JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 43, No. 1, January–February 2006

Engineering Notes

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Fluid-Throat-Induced Shock Waves During the Ignition Transient of Solid Rockets

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Introduction

PREDICTION and control of pressure and pressure-rise rate during the ignition transient of solid-propellant rocket motors with a nonuniform port are of topical interest. In certain designs, an ignition pressure spike and a high rate of pressure rise may adversely affect the steadiness and stability of burning, thermoviscoelastic response of the grain and inhibitors, and the dynamic response of the hardware parts.[1] An excessive pressurization rate can cause a failure even when the pressure is below the design limit.[2,3] Although, a great deal of research has been done in the area of solid rocket motors (SRMs) for more than six decades, the accurate prediction of the ignition transient in ports of high-performance solid rocket, with sudden expansion and/or steep divergence/convergence or protrusions has not previously been accomplished.[1–18]

For technological reasons, large solid-propellant boosters, such as the U.S. space shuttle, Titan SRMs, European Ariane 5 P230, and Indian SRMs are made from segmented propellant grains with nonuniform ports.[1–18] Luke et al.[4] reported that the U.S. Space Shuttle's redesigned SRM (RSRM) head-end pressure rise rate is almost twice as high as the Titan motors. Note that the head-end port of the RSRM is narrow, compared to the Titan motors. The SRMs being developed at the Indian industry with narrow upstream port also experienced high-pressure rise rate at the head end.[2,3]

The motivation for the present study is the desire to explain the phenomena or mechanism(s) responsible for the ignition pressure spike (Fig. 1), pressure-rise rate, instabilities, and pressure oscillations often observed during the static tests and the actual flights of a certain class of dual-thrust motors (DTM) with narrow port and steep divergence in the grain.[11] In the Indian industry, test-to-test variations (0–1.8 times the steady-state value) in ignition pressure spike is also noticed in flight motors.[5]

Although the previous studies have been helpful in understanding the fundamental process of ignition transient, the actual flow physics pertinent to the unexpected ignition pressure spike (on the order of five times the steady-state value), pressure-rise rate, and thrust oscillations often observed during the ignition transient of DTM remains obscure.[2,3] Two distinguishing features of DTM are its high volume loading and the unusual port configuration necessitated by the dual-thrust requirement (inset of Fig. 1). Qualitatively these motors are referred to as high-velocity transient (HVT) motors ($A_t/A_p > 0.56$ and $L/D \geq 10$). Within the given envelope, various measures were taken by researchers to eliminate the ignition pressure spike of the DTM, but none of the conventional remedies seemed to help.[1–13] Increasing the port area of the motor has often been proposed as one of the remedies for reducing the unusual ignition pressure spike. Unfortunately, this reduces the propellant loading density and affects the high-performance nature of the rocket motor due to the envelop restriction. Hence, the elimination of the unusual ignition pressure spike and the pressure-rise rate without sacrificing the basic grain configuration or the volume loading became a meaningful objective for further studies.[17,18]

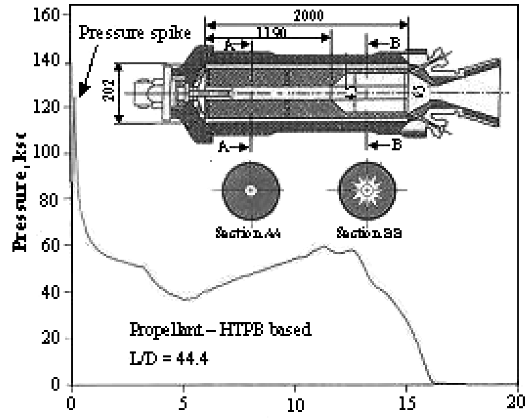

Fig. 1 Pressure–time curve of DTM with unusual ignition pressure spike with configuration in inset.[11]

Received 5 April 2005; presented as Paper 2005-4147 at the AIAA/ASME/SAE/ASEE 41st Joint Propulsion Conference, Tucson, AZ, 10–13 July 2005; revision received 23 July 2005; accepted for publication 25 July 2005.

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Salita[10] reported that shortly after the ignition of the solid boosters on the first shuttle flight (STS-1), a quasi-shock wave reflected off the launch pad and nearly damaged the control surfaces on the orbiter. The video of the launch, taken by NASA, proved that this was not due to the igniter shock. The analysis further showed that the compression wave created by ignition of the main grain was the cause of the ignition overpressure on the launch pad. However, the formation of the DTM quasi-shock wave with different physical origin was not reported in any open literature.[17] Albeit many studies have been reported on shock–boundary-layer interaction, none of these studies focused on the joint effect of the igniter jet, the grain geometry-dependent driving forces, and the boundary layer on the formation of shock waves in SRMs with divergent ports.[18]

Raghunandan[11] and Raghunandan et al.[12,13] proved conclusively through a series of papers that, under certain conditions in SRMs with sudden expansion and/or steep divergence of the port, secondary ignition can occur far downstream of the expansion region. Thereby the effective time required for the complete propellant surface area to be ignited decreases drastically, giving rise to high pressurization rate (dP/dt) in the second phase of the ignition transient. In this companion Note, inert (unignited) simulators of solid rockets are deliberately selected for parametric analytical studies, using computational fluid dynamics (CFD), to examine the occurrence of the internal flow choking at the subsonic inflow conditions without complications arising from the propellant combustion. The implication of internal flow choking can be quite serious for a practical motor. Internal flow choking results in the formation of shock waves inside the rocket motor, which will lead to an unacceptable start-up transient of SRMs.

Overview of the Numerical Methodology

Numerical simulations have been carried out with the help of a well-established two-dimensional standard $k-\omega$ model. This code solves standard $k-\omega$ turbulence equations with shear flow corrections using a coupled second-order implicit unsteady formulation. This model uses a control-volume-based technique to convert the governing equations to algebraic equations. The viscosity is determined from the Sutherland formula. An algebraic grid-generation technique is employed to discretize the computational domain. A typical grid system in the computational region is selected after the detailed grid refinement exercises. The grid points are clustered near the solid walls using suitable stretching functions. The motor geometric variables, initial wall temperature and material properties are known a priori. Inlet total pressure and temperature are specified and are in terms of pressure relative to the operating pressure. At the solid walls, a no-slip boundary condition is imposed. Note that the motor exit geometry (nozzle) is a short straight duct followed by the convergent duct. Therefore, a radial axisymmetric pressure distribution is approximated analytically, using the well-known equation for radial velocity distribution for duct flows and imposed at the exit boundary condition (inset of Fig. 2). The Courant–Friedrichs–Lewy number is initially chosen as 3.0 in all of the computations. Ideal gas is selected as the working fluid. The transient mass addition due to propellant burning is deliberately suppressed. The code has been successfully validated with the help of benchmark solutions.[2,3,13]

Results and Discussion

In the present numerical simulation, two different idealized physical models with divergent port geometries are examined. In the first phase, low-velocity transient (LVT) motors ($A_t/A_p \leq 0.56$ and $L/D < 10$) with different divergent ports are examined. In the second phase, attention is focused on an HVT motor with sudden enlargement of the port. The port geometry ($A_t/A_p = 0.58$, $L/D = 17.85$, and $L/d = 44.4$) is selected based on a typical DTM.

Figure 2 shows the influence of port geometry on the axial velocity variations of five different LVT motor cases but with same initial and boundary conditions. All of the results are consistent with the previous experimental and theoretical findings.[2,3,11–13] It can be

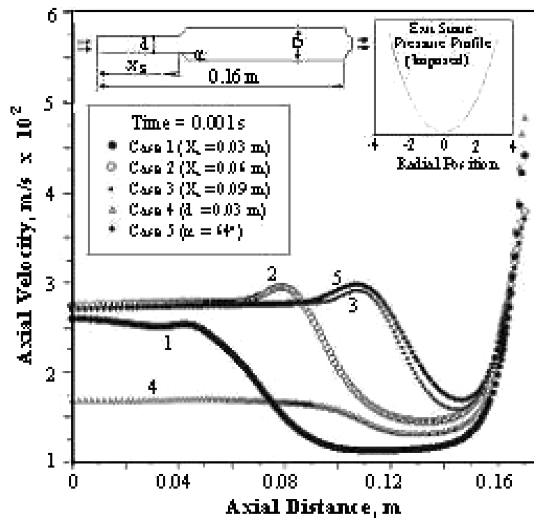

Fig. 2 Effect of port geometry on the velocity variations of LVT motors with peak near transition location; baseline values $L/D = 4$, $X_s/d = 3$, and $A_t/A_p = 0.375$.

seen from Fig. 2 that in cases 2, 3, and 5, the centerline axial velocity is highest just downstream of the divergence location. This can be explained with the help of boundary-layer theory. Note that because of the viscous friction, a boundary layer will be formed on the walls (ahead of the transition region) and its thickness will increase in the direction downstream to the divergence location. Because the volume of flow must be the same for every section, the decrease in rate of flow near the walls due to friction must be compensated by a corresponding increase near the axis. Thus, the boundary-layer growth occurs under the influence of an accelerated external flow. As a result, at larger distances from the inlet section, velocity will be relatively high and the flow will possibly become turbulent; consequently, the boundary-layer thickness will suddenly increase, leading to the sudden increase in the axial velocity due to the rocket motor port area fraction blocked by the boundary-layer displacement thickness. This will cause flow separation far downstream of the divergence region. Note that the separated flow characteristics, such as size of the separation bubble, flow redevelopment, and heat transfer in the recirculation region, are known to be more dependent on Reynolds number upstream of the step and step height.

The fourth case reported herein showed relatively low velocity at the axis due to the high port area (50% higher compared to the other four cases reported). As stated in the Introduction, increasing the port area of an SRM can reduce the unacceptable ignition pressure spike and pressure-rise rate, caused by the gasdynamics of the upstream narrow port, at the expense of propellant loading density. In the first case, the flow recirculation tendency behind the step, leading to reattachment and secondary ignition, was found to be much less because the location of the transition region was near the head end of the bore. When the transition location was fixed far downstream in the LVT motor, the tendency for flow separation was found to be very high. This led to the formation of a recirculation bubble and flow reattachment. Note that the flow reattachment will favor secondary ignition, leading to an unacceptable high-pressure rise rate during the ignition transient of solid rockets. Hence, the prudent selection of the transition location within the given envelope, without diluting the high-performance nature of the SRM, is critical for a designer. This task will be more complex in the case of an HVT motor. Note that shock waves, boundary-layer thickness, and turbulence are familiar concepts; nevertheless, they are not easy to define in such a way as to cover the detailed flow characteristics encountered in the HVT motors.

In the second phase, the appearance of an igniter-induced shock wave was examined in a typical HVT motor with uniform port. Note that the larger the upstream normal Mach number component, the larger the increase in downstream pressure and temperature, the

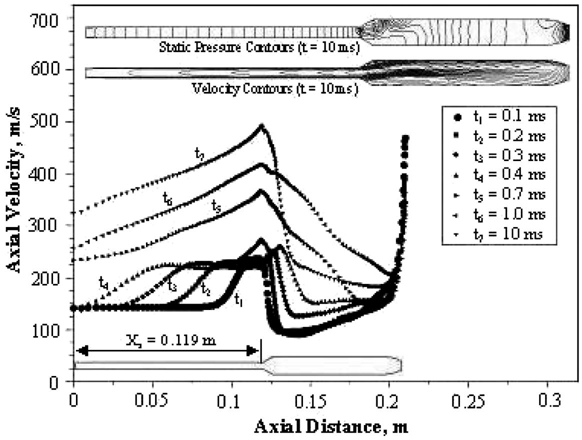

Fig. 3 Axial velocity variations of an HVT motor; two-dimensional pressure and velocity contours in inset.

greater the loss in stagnation pressure, and the smaller the downstream Mach number.[18] In this paper, these features are examined in an HVT motor with divergent port at an initial velocity of 143 m/s, (that is, at $t = 0+$, $P_i = 209{,}000$ Pa, $T_i = 690$ K, $k = 196$ m^2/s^2, and $\omega = 44{,}494$ s^{-1}) and are discussed later. The axial variations of centerline velocity in a typical HVT motor with divergent port at different time intervals are in Fig. 3. The CFD results surprisingly show that, at the given subsonic inflow conditions and without any igniter nozzle or geometrical throat inside the port of the motor, the flow accelerates to a supersonic Mach number near the transition region and suddenly dropped to a lower Mach number, $M < 1$. The sudden drop of the axial centerline velocity shown in Fig. 3 at $t = 10$ ms reflects to this effect. The two-dimensional contours (after choking) of static pressure and velocity are presented in the insets of Fig. 3 to establish the internal flow choking. Note that this internal flow choking phenomenon was not observed in LVT motor cases reported earlier. It is presumed that the flow must have accelerated through a throat, which is sonic. Note that, as stated earlier for the LVT motor cases, because of the viscous friction, a boundary layer could be formed on the walls of HVT motors, too (ahead of the transition region), and its thickness will increase in the downstream direction to the divergent location, leading to the formation of a temporary fluid throat at the transition location due to the area fraction blocked by boundary-layer displacement thickness. As a result, in general, at larger distances from the inlet section X_s, velocity will be high at the transition location, and this will lead to the formation of shock waves in certain class of HVT motors with a divergent port. The numerical results clearly show that the entire flow is subsonic inside the HVT motor except at the transition region.[17]

Analysis further revealed no evidence of thermal choking or choking due to high igniter mass flow rate, in the case at hand. These are corroborative evidence of the formation of a shock wave in the transition region due to a different physical origin named a fluid-throat effect. It was also observed that when the inlet port area was large, the formation of the sonic fluid throat was not discerned with the same igniter jet flow.[17] The results from the full-scale static tests of DTM and flight data of high-performance rockets with different port areas qualitatively supported these theoretical discoveries.[2,3,5,11]

Note that, near a solid surface, flow velocities are low due to the no-slip condition at the wall. Hence, in a region where the piezometric pressure is increasing, there are likely to exist certain streamlines, on which there are points whose total pressure is less than the piezometric pressure a little farther downstream. When this happens, these streamlines can only reach this farther point if their energy is increased by the action of the shear force exerted by adjacent elements of the flow. This condition is satisfied when $\partial\tau/\partial y > 0$, where τ is the local shear stress and y is the distance measured away from the grain wall. This process of energy conversion by the action of viscosity cannot be maintained indefinitely, and if the flow does not manage to negotiate the region of adverse pressure gradient, a point is reached at which the value of τ and, hence, of $\partial u/\partial y$ becomes zero at the surface. Downstream of such a point, which is known as a separation point, the velocity u close to the surface becomes negative, and so a region of reverse flow is established. Because of their ability to transfer momentum laterally, turbulent flows are more able than laminar flows to negotiate regions of adverse pressure gradients. Whether or not separation actually takes place, the general effect of the adverse pressure gradient is to give rise to a localized region of slow moving fluid stretching away from the wall. Because of the continuity condition, which can be applied over the whole cross-sectional area, the axial flow velocities must necessarily increase elsewhere to compensate for this effect. There is, therefore, a tendency for flows to become increasingly nonuniform whenever positive axial pressure gradients are encountered.

Note that the thickness of a turbulent boundary layer is larger than that of a laminar boundary layer because of greater energy loss in the former. The development of the wall boundary layer in turbulent flow is more complicated than in wholly laminar flow. Initially it takes the form of a laminar layer, but at some position along the rocket motor port there is a transition to a turbulent layer, where a sudden increase in axial velocity can be discerned (Fig. 2, cases 2, 3, and 5, and Fig. 3). The actual position of transition depends on a number of factors including Reynolds number, surface roughness, and the turbulence level of the igniter jet flow entering the motor port.

In the process of identifying which phenomenon or a combination of phenomena was causing the pressure spike, pressure-rise rate, and pressure oscillations in HVT motors with divergent port, the importance of hitherto unexpected features of the internal ballistics of HVT motors has come to the foreground. Through these findings, the ballisticians can explore possible remedies (such as boundary-layer trips) for eliminating the unacceptable pressure spikes and the pressure oscillations often experienced in HVT motors without diluting its high performance.

Conclusions

Influence of geometry-dependent driving forces on the formation of the shock wave during the ignition transient of SRMs has been examined using CFD with a standard $k-\omega$ turbulence model. It was observed that, in addition to the igniter-induced shock wave, at subsonic inflow conditions there is a possibility of the formation of shock waves in HVT motors with divergent port due to the formation of a fluid throat at the beginning of the turbulent transition region induced by area blockage caused by boundary-layer displacement thickness. The phenomenon of internal flow choking due to the fluid-throat effect is a new concept to the scientific community.[17] Because of the fluid-throat effect, the upstream narrow port of the DTM will act like a second igniter to the downstream port, leading to the formation of possible shock waves inside the motor during the ignition transient. Downstream of the shock, the flow experiences an adverse pressure gradient, usually leading to wall boundary-layer separation and reattachment. Shock waves, both normal and oblique, are events that occur over a very short distance, typically the same order of magnitude as the mean free path, that is, 10^{-7} m. From the point of view of continuum theory, they can be treated as localized discontinuities within the flow, which everywhere else satisfies the continuum hypothesis. Note here that most of the available models do not capture the shock wave phenomena encountered in the HVT motors. Nevertheless, the accurate evaluation of the Mach number along the axis is sufficient to propose the possible formation of shock waves in HVT motors. The authors have conjectured that the shock waves in HVT motors can generate additional turbulence. The shock waves and the new turbulence level will alter the location of the reattachment/secondary ignition point and also enhance the heat flux to the propellant surface, which in turn will enhance the flame spread rate and the transient burning. The cumulative effects of this entire phenomenon would result to amplify the magnitude of the ignition pressure spike in real motors even on the order of five times that of the steady-state pressure value, which will lead to hard and/or uncertain start of the motor. Further study of these phenomena is warranted.

Acknowledgment

This work was supported by the Korea Science and Engineering Foundation under the overseas research program with the Indian National Science Academy, New Delhi, India.

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