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Unsteady shock motions in an over-expanded parabolic rocket nozzle

S.B. Verma [a,*,1], O. Haidn [b,2]

[a] Council of Scientific and Industrial Research (CSIR), National Aerospace Laboratories, Experimental Aerodynamics Division, Bangalore 560017, India
[b] Technische Universität München, Garching b. München, 85748, Germany

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ABSTRACT

An experimental investigation has been conducted to identify a new flow condition in free shock separation that is found to contribute significantly towards the overall flow unsteadiness in a thrust optimized parabolic nozzle at certain operating conditions. Cold gas tests were conducted with a 1/10th scale, area-ratio 30 thrust optimized parabolic nozzle both under sea-level and high-altitude conditions. Although the latter tests showed absence of fully formed restricted shock separation at any operating condition unlike sea-level tests, the peak *rms* values at certain operating conditions were still seen to be considerably high and comparable with those experienced during flow transitions in sea-level tests. A detailed statistical analysis of the data revealed that the separated shear-layer in free shock separation condition can come in very close proximity to the nozzle wall but at no point of time randomly impinges on it. This sets the entire back-flow region into pressure fluctuations that is seen to increase the length of intermittent region as well as the overall flow unsteadiness considerably. This in turn is strictly dictated by the relative locations of the normal shock to the separation shock which induce the necessary momentum imbalance of flow across each of these shocks to move the separated shear layer within critical proximities of the nozzle wall. Beyond this critical limit, flow reattachment occurs and a transition from free shock separation to fully formed restricted shock separation occurs.

1. Introduction

Under sea-level ignition during lift-off, a high expansion rocket nozzle operates in over-expanded condition with flow separation occurring through the over-expansion shock. During the transient phase of start-up operation, the process of flow development undergoes significant adjustment processes as the separation location is continuously being pushed downstream until the desired chamber pressure is achieved. The complexity of the situation arises when the shock structure and the associated separated shear-layer development come in close proximity to the nozzle walls leading to unsteady flow conditions that are responsible for generation of lateral forces or side-loads in nozzles. Although shock unsteadiness is inherent to flow separation in supersonic flows [5,15], it can show an increase or decrease depending on various flow conditions prevalent inside a nozzle [30,32]. Unfortunately, the present knowledge of side-load physics is limited and the design methods are mostly empirical [31]. As a result it is important to attain a better understanding of the mechanisms that contribute towards generation of side-loads during transient engine operation so as to look for ways to reduce the side-loads.

In the past, various flow conditions that were observed to be responsible for the generation of lateral forces or side-loads in rocket nozzles have been identified. The first such report came from Nave and Coffey [16] in 1970 during the Apollo developmental program. They observed from their cold flow tests of the subscale J-2S engine that flow reattachment downstream of separation can lead to the generation of dangerous lateral forces in rocket nozzles during start-up and shut-down operations. These observations triggered a lot of concern and interest amongst the research community to identify various other flow conditions that could contribute towards the generation of these side-loads. Based on these studies, various models on side-load origin were developed over the years. Schmucker [23] developed a model based on the tilted separation line. Dumnov [9], from his experiments conducted on the RD-0120 engine, observed that one of the causes

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Abbreviations: C_O, overexpansion shock; C_R, reflected shock; CTP, compressed truncated perfect contour; FSS, free shock separation; NPR, nozzle pressure ratio, P_0/P_a; pRSS, partially restricted shock separation; RSS, restricted shock separation; T, triple point; TOP, thrust optimized parabolic; SLC, sea-level conditions; HASC, high altitude simulation chamber.

[*] Corresponding author.
E-mail addresses: sbverma@nal.res.in (S.B. Verma), haidn@lfa.mw.tum.de (O. Haidn).

[1] Principal scientist, Group Head, Flow Structure Management and Aircraft & Spacecraft Aerodynamics, CSIR-NAL Bangalore.

[2] Professor of Rocket Propulsion, Technical University München.

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Nomenclature

A_e	nozzle area at nozzle exit	mm^2
A_s	nozzle area at separation location	mm^2
$G(f)$	power spectral density	
f	frequency	Hz
f_m	mean shock frequency	Hz
L_i	length of intermittent region of separation	mm
P_0	pressure in the stagnation chamber	bar
P_a	ambient pressure	bar
P_b	back pressure inside the high altitude simulation chamber	bar
P_e	mean wall pressure close to nozzle exit	bar
P_w	local mean wall pressure	bar
r_t	radius of nozzle throat	mm
X	co-ordinate along the nozzle axis	mm
ε	area-ratio of the nozzle	
$(\sigma_w/P_w)_{\max}$	non-dimensionalized maximum value of *rms* pressure fluctuation	
$(\sigma_w/P_w)_{exit}$	non-dimensionalized of *rms* pressure fluctuation at nozzle exit	
σ_w	standard deviation or *rms* fluctuation of wall pressure $=\sqrt{\frac{\sum_{i=0}^{n}(P_{wi}-\overline{P_w})^2}{(n-1)}}$	
α_P	skewness coefficient $=\frac{\frac{1}{n}\sum_{i=0}^{n}(P_{wi}-\overline{P_w})^3}{\sigma_w^3}$	
β_P	kurtosis coefficient $=\frac{\frac{1}{n}\sum_{i=0}^{n}(P_{wi}-\overline{P_w})^4}{\sigma_w^4}$	
γ	intermittency, Eq. (3)	
$\phi(\zeta)$	probability density function	
ζ	$\frac{P_w-\bar{P}_w}{\sigma_p}$	

of side force generation is the pressure pulsation prevalent specifically in two regions of the separation zone, namely in a narrow zone around the separation point and the other downstream of separation location. He concluded that in the former region, the moving separation shock generates an intermittent wall pressure signal, whose value fluctuates from its undisturbed boundary-layer level to that of disturbed flow (back-flow region) downstream of the separation shock and is long known from two- and three-dimensional studies on SWBLI to generate severe local pressure loading [3,8] on the model surface. In addition to these, the most significant contributions came from the cold flow subscale tests results of Frey [10,11], Frey and Hagemann [12–14], Öestlund et al. [18], and Terhardt et al. [24] who identified the major source of side-load generation to be associated with transition from free shock separation (FSS, Fig. 1(a)) condition to restricted-shock separation (RSS, Fig. 1(b)) condition and *vice versa*. They observed that these flow transitions are a result of the presence of a cap-shock pattern, typical to such nozzles, that originates from the interaction of the overexpansion shock and an inverse Mach reflection of the internal shock at the nozzle centreline. The numerical simulations of Frey [10,11] and Frey and Hagemann [12–14] further revealed that the irregular/non-uniform rate of normal shock movement relative to the separation point at different nozzle pressure ratios (NPRs) altered the momentum imbalance of flow passing through the overexpansion and reflected shocks, as indicated in Fig. 1 by variation in the length of arrows along the over-expansion and reflected shocks, resulting in flow transitions [11,13]. Onofri and Nasuti [19] showed numerically that an inviscid mechanism is responsible for the generation of a trapped vortex downstream of the central normal shock, which generates side-loads. More recently, Nguyen et al. [17] reported that the formation and opening of the separation bubbles during start-up and shut-down also generated side-load peaks. Further, Verma and Ciezki [26], Verma [25] and Verma and Haidn [27] identified from their cold flow experiments that the flow unsteadiness accompanying the downstream jump in separation front during start-up sequence and the flow unsteadiness associated with different flow separation modes and that preceding the transitions [30] as additional causes contributing towards the generation of side-loads. Although a lot of work has been reported, efforts are still on to understand certain physical aspects of these flows with complex characteristics to find their possible link towards side-load generation.

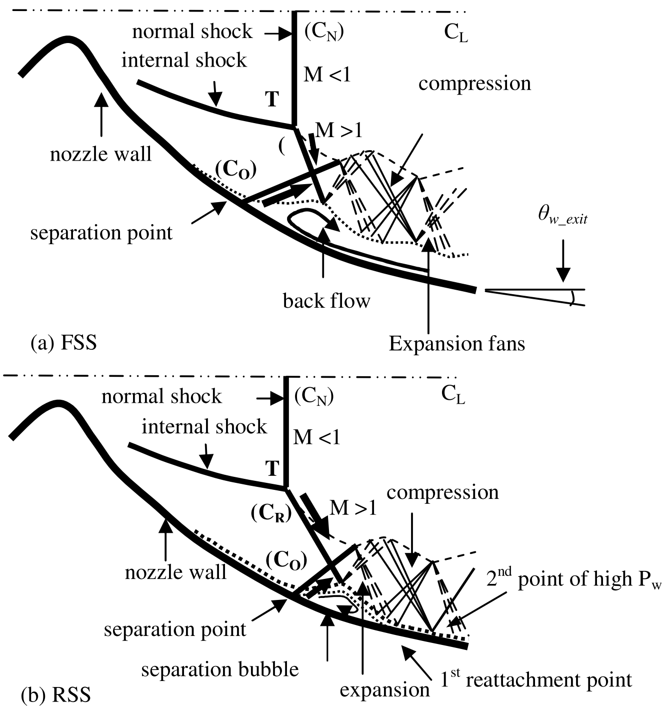

Fig. 1. Schematic of (a) free shock separation (FSS) and (b) restricted shock separation (RSS) condition inside a thrust optimized parabolic (TOP) nozzle.

In the present paper, a detailed statistical analysis is conducted to identify another flow condition in FSS condition that is found to contribute significantly towards the overall flow unsteadiness but has not been reported till date. For this purpose, fluctuating pressure signals are studied by holding the feeding pressure constant for 12 s at each NPR of interest both during start-up and shut-down sequences. This procedure helps to understand the various flow conditions the nozzle exhaust flow undergoes during start-up and shut-down sequences. The results are from tests conducted in two different test environments, namely under sea-level conditions (SLC) and inside a high-altitude simulation chamber (HASC) using a straight diffuser under self-evacuation mode. It was reported earlier [28] that the fully formed RSS flow condition, which was always observed during shut-down sequence under sea-level condition, was not at all observed to occur for tests inside the HASC. This was because the location of incipient separation and that of the normal shock were observed to change significantly thereby modifying the flow development process completely. However, the peak *rms* values at certain operating conditions inside the HASC were seen to be comparable with those observed during flow transitions in sea-level tests. This urged the authors to conduct a statistical study to identify the cause behind this observation. The test model used in the present study is the same TOP nozzle used