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ORIGINAL ARTICLE

Influence study of flow separation on the nozzle vibration response

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Abstract In the present paper, the vibration response difference of the upper stage nozzle with higher expansion ratio between ground and altitude simulation hot-firing test is analyzed. It indicates that the acceleration response of the nozzle under ground hot-firing test is much higher than that of the altitude condition. In order to find the essential reason, the experimental and numerical simulation studies of the flow separation are developed by using the test engine nozzle. The experimental data show that the nozzle internal flow occurred flow separation and the divergence cone internal wall pressure pulsation increased significantly downstream from the separation location. The numerical simulation and experimental results indicate that the increase of internal wall pressure and turbulence pulsating pressure are the substantial reason of vibration response increasing aggravatingly during the ground firing test.

1. Introduction

The increasing demand for higher performance in rocket launchers promotes the development of upper-stage nozzles with higher performance, which is achieved by increasing the expansion ratio basically. The engine like U.S.A J-2S engine, Space Shuttle sustainer Motor SSME, Russia RD-120 engine, Europe Vulcain Motor and Japan LE-7A prototype engine etc are equipped with the upper stage nozzle with higher performance in the propulsion area [1,2]. However, some launcher vehicle main stage engine will experience long periods of over-expanded operation with flow separation during ground firing testing, start-up or low altitude flight phase. Flow separation induces the dynamic load which leads to the failure of nozzle structure, even for the engine structure [3].

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So in the past four decade, many studies have been developed on the occurrence of flow separation. The current literatures mainly focus on the liquid rocket motor domain. Based on the flow field theory and cold or hot flow subscale simulation test, the free shock separation, restricted shock separation and the unsymmetrical load phenomenon of separation flow are investigated comprehensively and deeply [4–8]. C.X. Huang [9] preliminarily observed a theoretical work about flow deflection which occurs during the firing test, however, the underlying physical mechanism behind separation was not totally clear. Work in the late 1990s produced the numerical simulation of CHN solid rocket motor nozzle flow separation comprehensively [10,11], but not consider the two-phase flow influence, and also was deficient in experimental validation. Y.X. Wang et al. [12] present the numerical simulation and experimental study on the separation location of the engine nozzle internal flow field during static firing test. It captured the separation critical location successfully and investigated the effect regularity of the combustion pressure and nozzle inner contour on the location. The literature review above mostly explained the flow separation phenomenon by numerical method, yet there is little work discussing the difference of wall pressure fluctuation between the upstream area and downstream region of separation point which induce the potential variation of the nozzle vibration character.

In this paper, the vibration response difference of the upper stage nozzle with higher expansion ratio between ground and altitude simulation hot-firing test is analyzed comprehensively. And a computational fluid simulation and flow fluctuation pressure experimental study of the test engine nozzle are conducted to explain and validate the essential mechanism, that is, when the flow separation occurs, the wall pressure rising and pressure impulsion amplifying, which result in the increasing of vibration amplitude of the high expansion ratio nozzle under ground hot-firing test.

2. Nozzle vibration response analysis of ground and altitude simulation static firing test

For the large expansion ratio upper stage engine, its actual working condition is nearly vacuumed ambient. So during the development process of the solid rocket motor, the altitude simulation test system is necessary to construct the approximate vacuumed ambient under sea level for the engine static firing assess test. Besides altitude simulation firing test, the sea level structure hot-firing test for the components thermal structure validation and ground joint hot-firing test for the other missile subsystem are also demand during the development process. For the limitation of the altitude simulation test system, not all the validation firing test is carried in the vacuumed cabin. So need to be explained here, the ground static firing test has its specific validate purpose and it can not simulate the real working condition absolutely, but the estimate of nozzle components thermal protection and structure strength can be validated entirety.

In this section, the contrast analysis of the vibration data of the upper stage nozzle exit cone under ground and altitude simulation static firing test is carried out particularly.

2.1. Time-domain analysis

The vibration test point is located on the nozzle exit cone supporting lug. Figure 1(a) and Figure 1(b) present the measuring point acceleration versus time curves of the altitude and ground firing test respectively. It indicates that the acceleration amplitude of ground testing is from 50 g to 50 g, while the data of altitude simulation testing is only from 6 g to 6 g, the vibration amplitude of the ground test is much higher than that of altitude test.

Table 1 gives the acceleration information of ground and altitude simulation test. From the data above, it can be seen that the maximum, minimum, peak-to-peak value, RMS and the stand deviation which produced under ground firing test are far greater than that of altitude condition, that's mean,

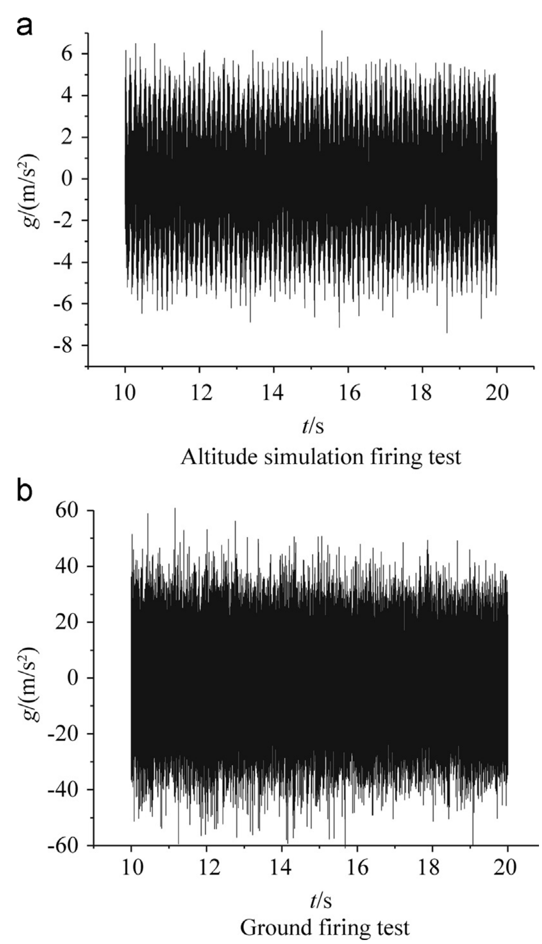

Figure 1 Acceleration vs. time curve. (a) Altitude simulation firing test and (b) ground firing test.