Solid Rocket Motor Internal Ballistics Using a Least-Distance Surface-Regression Method

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Abstract

In the present work, we have successfully developed a practical design tool to simulate the erosive volume and associate burning area which can be integrated to solve a nonlinear, pressurization-rate dependent combustion during grain regression in solid propellant. The least distance method is first proposed and verified with a two-dimensional test problem. Then the least method is implemented to solve a three-dimensional grain burn-back problem. A simple motor of two practical configurations is examined by this method with tetrahedral cells grid arrangement to predict the erosive volume and burning area. The predicted pressure curves do reasonably agree with the projected design data.

Keywords: Solid Propellant Surface Regression, Surface Tracking Methods, CFD

1. Introduction

Accurate prediction of thrust is needed to predict velocity, altitude and range that the rocket can reach. The basic idea behind a solid rocket motor (SRM) is simple: thrust arises from pressurization of a vented chamber by mass injection caused by the burning of the propellant. The combustion rate depends on the chamber pressure as well as the propellant's surface area and storage temperature. The solid propellant's shape, called the propellant grain determines the burning surface area. The propellant grain is usually not just a simple cylinder, but often has slots and fins in its interior cavity to increase the surface area. The propellant surface regresses as propellant is consumed, so the shape and area of the burning surface change dynamically with time. Simulation of the SRM internal ballistics is a challenging problem in its own right, both in terms of developing realistic sub-models and in the computational capacity required to solve them accurately. In recent years a considerable amount of effort has been dedicated to computational simulations of solid propellant combustion (Massa, Jackson and Short 2003), (Wang, Jackson and Buckmaster 2007), and (Willcox, et al. 2007).
In this paper, we will present a new simple technique to study the solid rocket motor internal ballistics by using 3-D surface regression tracking methods and to accurately predict the pressure curve in the combustion chamber.

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The direct numerical simulation of solid-propellant grain burnout requires the solution of a moving boundary problem, which is represented by the evolution of the three-dimensional solid grain shape. To carry out the solution, one must choose an algorithm to represent the grain surface at any instant and to compute its motion. The considerations for choosing a scheme for propellant combustion from the available methods are based both on the accuracy of the scheme and the simplicity of implementation. In the present work, we assume the propellant burning rate is isotropically homogeneous in the combustor. That is, the propellant erosive velocity is uniform in all directions. It can be analog to the propagation of wave front of a point source. Therefore, the required burning distance at a specific location will be the shortest one originated from the initial burning surface. Based on this principle, we have developed the least distance method, without involving too much math and only a simple physics is essential on the basic idea, to estimate the burning volume of uniform solid propellants.

1.1 The Least Distance Method

The detailed steps of the **Least Distance Method** can be itemized as follows:

1. Construct the initial burning surface approximately by assemblages of polygonal surfaces.
2. Construct a non-overlapping grids and cells in the interested region. No free space left between the grid cells.
3. Determine the shortest distance from each grid to each polygonal surface.
   There are only several distances needed to be calculated at each surface, namely the distance to the perpendicular projection point on the surface (if the point is not located outside of the surface), distances to all edges, and distances to all corners.
4. Assign the resulting shortest distance function on the grid as the shortest distance to every polygonal surface.

The above scheme is tested to investigate the evolution of an initial cross shape. Although the simulation with Cartesian cubic cells can yield more accurate result, those with tetrahedral cells can still provide reasonable prediction in this test problem. Since the propellant configuration in a practical combustor becomes complicated and difficult to simulate with a regular Cartesian grid system, the feasibility of tetrahedral cells becomes quite valuable. The resulting contours are presented in Figure 1. The simulation errors in the burning volume for the cubic and tetrahedral cells are calculated. More details can be found in our conference paper (Chiang and Hwang 2008). After a careful consideration of programming flexibility, accuracy and computational resource available, the least distance method combined with tetrahedral unstructured cells is employed to simulate the burning volume (and area) of three-dimensional solid propellants and to determine the burning distance as well as the evolving grain shape.

1.2Lumped System Gas-Phase Quasi-Steady Analysis

A lumped system for pressure is employed for the gas-phase analysis. The time variation of pressure is mainly caused by the combustion heat released as well as the volume expansion due to surface regression of propellant grain. We assume the grain is homogeneous solid mixture. In general, the surface regresses normal to itself with a speed r_b depends on the propellant initial temperature, the chamber pressure and weakly on the velocity of the combustion gases in the port. The St. Robert relation is used to describe pressure dependent burning of the solid propellant and production of propellant gases. Hence r_b may be approximated by an equation of the form

$r_b = ap_0^{\,n}$ where a and n are constants and $n < 1$.

In this research we have assumed the flow is choked at the nozzle throat and temperature reaches its equilibrium temperature upon ignition. The ideal gas law $p_0=\rho_0 RT_0$ is also employed. When we consider the conservation of mass in the gas chamber due to gas generation at the propellant surface, $\dot{m}_g = \rho_p A_b r_b$, and volume expansion due the surface regression $\frac{dV_0}{dt} = A_b r_b$, the governing equation of chamber pressure can be derived as

$$\frac{v_0}{RT_0}\frac{dp_0}{dt} = A_b a p_0^n(\rho_p - \rho_0) - A^* p_0\sqrt{\frac{\gamma}{RT_0}\left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/(\gamma-1)}}$$

where $v_0, \rho_0, T_0,$ p_0 are instantaneous gas volume, density, temperature, and pressure,

respectively. A^* is the nozzle throat area and A_b is the area of the burning surface. ρ_p is

the solid propellant density. The above nonlinear ODE can be solved by a typical fourth-order Runge-Kutta method. At each time step the burning distance is calculated as $d_b = \Delta t * r_b$. The new burning surface can re re-constructed based on the updated burning distance.

2. Results and discussions

Given a particular propellant formulation, the performance of a solid rocket motor is due largely to the grain design. We have conducted two cases of different grain design as benchmark simulations to verify our codes. The two designs are internal straight burning tube (case 1) and double taper tube with 10-pointed star addition (case 2), respectively. The dimensions of above cases are taken roughly from the design drafts of the Falcon LAUNCH V motors.

A cylindrical grain design of a double taper with addition of star is shown in Figure 2. We

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use the GRIDGEN software to create both structured and unstructured meshes (as shown in Figure 3) in solid propellant. The least distance method is used to simulate the burned volume and its associate burning area for the solid propellant. The variations of the accumulation of burned volume and the instantaneous burning area in case 2 as burned distance increases are presented in Figure 4. There are three main components to compute to determine the total area of the burn for a star design. First is the area along the side of star which exists along the main propellant grain. Second is the aft-end section of the star, assuming one aft end is burning along with the main section. Third is an area loss since the star will be taking the place of a once present section on the main propellant grain.

The comparisons of the predicted pressure curves of the two cases with the corresponding "projected data" (or desired data) of Falcon LAUNCH V motor are given in Figures 5 and 6, respectively. Note that the so-called projected curve is obtained neither from the computational data nor from the experimental data. It is just a guess that based on the grain design supposed to yield. As indicated in Figure 5, the problem with the traditional internal burning tube grain design (case 1), which provides only a completely regressive burning profile, is not enough surface area exists at the beginning of the burn. This causes the pressure to rise to very high levels towards the end of the burn and creates a potential flow separation problem. Our computed result is quite comparable to their predicted result.

The second case uses a star design to add more initial burn area that allows for greater start-up pressure. Combined with a double taper grain design, the later portion of the burn becomes regressive. As the star burns, its surface area decreases as the outer portion of the grain expands, exposing more surface area. This double taper and star grain combination design should result in a neutral-regressive profile burning which is much more desirable than a completely regressive burn profile. Also it can follow the ambient pressure curve more precisely. Additionally, the star design increases volumetric efficiency; increasing total impulse. The additional initial burn area should also keep the pressure in the chamber at a constant level, which allows for a higher average pressure during the burn which increases efficiency. The calculated pressure also shows an early difference from their desired design data as indicated in Figure 6. The discrepancy may be attributed to too many unknown parameters we have employed in the calculation. These parameters include such as thermo-physical properties of the grain, nozzle throat area, flame temperature, molecular weight of the gas, just to name a few. We have found out that in order to avoid the early pressure difference, either the exit diameter would have to be decreased (decreasing efficiency), or the start-up pressure would need to increase (increasing the already large maximum chamber pressure). Nevertheless, the tendency of pressure variation, the burning time and average pressure seem to have a good agreement.

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Concluding Remarks

In the present work, we have successfully developed a practical design tool to simulate the erosive volume and associate burning area. Nonlinear, pressurization-rate dependent combustion during grain regression in solid propellant rocket is simulated computationally. Several test problems are solved to convey the programming complexity, simulation accuracy and required CPU time to the proposed methods. The least distance method is implemented with different grid arrangements to solve a 3-D grain burn-back problem. The results show reasonable predictions in the erosive volume and burning area, and pressure variation of two practical configurations can be obtained. Although further refinements are still required to improve the simulation accuracy, the present method can be a practical tool for a SRM preliminary design.

Figures

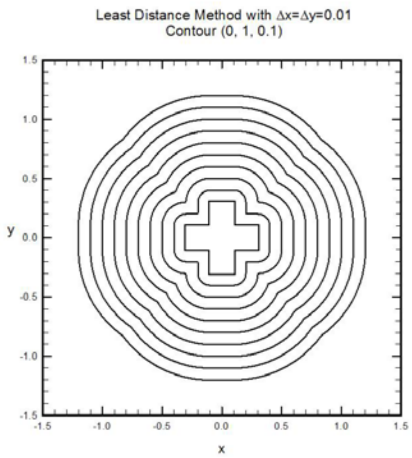

Figure 1 Evolution of an initial cross shape by using the least distance method.

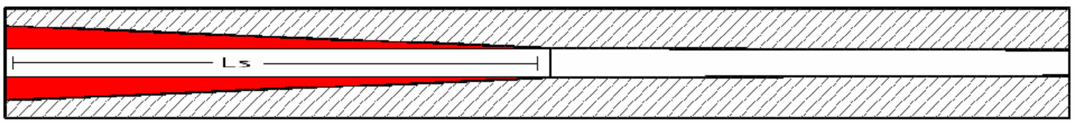

Figure 2 Double Taper with addition of star. Location of star is indicated by red shading.

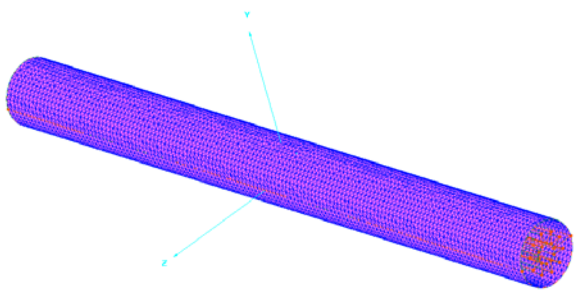

Figure 3 Unstructured meshes of solid propellant (double-taper tube with 10-point star

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configuration).

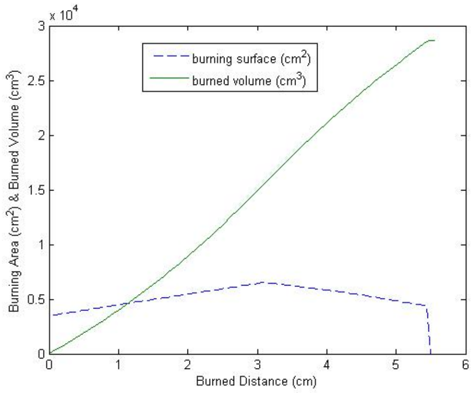

Figure 4 Variations of burned volume and burning area predicted by the least distance method, case of double-taper tube with 10-pointed star configuration.

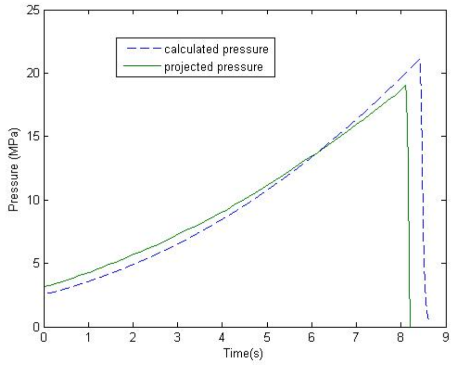

Figure 5 Comparisons of calculated pressure with projected pressure, case of internal burning straight tube.

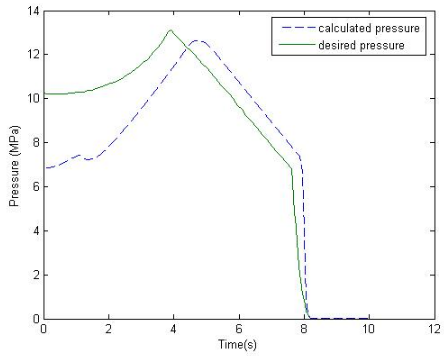

Figure 6 Comparisons of calculated pressure with desired pressure, case of double-taper tube with star configuration

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