Acta Astronautica 122 (2016) 137–145

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Transient three-dimensional side-loads analysis of a thrust-optimized parabolic nozzle during staging

Ruyan Jia*, Zhenyu Jiang, Weihua Zhang

College of Aerospace Science and Engineering, National University of Defense Technology, Changsha 410073, China

ARTICLE INFO

Article history:
Received 14 April 2015
Received in revised form
27 November 2015
Accepted 31 January 2016

Keywords:
Stage separation
Thrust-optimized parabolic nozzle
Nozzle flow separation
Nozzle side loads
Numerical simulation

ABSTRACT

The objective of this effort is to numerically investigate side-loads and correlative flow physics of a thrust-optimized parabolic nozzle during the fire-in-the-hole staging event. The three-dimension transient flow in nozzle is examined by the time-accurate numerical method with time-varying chamber pressure and separation gap width. The main properties (amplitude, phase position and frequency) of computed side-loads were also analyzed. The ordinary nozzle flow separation patterns, free shock separation (FSS) and restricted shock separation (RSS), were obtained. The transition processes from FSS to RSS and finally full flow during staging event were specially emphasized. As the simulation results presented, two types of asymmetric flow physics incur strong side-loads: random transition between FSS and partial quasi-RSS due to fish tailing effect of the supersonic jet, axial flow oscillation across the nozzle lip due to relative movement between supersonic jet and front edge of the lower stage. Side-loads caused by fish tailing effect and lip oscillation have equivalent maximum amplitudes but almost perpendicular directions, while the frequency of the former is much higher than that of the latter. The side-loads due to asymmetric flow separation in the thrust-optimized parabolic nozzle are significantly intensified by the obstruction of the lower-stage dome during the staging event. Therefore, the side-loads influence should be carefully considered in advanced upper-stage nozzle of thrust-optimized parabolic contour when involving with staging.

1. Introduction

A satellite launch vehicle in general, consists of several stages and these are separated at appropriate instants along the flight trajectory. The separation of spent booster stages is among the most critical operations of a multistage launch vehicle. The Fire-In-The-Hole staging (also named as Hot Separation or Jet-on Separation) is to ignite the upper stage motor a few seconds prior to the stage separation and burnout of the lower stage. The separated lower stage is pushed away by the impinging plume of the upper stage motor. As the stages began to move apart, the circumferential gap at the separation plane allows the rocket-exhaust-pressurized interstage cavity to vent (Fig. 1) [1,2]. During the staging event, the pressure in the interstage cavity initially builds up prior to physical separation of the stages. Because of this higher effective back pressure for the upper stage nozzle flow, flow separation is prolonged relative to an altitude start condition. This internal flow separation is unstable and tends to be asymmetric, leading to sustained nozzle side loads. The possible effects of staging-induced lateral forces on the aerodynamic stability of the upper stage vehicle must be considered. Such side loads have occurred during staging events of the Minuteman, Scout, Agena, Titan, Peace-Keeper, Small ICBM and other systems in history [3,4].

* Correspondence to: College of Aerospace Science and Engineering, National University of Defense Technology, 47 Yanwachi Street, Changsha 410073, China.

E-mail address: jry890216@126.com (R. Jia).

http://dx.doi.org/10.1016/j.actaastro.2016.01.023
0094-5765/

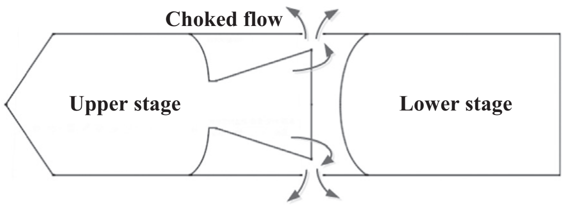

Fig. 1. Scheme of fire-in-the-hole staging event [5].

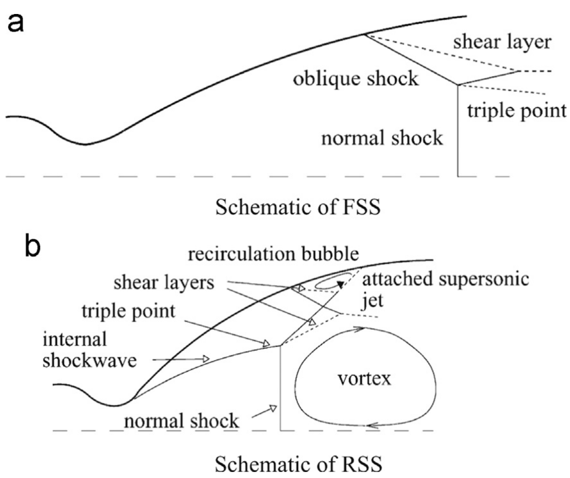

Fig. 2. Schematic of flow separation shock pattern [15].

In recent years, the side load problems found in the development of new launch vehicle engines, such as Japanese LE-7A [6] and European Vulcain [7], recall the research topic of nozzle flow separation and soon the interest rose worldwide [8–10]. The overall flow topology found in the nozzle depends on the Nozzle Pressure Ratio (NPR) and the nozzle contour. In general, two types of separation patterns are observed in the transient process of over-expanded nozzle flows. Fig. 2 shows two types of separation patterns. One is free shock separation (FSS) and the other is restricted shock separation (RSS) [11,12]. FSS is a regular type of the separation pattern and the structure can be observed in various types of nozzles such as conical contour nozzles and bell type nozzles. The flow separates fully from the nozzle wall due to an oblique shock that originates from the nozzle wall and is directed towards the nozzle center line (as indicated in Fig. 2a). In RSS, the separated flow reattaches just downstream of the separation point and forming a recirculation bubble. A stable vortex is trapped downstream of the normal shock (as indicated in Fig. 2b). RSS is a peculiar type of separation pattern observed only in thrust optimized nozzles [13] and compressed truncated perfect nozzles [14] at a certain range of pressure ratios.

As far as numerical simulation of side-loads is concerned, the first investigation was published by Deck and Guillen [16] in 2002 and concerned the FSS structure in a truncated ideal nozzle. Yonezawa et al. [17] calculated the characteristics of flow pattern and shock structures for three different nozzles. Deck and Nguyen [18] compared side-loads for both FSS and RSS structures in the hysteresis regime. Shimizu and Miyajima [14] stressed the importance of the mixture ratio in the transition process between FSS and RSS in the compressed truncated perfect nozzle. Wang [19–22] calculated the J-2X engine flow

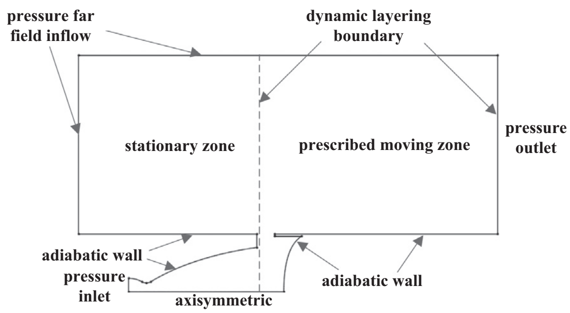

Fig. 3. Two-dimensional projection of the computational domain and type of prescribed boundary conditions.

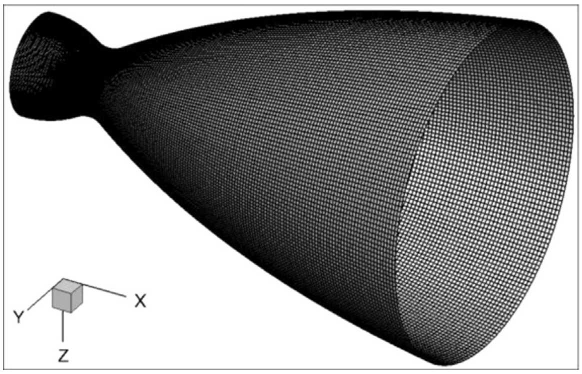

Fig. 4. Grid layout of nozzle surface.

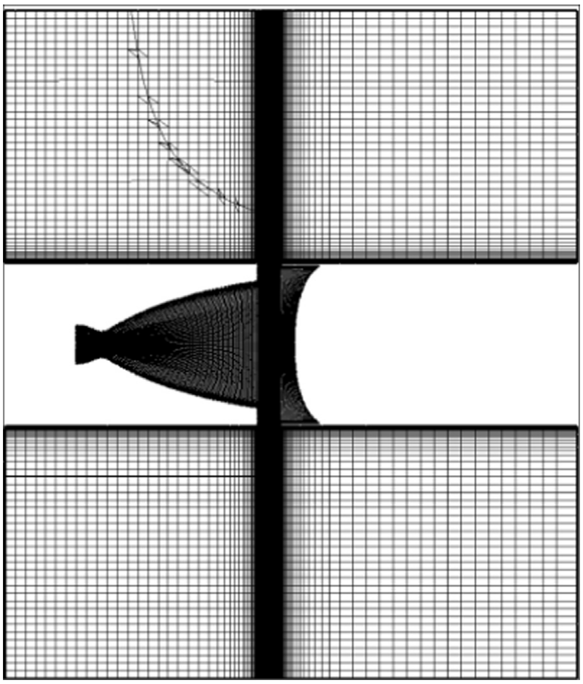

Fig. 5. Grid layout of XOY plane.