Design of a Small Scale Aerospike Nozzle and Associated Testing Infrastructure for Experimental Evaluation of Aerodynamic Thrust Vectoring

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A system for cold flow testing of an aerospike nozzle has been developed in an effort to examine the effectiveness of aerodynamic thrust vectoring and truncated nozzle base bleed. These tests are designed to produce results that will support the design of a system for hot flow testing of the same technologies. Design of a nozzle suitable for testing with reasonable cold-gas mass flow rates and measurable forces and moments involved an extensive parametric study. Conceptual-level computational fluid dynamics results for aerodynamic thrust vectoring and base bleed are also described.

I. Introduction

Achieving the large range of human and robotic space exploration missions outlined in NASA’s national space vision will require significant advances in technology from all systems of a space vehicle, especially propulsion systems. Advances in propulsion technologies offer the greatest potential for spacecraft mass reduction. Mass reductions are especially critical for planetary landing and ascent propulsion systems like those proposed for the Mars Ascent Vehicle where the cost of delivering mass to the surface is so high.

While aerospike nozzles have long been known for their altitude compensation ability during endo-atmospheric flight, they also present significant potential advantages for purely in-space applications. Aerospike nozzles can be both more efficient and significantly smaller than conventional high expansion ratio bell nozzles. Given a fixed vehicle base area, an aerospike nozzle can present higher area expansion ratio than a bell nozzle, providing better performance in a space environment or near vacuum environment like Mars. The potential for nozzle mass reduction and increased specific impulse (Isp) using an aerospike nozzle translates to a 15-18% decrease in the propellant mass and total system weight. Additionally, one of the often-overlooked advantages of the aerospike nozzle is the ability to achieve thrust vectoring aerodynamically without active mechanical nozzle gimbals, and offers a significant potential for reduced system complexity and weight.

Figure 1 compares two aerospike-based nozzle designs to their conventional counterparts with the same effective expansion ratios. The image on the left compares the original Saturn V first stage F-1A engine to its proposed replacement J-2T-250K aerospike engine (featuring a truncated plug nozzle). It should be noted that both of these engines are optimized for earth atmospheric conditions. At Mars and vacuum conditions, the size difference is greater. This size difference is illustrated by Fig. 1b where the proposed 12.1 kNt Altair Lander Engine is compared to its aerospike equivalent. In both examples, the size differences are pronounced. Despite its well-known potential benefits over conventional conical or bell-nozzle designs, the aerospike rocket configuration has never been deployed on an operational space vehicle because of a perceived low technology readiness level (TRL). One of the major reasons for this perception is the lack of high quality ground and flight test data and its correlation with analytical flow predictions. This dearth of data is especially true with regard to off-nominal design performance, thrust vectoring, and thruster-out scenarios for clustered aerospike configurations.

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The analytical and experimental work outlined in this paper is a first step in conducting fundamental experimental and analytical research to fill in the “gaps” in the experimental data chain. A primary experimental emphasis is to develop methods for using the aerospike nozzle for aerodynamic thrust vectoring. Redundancy management and off-design performance issues will also be addressed. The goal is a rapid upgrade of the systems technology to level 4 with in a year, and an eventual upgrade to TRL 6 by the end of a three-year research period. Such an upgrade in the TRL-level would make the aerospike design competitive with conventional nozzle designs, and will enable aerospike-based propulsion systems to be considered as a valid flight design option for future space vehicle designs.

II. Research Efforts

II.A. Aerodynamic Thrust Vectoring

As mentioned in the introductory section, the aerospike nozzle offers the ability to achieve thrust vectoring without an active nozzle mechanical gimbal. Thrust vectoring can be achieved using conventional methods like differential chamber pressure throttling. For an operational rocket system with propellant combustion, combustion stability and injector pressure ratio eventually limit the ability to throttle the chambers differentially. The degree of differential throttle ability of an aerospike nozzle is clearly propellant and combustion chamber dependent. An intriguing, combustion-independent possibility for thrust vectoring using an aerospike nozzle is aerodynamic flow manipulation. By injecting propellant asymmetrically into the plug base, or at points along the nozzle contour, it is possible to achieve a local flow asymmetry that has the potential to produce significant lateral forces. This concept was demonstrated on the NASA X-29 vehicle where nose flow injection resulted in differential vortex manipulation, and produced yawing moments far in excess of the impulse provided by the injection jets. When propellant is injected into the flow, it spontaneously combusts in the hot exhaust gas and produces a localized flow disturbance. The resulting low-pressure region as the flow changes direction to pass over this disturbance produces a lateral net force on the spike wall. Figures 2 and 3 depict this concept.

These figures were created as part of a preliminary computational fluid dynamics investigation on the effects of secondary flow injection. The geometry and flow rates used for this analysis correspond to the parameters selected for the cold flow tests which will be described later in this report. Figure 2 shows the pressure contours generated by secondary flow injection normal to the spike surface. The flow creates a shock wave that leaves a low pressure region in the wake of the flow injection. This results in a net side force in the opposite direction of the secondary flow velocity. Figure 3 shows the mach contours that correspond to the pressure distribution in Figure 2.
Such a flow manipulation scheme has the potential to eliminate less effective reaction control thrusters and more massive engine mechanical gimbals and reduces the mass and complexity of a propulsion system for small satellite or lunar/planetary lander applications.

II.B. Base Drag Compensation

Much of the form factor savings provided by aerospike nozzles over bell nozzles is only realizable when the aerospike nozzle length is truncated. As the area of an aerospike nozzle parallel with the axis rapidly diminishes towards the end of the nozzle, this has little effect on overall thrust. The aerospike that will be used for the first round of cold flow testing will be truncated at 57 percent of its full length. This truncation results in a low pressure region on the back of the aerospike that decreases the overall thrust and efficiency of the nozzle. This effect can be compensated to some degree by applying “base bleed” or ejecting some portion of the mass flow through one or more holes in the truncated base area of the nozzle. This can either serve to help re-pressurize some portion of the back of the nozzle or simply limit the unused area on the base of the nozzle. Fluid dynamics results for pressure contours for base bleed out of a simple hole in the base of the nozzle are shown in Fig. 4. Resulting Mach number distributions are shown in Fig. 5.

Current fluid dynamics results show that a supersonic ejection port in the nozzle base does little to re-pressurize the rest of the base area, as the flow immediately separates from at the ejection point. This still can serve to increase nozzle efficiency, however, as the base ejection still produces thrust and eliminates part of the original low pressure region. Future work will examine the effects of expansion ratio on base bleed and determine net specific impulse gains from doing so.

III. Cold Gas Test Design

Experimental research will begin with a series of cold-gas tests. These tests will provide data for the calibration of analytical tools which will be used to design hardware required for subsequent hot flow tests.
Figure 3. Mach number contours generated with computation fluid dynamics for secondary flow injection on an aerospike nozzle.

Figure 4. Pressure contours for various levels of base bleed on an aerospike nozzle.
Figure 5. Mach number contours for various levels of base bleed on an aerospike nozzle.

III.A. Lab Scale Aerospike Design and Parametric Study

The design challenges associated with creating a lab-scale aerospike nozzle are not unlike those associated with designing a thruster for launch or space applications. For the first phase of testing, cold flow tests will be performed to gauge the effectiveness of aerodynamic thrust vectoring. For high measurement fidelity, axial loads on the order of 200 to 400 newtons with side forces approximately an order of magnitude lower are desired. However, for low specific impulses achieved by cold gas thrusters, even these modest thrust ranges require a high mass flow rate that can be difficult to reach with CO₂ components. The aerospike nozzle itself needs to be of reasonable size for machineability constraints. In addition, the experimental investigation centers on aerodynamic thrust vectoring for application in high altitude or space applications so the flow field generated on the test aerospike nozzle must be similar to that generated by optimally expanded or over expanded conditions. These considerations result in a multi-parameter design space without a well defined optimum.

In an effort to examine the tradeoffs associated with the aerospike design, a parametric study was conducted utilizing basic compressible fluid routines and an industry standard code used for plug nozzle design. Parametric curves were generated for nozzles optimized for the altitude of Logan, Utah, as well as nozzles over expanded by a ratio of 0.5 and 1.0. Chamber pressure and outer throat annulus diameter were used as the independent variables for all of these curves. These curves are shown in Figures 6 to 8.

The aerospike feed system design would be vastly simplified by substantially reducing the aerospike mass flow rate. Unfortunately, the size of an optimally expanded aerospike for flow rates below approximately 1 kg/s quickly become unmanageably small. Hence, it makes sense to choose the maximum mass flow rate and operating pressure such that easily available hardware, most notably pressure regulators, can handle the flow rate. The regulator selected for this project has a maximum flow rate of approximately 1.4 kg/s for carbon dioxide under operating conditions. Some margin needs to be allowed for error, so a flow rate of 1.0 kg/s was chosen at 690 k.

In order to test the effects of aerodynamic thrust vectoring for space or high-altitude conditions, it is important that the flow field and resulting pressure contour on the aerospike surface is similar to the conditions that would be observed on a space thruster. At the sonic outlet of an aerospike nozzle, a series of expansion
fans propagate towards the plug from the outer lip of the throat. These expansion fans impinge upon the aerospike plug, reflect outwards towards the free boundary, and reflect from the free boundary as compression waves. For optimal and under expanded conditions, these reflected compression waves have propagated down the flow field sufficiently that they do not impinge upon the plug surface. However, for over-expanded conditions, the free-stream boundary contracts towards the plug, and these reflected compression fans do impinge upon the spike, causing a sharp local increase in pressure and corresponding drop in Mach number. It is obvious that aerodynamic thrust vectoring could be highly dependent on local surface pressure and fluid velocity. Hence, the plug nozzle used for testing must either be optimally expanded, under expanded, or over expanded but truncated before the compression waves impinge upon the spike.

If an aerospike plug is designed to be optimized for the atmospheric pressure in Logan, Utah or is slightly over expanded, this results in a plug diameter in the range of 2.5 to 3.5 cm for the range of acceptable flow rates and operating pressures discussed previously. Although a plug designed to be under expanded or optimally expanded at local pressures would more closely approximate a space thruster, lower expansion ratio nozzles require larger flow rates or smaller spikes, neither of which was deemed acceptable. Thus an aerospike design with a higher than optimum expansion ratio is favorable. However, in order to ensure that compression waves do not reach the end of the spike computational fluid dynamics analysis is required to choose the expansion ratio where the resultant compression waves miss the end of the spike and the surface pressure on the spike remains roughly monotonic with axial position.

To verify the results of the parametric study, and to ensure a roughly monotonically decreasing pressure profile along the spike, several of the possible lab scale aerospike configurations suggested by the parametric study were analyzed with a computational fluid dynamics solver, specifically ANSYS FLUENT. Three different spike profiles were created, corresponding to optimal expansion for Logan, Utah, over expanded by 0.5, and over expanded by 1.0. The results from this analysis showed that the compression fan generated on an aerospike nozzle over expanded by 0.5 would not reflect back on a spike truncated at 75% length or less. Hence the spike was truncated at a length convenient for manufacturability at a length somewhat less than 75%. The resulting nozzle parameters for the final aerospike design are listed in Table 1. A photo of the actual aerospike is shown in Fig. 10.

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<tr>
<th>Table 1. Aerospike Design Parameters</th>
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<td>Aerospike Parameter</td>
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Figure 6. Parameter trade space for the design of a cold-gas aerospike slightly over-expanded for the atmospheric pressure in Logan, UT.
Figure 7. Parameter trade space for the design of a cold-gas aerospike slightly over-expanded for the atmospheric pressure in Logan, UT.
Figure 8. Parameter trade space for the design of a cold-gas aerospike significantly over expanded for the atmospheric pressure in Logan, UT.
III.B. Cold Gas Feed System Design

Design has been completed for the aerospike feed system and associated plumbing. The aerospike itself and the plenums directly around it are shown in Fig. 9. The aerospike assembly consists of three pieces, the aerospike itself, and a top and bottom piece that form the walls of the plenum and the outer edge of the annular throat around the aerospike. The lower piece interfaces both with feed line hoses and a six degree of freedom thrust stand designed for the project. The plenum is split into four chambers that currently allow cross flow between them for pressure equalization but are designed such that they can be sealed from each other to allow for differential plenum thrust vectoring.

A basic schematic of the associated cold-gas feed infrastructure is shown in Fig. 11. Liquid carbon dioxide is stored in six standard tanks. Flow out of the tanks is controlled via a pneumatic ball valve. The pneumatic valve actuator is controlled with a small 12 volt DC solenoid valve. After the ball valve, carbon dioxide flows into an expansion tank that drops the pressure from the saturation pressure for carbon dioxide, which is in the range of 700 to 800 psi, to approximately 150 psi downstream. The downstream pressure is further controlled via a back flow regulator. A standard regulator in parallel with the back flow regulator then further drops the pressure to approximately 100 psi, the desired pressure in the aerospike plenums. At full pressure, the flow through this regulator will be on the order of one kilogram per second and the flow through the back flow regulator should start at approximately half that and will eventually stop altogether as the system pressure drops due to decreased temperature in the liquid carbon dioxide bottles. Thermocouples and pressure transducers will be used to monitor the temperature, pressure, and to estimate the flow rates in the feed system. An additional electronic regulator in parallel with the main flow regulator will control the upstream pressure of the secondary flow injection ports.

![Figure 9. Aerospike designed for cold-flow testing.](image)

IV. Conclusions

The design work on an aerospike nozzle design and associated testing hardware has been completed in preparation for a series of cold-flow tests on a truncated aerospike nozzle. The system will allow the evaluation of aerodynamic thrust vectoring and thrust augmentation through truncated aerospike base bleed.
Figure 10. Aerospike nozzle designed for cold flow testing shown with penny.

Figure 11. Carbon dioxide gas plumbing schematic for aerospike cold-flow testing.
This series of tests will facilitate calibration of analytical prediction tools which include computational fluid dynamics results. Completion of cold gas testing should provide an adequate knowledge base before the project advances to hot flow testing.

References