Attitude Control Using Aerodynamic Vectoring on an Aerospike Nozzle

Nathan Erni, Fellow and Crystal Frazier

Abstract—This project proposes the demonstration of a novel, compact propulsion system, scaled for CubeSat-sized spacecraft. The tests will demonstrate a system that will provide the ability to precisely position CubeSats to form a large constellation whose members work collectively to accomplish a meaningful tactical objective. The distributed nature of this “swarm” offers distinct advantages not achievable by a single, large-scale spacecraft. Because of their small sizes, CubeSats must be constructed using the most efficient packaging possible. Thus the design challenges associated with creating CubeSat-scale propulsion systems are greater than those associated with designing thrusters for conventional spacecraft. Deploying conventional propulsion systems with gimbaled bell-nozzles for attitude control is infeasible in such small form factors. The proposed design, based on the aerospike nozzle concept, overcomes this difficulty. While the aerospike nozzle has long been known for its altitude compensation capability during endo-atmospheric flight, the aerospike also presents significant advantages for purely in-space applications.

I. INTRODUCTION

A aerospike nozzle is an alternative to conventional nozzles used on space rockets. With a conventional nozzle, supersonic gasses are propelled out of a structure shaped to match an isentropic expansion at a given altitude. Because conventional nozzles are designed for use at specific altitudes, they tend to produce over-expanded or under-expanded flow at other altitudes, leading to a loss in thrust and specific impulse ($I_{sp}$) - an efficiency measure for propulsive systems measured by change in momentum per amount of propellant used. According to research performed over past decades, the use of a system incorporating an aerospike rocket nozzle has the potential to reduce mass and increase specific impulse when compared with a similar system employing a conventional nozzle. This is done by forcing gas to flow along the outside of a spike. The outer flow boundary is not rigidly constrained and is able to expand or contract as appropriate.

Studies alone, however, are not enough to be considered for a NASA proposal. Concepts must be above Technology Readiness Level (TRL) 2 with rapid demonstration to TRL 4 expected and development to TRL 6 practical within a four to six year horizon.

The Utah State University Aerospike program has taken the concept of an aerospike nozzle and developed it into a physical system. By designing and producing a working cold-gas aerospike nozzle, this technology is one step closer to being usable for NASA missions. In addition to realizing the projected mass savings of an aerospike nozzle, the most innovative and revolutionary concept explored in this paper is the use of puff thrusters for Thrust Vector Control (TVC). “Puff thrusting” is the term that has been applied to a system of injecting pulse-modulated bursts of gas normal to the existing flow field along the aerospike. Such injections disturb the flow and cause a pressure differential across the face of the spike, resulting in thrust vectoring. Such methods, when characterized, replace the massive gimbals currently employed on conventional nozzles, furthering mass, size, and reliability savings. These innovations in TVC are also in line with NASA’s goals for the future of spaceflight. By providing actual hardware measurements, namely recording and analyzing the force and moment data produced by these techniques, this innovative technology will be advanced.

II. PREVIOUS WORK

A. Prior Art

Testing on aerospike nozzles began in the 1950s in preparation for the Saturn V rocket[1]. After extensive research and test series, Rocketdyne concluded that there was no apparent benefit for the use of an aerospike over a conventional nozzle. The series of tests performed were based on liquid injection and indicated that an annular throat aerospike nozzle is at least comparable to and in many instances better than the 80% length bell nozzle at design pressure ratio[2], [3]; however, had less or equal thrust vectoring capability. Research continued into the 1970s as an aerospike nozzle was under consideration for the Space Shuttle’s main engine[4], [5], but again was not selected. Efforts on aerospike research declined until the 1990s when NASA proposed a linear aerospike as a propulsion system for the X-33 and the VentureStar[6]. These programs were later canceled.

More recent, analytical research has been conducted worldwide by several institutions for the development and performance analysis of TVC[7], [8], differential throttling[9], clustering performance[10], [11], [12], [13], slipstream effects[14], [15], [16], base bleed injection[17], [18], [19], optimal contours[20], and acoustics[21]. Hardware experiments have been conducted by Arizona State University[22], University of Washington[23], and California Polytechnic[24]. California State University in conjunction with Garvey Spacecraft corporation have conducted several experiments along with launching several sounding rockets[25], [26].

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B. Cold Flow Testing

Utah State University recently performed analytical and experimental evaluations on aerodynamic thrust vectoring on aerospike nozzles. The experiments conducted involved sizing an aerospike for slightly above optimal amplification for the testing altitude. This allowed for compression waves to extrude past the end of the nozzle to create a pressure distribution along the spike independent of atmospheric pressure, thus approximating space conditions. Different spikes were designed and manufactured for an annular mass flow rate of around 1 kg/s of carbon dioxide with a secondary injection flow rate between 2% to 3% of the annular mass flow. The designed spikes were truncated to 57% of the original spike and housed the secondary injection ports at 20%, 80%, and 90% of the truncated spike. Amplification factors were defined by the ratio of side force with a main axial flow to the side force generated by the secondary injection without the primary flow. Test experiments indicated the optimal injection site is located at 90% of the truncated spike producing amplification factors of more than 50% for the side-force specific impulse[27].

III. SPACE APPLICATIONS

While aerospike nozzles provide many advantages for space applications such as mass reduction, increased Isp, and aerodynamic thrust vectoring, the main focus of this paper is to show the feasibility for vectoring a CubeSat using an aerospike nozzle. The current deployment method for a CubeSat is by a Poly-PicoSatellite Orbital Deployer (P-POD) developed by California Polytechnic State University[28]. Each P-POD is mounted to a launch vehicle and carries up to three 1U CubeSats. Once the desired orbit is reached the P-POD releases the CubeSats. Size restrictions limit CubeSats from having any integrated propulsion or vectoring apparatus, thus the CubeSat orbits freely. Test experiments performed in this paper are designed to provide proof of concept for adding low mass and volume thrust vectoring modules to CubeSats. In practice, this will allow CubeSats the freedom of changing orbit patterns, bulk deployment, and precise positioning.

IV. OBJECTIVES

The proposed demonstration of a scaled small satellite will provide the capability to precisely position, given an angular command, a satellite for one-axis attitude control simulations. This research acts in conjunction with phase one of the CubeSat-Scale Propulsion System (CCSPS) to minimizing the deployment gap by rapidly upgrading the TRL from the current level 3 to 7. It will also demonstrate a hardware in the loop simulation to show the advantages of using an aerospike nozzle to control a CubeSat over a conventional nozzle. These advantages will be shown by using a single aerospike nozzle with two secondary injection ports for angular control.

V. METHODOLOGY

A. Aerospike Design

To better relate to space applications an aerospike nozzle was engineered to be over-expanded allowing for compression waves to extrude past the end of the nozzle to maintain a pressure distribution along the spike independent of atmospheric pressure. Prior research has shown that spike truncation, in space, has a negligible effect on total thrust [29]. It is also noted that total thrust diminishes with respect to pressure and area. The portion of the aerospike that is truncated houses a small volume along with diminishing pressure concluding that the total thrust loss by truncation would be minimal. A trade study for different aerospike parameters is shown in Figure 1. Based on the trade study and design requirements a 40% truncated aerospike has been designed to operate at 190 psi with secondary injection ports operating at 2% to 3% of the total annular flow. All design parameters can be seen in Table I. The contour of the spike was formulated using a MathLab script based on LabVIEW code written by Dr. Whitmore for spike optimization. Figure 2 illustrates the geometries of the aerospikes.

An aerospike nozzle, Figure 3, was designed using Solid Edge based upon the geometries in Figure 2. The nozzle has a total annular flow rate of 1.02 kg/s with two secondary injection ports each with an approximate flow rate of 0.0204 kg/s. The plenum was designed to allow the CO2 gas to equalize throughout the chamber in order to maintain a symmetrical flow along the aerospike. Due to the small scale of the aerospike the complexity of fabrication is increased and is still ongoing.

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B. Satellite Design

Four $CO_2$ tanks, each containing 24 oz., are used to sustain the needed flow rates for a sufficient amount of testing time. The satellite is designed to be a stand-alone unit, thus holding all tanks, plumbing, wiring, power, and instrumentation for control and data collection (Figure 4). Electronic ball valves are used for controlling annular and secondary flows within LabVIEW software. Temperature and pressure measurements are recorded at the manifold, plenum, and injection sites. Angular position is monitored and logged at all times.
C. Housing Design

This satellite is held within a housing cage keeping all coordinates fixed except for the yaw rotation (Figure 5). Low friction ball bearings are used for the satellite’s yaw rotation mitigating the friction coefficient to better simulate space conditions.

D. Control Algorithms

All control algorithms will be coded within the LabVIEW interface GUI (Figures 6 and 7). Wireless DAQ cards are positioned on the satellite’s frame to monitor and control all sensors and valves. Control of the satellite will be implemented on an off-satellite computer using different algorithms such as pulse-with modulation, bang-bang, linear-quadratic regulator (LQR), and proportional-integral-derivative (PID) controllers.

VI. EXPECTED RESULTS

Figures 8, 9, and 10 show results from MatLab simulations using a PWM controller. Amplification of the secondary injections are expected to be seen during annular flow, however the satellite can be controlled with or without the presence of annular flow.
VII. CONCLUSIONS

This paper supports the concept of using secondary injection ports on an aerospike nozzle for attitude control on a CubeSat. The proposed hardware in the loop demonstration will realize the ability to precisely position a satellite in a single axis coordinate frame. This demonstration is the first phase leading to controlling CubeSats in a six degrees of freedom (6DoF) system. This research will lead to the development of a compact propulsion system for CubeSats to accomplish meaningful tactical objectives in “swarm” environments.

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REFERENCES


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