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Origin of side-loads in a subscale truncated ideal contour nozzle

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ABSTRACT

An experimental investigation was conducted in a cold flow test facility to identify the origin of various flow conditions that lead to side-load generation in a truncated ideal contour nozzle (of area-ratio 20.66) especially at moderate nozzle pressure ratio range of 20 to 42 during the start-up and shutdown sequences. The major contributors seem to be the transition in flow conditions namely, the change in the circumferential shape of re-circulation region inside the nozzle from a cylindrically dominated regime to a conical one and the end-effect regime that initiate highly unsteady flow conditions in the separation region preceding these transitions. Other flow transitions such as those initiated by the onset of test gas condensation and *vice-versa* result in a downstream or an upstream jump in separation, respectively, that causes the overall side-load signal to increase. During this flow regime, an increase in the length of the upstream influence region accompanied by a rise in the peak standard deviation value is also observed.

1. Introduction

Flow separation in an over-expanded convergent–divergent nozzle occurs when the nozzle expansion ratio is too large for a given nozzle pressure ratio, e.g., when the main stage rocket engine uses a high area-ratio nozzle and is operated under low-altitude conditions. Flow separation in such a case becomes inevitable with high risk of side-load generation. This is because during sea-level transient conditions, such as impulsive start-up (as during lift-off and ground testing) or shutdown (as during ground testing), the separation may not be axially symmetrical and the associated shock unsteadiness may cause momentarily large side-loads on the nozzle shell. These side-loads are known to cause failures of nozzle shell structure and thrust vector control gimbal actuators [1]. However, side loads may have different origins, on the basis of which, different models have been developed for their prediction. Such origins maybe due to asymmetric separation line, pressure pulsations at the separation location and downstream, aeroelastic coupling and flow instability.

Most of these studies were initiated by the side-load activity first reported by Nave and Coffey [2] on the J2-S engine. The study, for the first time, identified various flow conditions prevalent in overexpanded nozzles such as the free shock separation (FSS), the restricted shock separation (RSS) and the end-effects. The role of the latter on side-load origin and those cause by transition between FSS to RSS and vice-versa were also introduced [2]. Based on this study, initially Schmucker [3] developed a side-load model based on the tilted separation line and later Dumnov [4] did it based on random pressure pulsations near the separation line and in the recirculation region downstream. These models were based on purely the FSS condition. Studies on nozzle flow separation were later revisited with numerical simulations by different groups in USA [5] and Europe [6], respectively. More recently, Frey and Hagemann [7,8] and Frey et al. [9] presented a systematic and complete study of the various transition phenomenon through comparison between numerical simulations and experiments. This type of flow transition however was seen to occur only in parabolic (e.g., SSME and Vulcain engines) and compressed perfect nozzles (e.g., LE-7 engine), which feature an internal shock formed downstream of the circular arc forming the throat. In comparison, a truncated ideal contour or TIC nozzle (e.g., Viking and RD-0120 engine) does not encounter such flow transition conditions due to the absence of the internal shock. However, intense side-load activity has still been reported in the rocket nozzles equipped with TIC design as well such as the RD-0120 [4] engine (Russian Energia Launcher). As a result, it becomes important to investigate the flow conditions that lead to side-load development in TIC nozzles.

The main objective of the present study is to identify the origin of various flow conditions in cold flow testing of a TIC nozzle

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Nomenclature

dP_0/dt	rate of change of nozzle feeding pressure	bar/s
$dNPR/dt$	rate of change of nozzle pressure ratio	
F_{xy}	side-load data measured in the X–Y plane	N
F_{xz}	side-load data measured in the X–Z plane	N
M_{inc}	Mach number at incipient separation location	mm
P_0	feeding pressure in the stagnation chamber	bar
P_a	ambient pressure	bar
P_e	mean wall pressure close to nozzle exit	bar
P_{inc}	mean wall pressure at incipient separation location	bar
P_w	local mean wall pressure	bar
r_t	radius of nozzle throat	mm
T_a	ambient temperature	K
T_{inc}	wall temperature at incipient separation location	K
T_0	temperature in the stagnation chamber	K
X	co-ordinate along the nozzle axis	mm
X_{inc}	streamwise location of incipient separation point	mm
X_{sep}	streamwise location of physical separation point	mm
ε_e	area at the nozzle exit	mm^2
ε_{inc}	area at the point of incipient separation	mm^2
$(\sigma_w/P_w)_{max}$	non-dimensionalized maximum value of *rms* pressure fluctuation	
σ_w	standard deviation or *rms* fluctuation of wall pressure $= \sqrt{\frac{\sum_{i=0}^{n}(P_{w_i}-\overline{P_w})^2}{(n-1)}}$	
φ	circumferential location of pressure transducers	degrees
NPR	nozzle pressure ratio	P_0/P_a

($\varepsilon = 20.66$, $M = 4.76$) that leads to side-load generation especially at moderate nozzle pressure ratio (NPR) range of 20 to 42. A recent study by Stark and Wagner [10] attributed the generation of side-load peak at low NPR of 4 to 6 in TIC nozzle to laminar-turbulent boundary layer transition via asymmetric circumferential transition. This and most of the previously reported studies [7–9] on TIC nozzles have focused on the mean flow conditions and the associated exhaust flow patterns. Very few studies [11,12] report the association of flow unsteadiness preceding a flow transition in a TIC nozzle to be responsible towards side-load generation. While ref. [12] reported the overall flow asymmetry observed and the variation in peak standard deviation values at various NPR, the reason for the origin of various flow conditions responsible for the latter was not discussed. The present paper is an effort in that direction.

2. Experimental set up and procedure

2.1. Test facility

A series of experiments were conducted in the cold flow test facility at P6.2 in DLR Lampoldshausen, Germany (see Fig. 1(a)). Gaseous nitrogen at ambient temperature is used as test gas. Under present test limitations, with the nozzle blowing into atmospheric pressure, a maximum nozzle pressure ratio (NPR) up to 60 can be achieved. The sub-scale TIC nozzle (design Mach number 4.76) employed in this study has a throat diameter of 0.02 m, yielding maximum mass flows in the range of $m = 4.2$ kg/s. The nozzle area ratio is 20.66. The wall angle at the last point of the circular arc forming the throat is 16° and that at the nozzle exit, 5.84°. The results reported in ref. [10] are for the same TIC nozzle model tested in the same test facility using the same test gas supply source though the test sequence may vary. As a result, the data from ref. [10] and present tests is comparable. Fourteen Kulite type of pressure transducers (with a pitch of 8 mm) are used in the divergent section of the nozzle along a single axial line. In order to check for flow asymmetry and unsteady separation conditions, pressure points were also fabricated in streamwise direction at circumferentially opposite location, $\varphi = 180°$, for locations 5 to 12 at $\varphi = 0°$ (see Fig. 1). Fig. 1(b) shows the choice of axis and the pressure transducer locations for the present tests. A truly simultaneous data acquisition system is used which has the capacity of measuring 64 channels at 1 kHz and 16 at 50 kHz or 8 at 100 kHz. Color schlieren technique is used to visualize the exhaust flow patterns. Each transducer is threaded into the nozzle wall. A small orifice (of 1 mm length and 0.5 mm diameter) connects these transducers to the flow.

2.2. Wall pressure sensors and data acquisition

The pressure transducers used in the nozzle wall pressure experiments are the Kulite Semi-conductor Inc. (model XT-154-190M). They have a pressure-sensitive area of 0.71 mm in diameter and an outer case diameter of 2.4 mm. According to the manufacturer's specifications, these transducers have a natural frequency of 50 kHz. They are capable of operating in the temperature range of −55 °C to +175 °C and humidity 0 to 100% RH. The accuracy, according to the manufacturer's specification is within 0.5% in the operating pressure range of 0–0.1 MPa. The sensitivity of the transducers is typically 0.97 V/MPa. The transducers were calibrated statically against atmospheric pressure. Sampling frequency for all transducers is 1 kHz with a low-pass filter cut-off frequency of 160 Hz. The experimental uncertainty of time-averaged surface-pressure measurements is of the order of ±1%. However, in the intermittent region of separation that is associated with high levels of flow unsteadiness (typical standard deviation of 2%), the average pressure uncertainty is likely to be somewhat greater. Each test was repeated twice, and the repeatability of the standard deviation values was found to be roughly within ±0.02.

For side-load measurements, a thin-walled bending tube section [4], made of a special aluminum-alloy is connected upstream of the convergent nozzle section [9,13]. The bending tube resists the high nozzle feeding pressure, but is sensitive to lateral forces. Pairs of two strain gauges are applied in each quadrant. Opposite pairs build a full Wheatstone bridge to measure one of the forces in two lateral directions. Due to the wiring positioning only bending strains are measured. All other strains provoked by the inside pressure, the longitudinal nozzle force and temperature effects, are compensated. The bending tube is statically calibrated using three weights successively hung from the nozzle exit and released. The impulsive release of each weight gives both the static and dynamic response of the system. The measured voltages from these gauges during the test run can therefore be interpreted as forces acting on the nozzle. The voltage signals from strain gauges were acquired at 1 kHz with a low-pass filter cut-off frequency of 160 Hz.

A Color Schlieren System in the typical Z-setup was used to visualize the nozzle exhaust flow. The present Color Schlieren method uses the dissection technique developed by Cords [14] and a color coding similar to that of a rainbow is used to avoid misinterpretations due to color mixing [15]. A color filter source mask is placed in the focal plane of the first Schlieren mirror (details of the set up can be seen in Ref. [7]). The Schlieren apparatus is adjusted in a way that the green color represents refractive index gradient near zero. A modified Xenon flash light by Drello with a flash duration of 13 µs and a flash energy of 18 J has been used. In front

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