with all other such plots that follow) was provided by LaRC. The pressure transducer locations are indicated. The thick dashed line represents a downstream longitudinal limit for integration purposes, as proposed by LaRC to provide an ISTAR RBCC-like geometry.[7] Note that the ISTAR RBCC involves a smaller area ratio (and relatively shorter nozzle) than the NASP5B. This is referred to as the "truncated" integration. The long-dash dot line represents the longitudinal limit for the "full" integration. Note that vehicle control surfaces are omitted from the comparison. Although the absolute pressure values have been purposely omitted from the contour legend, the reader will note that the low-pressure end of the color scale is always blue.

Comparisons for the integrated forces (axial and vertical) and pitch moments are provided in Table 4. Results for the truncated and full integrations are provided. The forces are normalized by the ideal thrust, and so represent force coefficients (Cf,axial and Cf,vertical). The pitch moment is normalized by the ideal thrust and reference length (i.e., rough distance between the SERN area mid-point and vehicle center of gravity), and so represents a pitch moment coefficient (Cm,pitch). The relative error of the numerical values is also provided. Note that these integrated loads do not include any momentum flux, and are not offset by the ambient pressure in the integration, and so are not physically meaningful except for comparison's sake. The numerical predictions agree very well with the experimental results for both truncated and full integrations (< 3%), despite the differences in the local pressure distribution for the full integration (Fig. 4).

Table 4. Normalized forces and moments (Case 1a)

Truncated Integration			
Metric	Numerical	Experimental	Error (%)
Cf,axial	0.292	0.295	-1.1
Cf,vertical	1.228	1.249	-1.7
Cm,pitch	-1.288	-1.290	-0.1

Full Integration			
Metric	Numerical	Experimental	Error (%)
Cf,axial	-0.105	-0.109	-2.9
Cf,vertical	-0.578	-0.591	-2.2
Cm,pitch	0.897	0.901	-0.5

Fig. 5 includes the numerically predicted SERN pressure contour map with "oil-flow" streamlines (left) and a close-up pitch plane slice along the vehicle centerline with Mach contours (right). The Mach contours illustrate a massive separation region, which initiates along the SERN at a x-position just before the cowl TE and extends downstream about 20% of the SERN length. The termination line for reattachment can be observed among the oil flow lines. This phenomenon appears quite similar to the restricted shock separation (RSS) found in conventional 2-D and axisymmetric nozzles, mentioned earlier. The transverse extent of this RSS reaches a significant portion of the SERN width, as implied by the oil flow lines. It should be emphasized that this massive RSS is very likely to exist in the experimental results due to the excellent agreement for this region in Fig. 4.

Figs. 6 and 7, and Table 5, provide comparisons and results for Case 1b (Mach 0.9, $SNPR=0.272$). Fig 6 includes the direct comparison between the numerical and experimental results for the pressure distribution along the SERN internal surface. Table 5 quantifies the comparison for the integrated forces and pitch moments. Fig 7 illustrates the oil flow lines (left) and pitch plane Mach contours (right) in the vicinity of another significant RSS region.

The numerical results agree reasonably well in Fig. 6 considering the complexity of the 3-D transonic, separating flowfield. Table 5 suggests the comparison for the integrated forces and pitch moment is quite good (i.e., < 13% and < 2% for the truncated and full integrated values, respectively). The RSS region is slightly longer and thinner (Fig. 7) than for Case 1a, and has its onset shifted downstream about 5% of the SERN length.