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Numerical and Experimental Characterization of the Aerodynamic Flowfield in a Linear Aerospike Nozzle with Differential Throttling

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This thesis presents combined experimental and numerical investigations of linear aerospike nozzles to evaluate the effectiveness of fluidic thrust vectoring through differential throttling under steady- and unsteady-state operating conditions. Two linear aerospike nozzle configurations, obtained by truncating the same ideal plug contour at 20% (LASN-20) and 40% (LASN-40) of its length, are examined experimentally and numerically using two-dimensional representations based on CAD models of an in-house test facility. The objectives are to assess the ability of the numerical framework to accurately predict flowfield behavior over a wide operating range, establish a comparative assessment of the thrust-vectoring performance of both nozzle configurations, and validate the numerical predictions using newly developed experimental methodologies.

Differential throttling is achieved experimentally by dividing the nozzle chamber into two sections and introducing controlled chamber-pressure imbalances using a novel blockage-insert methodology. Numerically, differential throttling is reproduced through asymmetric inlet boundary conditions. A comprehensive steady-state investigation is performed using Reynolds-Averaged Navier–Stokes (RANS) simulations with a density-based compressible solver. Three turbulence models, namely Spalart–Allmaras (SA), realizable k–ε, and SST k–ω, are evaluated. Validation against experimental measurements demonstrates that the realizable k–ε model predicts the mean plug-base pressure within approximately 1.25% of the measured value, while both the SA and realizable k–ε models accurately reproduce plug-surface pressure distributions. Excellent agreement is obtained between numerical and experimental pressure data under both symmetric and differentially throttled conditions. The simulations successfully capture the transition from symmetric to asymmetric flowfields, quantify the associated axial and lateral thrust components, and predict thrust-deflection angles of approximately 6° for differential-throttling levels of about 5%–20%, depending on nozzle pressure ratio.

A new thrust-measurement methodology is also developed, employing three precision scales arranged in a 120° configuration and calibrated to determine axial and lateral thrust components from measured reactions. The resulting thrust measurements show good agreement with corresponding numerical predictions.

The unsteady investigations focus on the LASN-20 configuration. Unsteady RANS simulations employing the SA turbulence model are validated against transient pressure measurements obtained at nine pressure-port locations under three operating conditions. Synthetic inlet-pressure profiles derived from experimentally characterized chamber-pressure

responses are used to investigate startup transients. The numerical framework successfully reproduces the measured pressure histories and provides detailed insight into transient flowfield evolution.

The transient response is shown to depend strongly on both the rate and direction of the imposed differential throttling. For positive differential throttling, all forcing functions converge to the same steady-state thrust-deflection angle of approximately 7.2°, indicating that the final vectored state is governed primarily by differential-throttling magnitude rather than forcing-function shape. However, the transient response differs significantly. Step-input forcing generates the largest peak thrust-deflection angle (16.15°) and the shortest rise time (0.019 s), whereas ramp, first-order, and cosine-based forcing functions progressively reduce transient amplitudes and oscillatory behavior, with the cosine-based profile producing the smoothest response. Flowfield analyses identify plug-surface pressure asymmetry, together with its interaction with the expansion structure, free-jet boundary, and base wake, as the principal mechanism governing thrust-vectoring dynamics. Equal differential-throttling magnitudes of opposite sign produce different transient and steady-state responses, yielding thrust-deflection angles (at $NPR_B = 50$) of approximately 7.2° and $-9.5°$, respectively, demonstrating that increasing and decreasing chamber pressure do not generate mirror-image flowfields.

The study further demonstrates that distributed differential throttling involving both chamber sections (SPC-2) provides more balanced thrust-vectoring authority and improved dynamic behavior than single-chamber operation (SPC-1). Extended-stabilization analyses show that symmetric-to-asymmetric transitions produce steady-state thrust-deflection angles (at $NPR_B = 50$) of approximately $\pm 9.3°$, whereas direct reversals between oppositely vectored states generate the strongest transients, with peak thrust-deflection angles approaching $\pm 15°$. Despite these differences, all investigated maneuvers converge to stable equilibrium conditions, confirming the controllability, repeatability, and robustness of the differential-throttling-based thrust-vectoring approach.

Overall, the results demonstrate that a two-dimensional CFD framework can reliably predict both the steady and unsteady behavior of linear aerospike nozzles operating under differential-throttling conditions while offering substantial reductions in computational cost. The combined numerical–experimental methodology developed in this work, including the novel blockage-insert-based differential-throttling approach and the calibrated thrust-measurement system, provides a robust foundation for the characterization, validation, and future development of fluidically vectored aerospike propulsion systems.