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Study of Restricted Shock Separation Phenomena in a Thrust Optimized Parabolic Nozzle

S. B. Verma* and O. Haidn†
DLR, German Aerospace Center, D-74239 Lampoldshausen, Germany

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An experimental investigation has been carried out on a subscale thrust optimized parabolic nozzle (area ratio of 30) to study the flow characteristics prevalent during a partially formed restricted shock separation and a fully formed restricted shock separation condition, each of which are observed to be discrete in nature. Whereas the wall pressure signal near the nozzle exit randomly alternates between its value in the backflow region and that above ambient (i.e., flow randomly alternates between a free shock separation and restricted shock separation transition condition and vice versa) as a function of time for a partially formed restricted shock separation condition, the wall pressure in a fully formed restricted shock separation condition fluctuates in values above ambient in the region of flow reattachment. Further, the transient conditions of free shock separation to partially formed restricted shock separation and end-effect regime are studied in detail. The preceding transitions and retransitions suggest a variation in the relative axial positions of normal and separation shocks that favors a fully formed restricted shock separation to occur during shutdown. A second separation bubble is also observed in the restricted shock separation condition, the formation and opening of which is seen to contribute toward side-load peaks. Results also indicate that the separation shock translates back and forth (flapping motion) and experiences spanwise perturbations (rippling motion). The results are based on simultaneously acquired real-time wall pressure measurements, surface oil visualization technique, high-speed schlieren images, and signals from strain gauges installed on the nozzle bending tube.

Nomenclature

C_O = overexpansion shock
C_R = reflected shock
C_N = normal shock
f = fluctuation frequency, Hz
$G(f)$ = power spectral density, bar^2/Hz
P_a = ambient pressure, bar
P_{inc} = wall pressure at the point of incipient separation, bar
P_{pl} = plateau pressure after separation, bar
P_w = local wall pressure, bar
P_0 = pressure in the stagnation chamber, bar
r_t = radius of nozzle throat, mm
T = triple point
t = time at a particular sequence of events, s
V = voltage signal from the strain gauges installed in the bending tube, mV
X = coordinate along the nozzle axis, mm
X_{exit} = X location at nozzle exit, mm
X_{inc} = point of incipient separation (measured up to the first rise in wall pressure), mm
X_{sep} = point of physical flow separation (measured up to the upstream extent of oil-pigment accumulation as seen from surface oil flow tests), mm
$X_{\text{sep}_{\text{bub}}}$ = length of separation bubble (measured from the upstream to downstream extent of oil-pigment accumulation as seen from surface oil flow tests), mm
θ_w = nozzle wall angle, deg
$\theta_{w_{\text{exit}}}$ = nozzle exit wall angle, degrees
σ = rms fluctuation of the local wall pressure
ϕ = angle measured along the nozzle circumference, deg

Introduction

HIGH expansion nozzles such as the thrust optimized parabolic (TOP) and the compressed truncated perfect contour (CTP) are used in the main engines of present day launch vehicles to increase the vacuum performance. However, during sea-level ignition, such as the transient startup condition, the flow tends to separate inside such nozzles. The strong unsteadiness associated with the separation shock in combination with any flow asymmetry can generate dangerous side loads. The shock structure in the exhaust of such nozzles can further dictate the side-load activity considerably. For example, the exhausts from the TOP and CTP nozzles feature an internal shock that originates slightly downstream of the point (at the beginning of the divergent section) where the wall contour undergoes a transition in its curvature from circular arc (which forms the throat section) to parabolic contour. At this transition point, the wall contour and wall slope are both continuous, whereas the wall curvature is discontinuous [1]. Further, the parabola is not adapted to the expansion waves coming from the throat (unlike the ideal nozzle design). As a result, compression waves are induced by the parabola leading to formation of an internal shock [2–7]. The exhaust flow structure from such parabolic nozzles gives an appearance of a cap and hence is popularly known as a cap-shock pattern [6–8]. This shock pattern results from an interaction of the overexpansion or the separation shock (coming from the nozzle wall) and an inverse Mach reflection of the internal shock at the nozzle centerline (see Fig. 1). Such cap-shock patterns have also been observed in the hot-firing tests of the space shuttle main engine, the Vulcain 1 and 2 engines [6,9], and the Japanese LE-7A engine [10,11] and are known to be associated with considerable side-load activity [9,10,12].

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*Research Scientist, Experimental Aerodynamics Division, National Aerospace Laboratories, Council of Scientific and Industrial Research, Bangalore 560 017, India; sbverma@ead.cmmacs.ernet.in.

†Head of Technology and Vice Director, Institute of Space Propulsion; oskar.haidn@dlr.de. Associate Fellow AIAA.