J. Engg. and Appl. Sci. Vol. 35 No. 2 July - December 2016 *ISSN 1023-862X - eISSN 2518-4571*

PARAMETRIC SENSITIVITY ANALYSIS OF CONVEX STAR PORT PROPELLANT GRAIN FOR SOLID ROCKET MOTOR

Aqeel Nawaz[1], Muhammad Ali Kamran[1]

ABSTRACT

Grain design takes the central place in a solid rocket motor design activity. Ballistic quality of a designed grain can be evaluated by two vital indexes known as neutrality and sliver content. Sliver content results in tail-off of the thrust-time curve. These two measures of merit are an important part of acceptable grain design. This paper is restricted to the study of convex port star grain geometry and describes parametric evaluation to assess the effects of seven independent and defining geometric variables of the star and other ballistic factors including density of propellant and characteristic exhaust velocity on the burn pattern and performance profile for qualitative analysis of sliver fraction (tail-off)and neutrality. The purpose of the study is to expand the design domain by evaluating entire convex Star family under both neutral and least sliver content conditions.The computer program associated to it is essentially the ballistic design analysis of the convex star grain configuration.Results showed that neutrality and sliver fraction are dependent oncertain parameters. It has been observed that for good neutrality, higher angular fraction and star angle close to neutrality must be maintained. Sliver fraction depends upon the star geometry and can be reduced by decreasing angular fraction leading to reduced tail-off. Thus neutrality and reduced tail-off cannot be achieved simultaneously and trade-off has to be made. However, higher value of characteristic exhaust velocity (C) will reduce tail-off.*

Key Words: *Grain design, tail-off, ballistic design, neutrality*

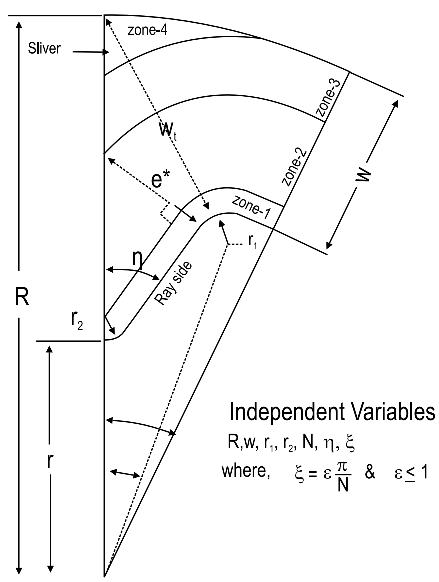

Figure 1. Definition of the star grain configuration[1]

INTRODUCTION

The propulsion device used to propel space launch vehicles, rockets etc producing thrust by ejecting stored matter is termed as Solid Rocket Motor (SRM). The specific shape/configuration of the propellant casted inside the SRM is termed as grain or propellant grain. Since the desired characteristics (e.g. thrust, pressure) vary with time during any mission, design of SRMsis a complicated process. The geometric shape of grain configuration and properties related to propellant being used influences the performance parameters of the SRM. In fact, the only way in which the characteristics can be controlled is by managing the rate of combustion of the propellant set accordingto specific grain configuration's geometry and its chemical formulation. The grain geometry is dependent upon various independent design variables which define that specific geometry. During operation, as the grain regresses, exposure of new burning surface areas dictates the burn pattern that in turn defines the thrust time profile. Propellant properties including characteristic exhaust velocity (C*) and density have also significant impact on the thrust time profile.

Different grain configurations are currently being used according to the operation requirements including End Burner, Rod and Tube, Multi-fin, Double anchor, Tubular, Star, Wagon Wheeletc[1]. The shape of these grains may be two dimensional (cross sectional area does

1 Department of Mechanical Engineering, University of Engineering & Technology, Peshawar.

not vary along the length)or three dimensional (varying cross section area along the length). However, amongst the available configurations, star grain configuration is most popular due to its applicability over a wide range of web fractions and volumetric loading fractions. It also provides neutral burning in two dimensions to a large extent, by the interaction of the regressive-burning star wedges and progressive-burning tube, withouta need of end effects and slots[1]. Certain disadvantages like sliver leading to undesirable tail-off is objectionable but effect of the same can be reduced by carefully analyzing and optimizing the geometric parameters of star shape.

The research for high performance SRMs demands extensive calculations. Several CAD based approaches exist for grain geometry initialization and surface regression. Ref[2] has used CAD for grain initial geometry and surface burn back is simulated through a computer code. Ref[3] stated the limitations of CAD based interface propagation technique foraccomplishing grain burnback analysis. CAD based calculation system is tedious requiring thorough drafting capabilities may give inaccurate results. Therefore in a grain design optimization process where a large number of grain configurations are to be considered, generating CAD model for each candidate design is often prohibitive. For such cases, analytical developments for grain burnback calculations have become versatile and imminently practical[4]

Star GrainGeometry

Lefebvre[5] classified the burning process of 2D star grain into four zones, defining the geometry as a function of seven independent geometrical variables.Thedefining variables make virtually infinite mathematical designs of star configuration possible. The analytic potential has resulted in a series of researches on different methods of analysis, which differ from each other in the choice of variables and the analytic format adopted for evaluation[6].

The seven independent geometric variables that define the star are (see fig. 1)

R = grain outside radius

w = web thickness

r_1 = fillet radius

r_2 = cusp radius

N = number of star points

ξ = angle coefficient

η = valley angle

Valuesof these parameters can be changed within large ranges, so that a very large number of star configurations can be drawn.Based on different geometrical evolution of the star during the web combustion, 14 configurations can be recognized with four zones of burning[7] (see fig.2). The first zone consists of two progressive burning arcs, a neutral burning ray side and regressive burning cusp radius r_2, which is the predominant variable in this zone that limits the duration of burning imparting a net effect of linear progressive burning.

The second zone consists of two progressive burning arcs and the regressive burning ray side, which is also the limiting variable in this zone. This zone is linear and may be progressive, regressive or neutral depending upon N and η.

Third zone consists of two progressive burning arcs and hence it is always non-linearly progressive. The actual grain web ‘w’ vanishes at the end of this zone and only sliver content of the grain is left behind which is the fourth zone of burning. In some cases, third zone is eliminated to keep neutrality as long as possible provided that ‘η’ is of appropriate value for neutral burning.

Fourth and last zone of burning consists of rapidly

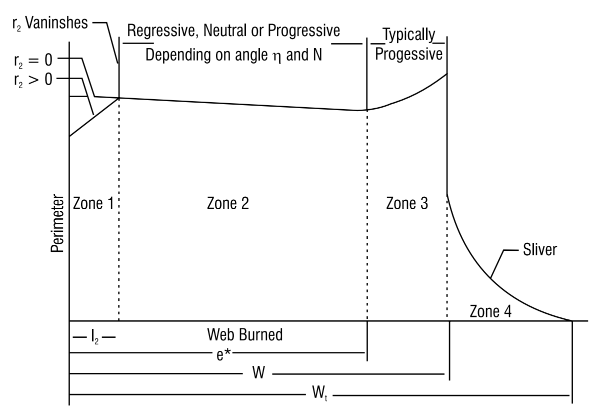

Figure 2. Burning characteristics of the star[1]

non-linear regressing arc, which is essentially the sliver. Sliver content leads to tail-off and it is an unavoidable feature in star grains.

It is clear that in order to achieve good neutrality; progressive zones of the star must be reduced. Hence, to accomplish neutral burn pattern, such a combination of geometric variables needs to found out which lead to neutrality over web especially in first and third zone.

Problem Statement

Generally, volumetric loading, sliver and burning neutrality are the three parameters which define the performance of a star shaped grain[8]. For a particular design, a certain requirement of volumetric loading has to be maintained with maximum neutrality and minimum sliver content, which are the two major variables requiring an optimization. Therefore, ballistic analysis includes identification and evaluation of these variables (i.e. N, w_f, r_1, r_2, ξ & η) for neutrality and sliver content to identify the optimal design.

With the aim to operate the SRM at uniform pressure close to maximum expected operating pressure (MEOP) and find relationship between neutrality and sliver or tail-off, the research presented in this paper evaluates and discusses the effect of variation of two important star angles (angle coefficient and valley angle)on the performance of SRM by qualitative analysis of neutrality and sliver tail-off for a given volumetric loading. As discussed above, a large number of star geometries can meet the mission requirements (in this paper, only volumetric loading is considered), however, not all of them will be equally efficient (in terms of mass of propellant and neutrality). Hence there is a need to identify the most optimal solution from a given set of possible solutions. This study is a step towards that optimization process. Specifically, the parametric study is carried out to evaluate the effects of star grain geometric parameters and other ballistic factors including density of propellant and characteristic exhaust velocity on the pressure-time profile for qualitative analysis of neutrality and sliver fraction.

METHODOLOGY

The star grain shape can be defined through seven variables in a variety of ways. In the analysis presented in this paper, the star geometry was defined by two angles 'ξ' and 'η', thus reducing the number of independent variables to six N, w_f, ξ, η, r_1, r_2. Performance measuring parameters and their measurements have been presented in the following paragraphs.

Sliver fraction is the measure of the ratio of remaining area of grain after web burn out with the area of grain. Mathematically;

Sliver fraction= A_s/A_g

where

A_s = cross-sectional area of silver

A_g = cross-sectional area of grain, evaluated as $A_g = A_t - A_{pi}$

A_t = total cross-sectional area

A_{pi}= initial port area of grain

Sliver fraction leads to tail-off which is undesirable and considered as lost thrust. The tail-off factor is defined as the ratio of tail-off duration (T_t) to burn time (T_b).

Neutrality isdefined as the ratio of maximum to average burning area, and is alsoa measure of the ratio of maximum to average pressure. Hence, it can also be used to determine MEOP if average pressure is known. Lower value of neutrality factor indicates neutral burning.

Neutrality is evaluated by the evenness of the thrust time curve. Neutrality factor (Γ) has been calculated as.

$$\Gamma = P_{max}/P_w$$

where,

P_{max}= maximum burning perimeter over web

P_w= Average burning perimeter

Burning course of two dimensional star grain has been simulated by computationally intensive analysis involving number of star shape design variables. Lumped parameter method has been incorporated considering control volume and all the exposed burning surfaces have been assumed to contribute to the control volume under analysis.

For a given combination of configurations, the computer program associated to this paper calculates the combinations of angle coefficient (ξ) and valley angle (η)which satisfy the limiting value of volumetric loading (V_L) and web fraction (w_f) resulting in maximum neutrality and minimum sliver fraction. Therefore, the analysis treats V_L and $w_f$as independent variables, along with the four star variables (N, R, r_1& r_2) that define a set of stars. The star angles ξ & η are treated as dependent variables.

For qualitative study to parametrically analyze the effects of star geometric variables on the neutrality and tail-off or sliver, a star grain with hypothetical values has been analyzed.

RESULTS AND DISCUSSION

Effect of Angular Fraction (€)

The value of Angular fraction, defined as the ratio of Angle coefficient to π/N was varied from 0.5 to 0.9. Fig.3 shows the burning area evolution over the web for the different angular fractions. All curves shown here meet the given ballistic requirements. At higher angular fraction, rise in neutral pressure is more pronounced, which results in reduced neutrality. On the other hand, sliver fraction has risen at higher angular fraction resulting in increased tail-off duration. This shows that high neutrality will result in more sliver mass. Hence the right balance between neutrality and sliver content is required while determining the best angular fraction to meet specific ballistic requirements.

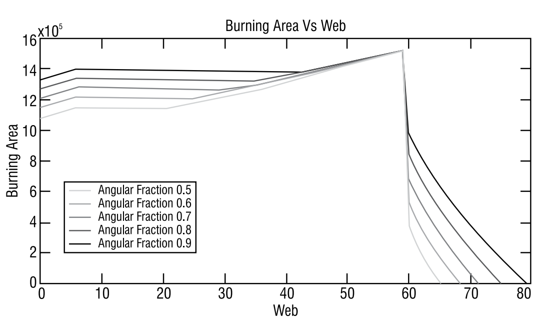

Figure 3. Effect of angular fraction on neutrality and sliver fraction

Effect of Valley Angle (η)

The value of valley angle was changed between 30° to 34°. It can be clearly seen from Fig. 4 that the initial burning area decreases as the valley angle is increased. Thus, the minimum pressure generated would be lower at high valley angles, adversely affecting the neutrality. However, all curves converge after the combustion process approaches zone 4 of burn pattern. This shows that the effect of valley angle only affects the initial burning area. At tail-off, all the curves have merged together; hence tail-off factor is not affected causing no change in sliver mass. Although the sliver mass remains the same, the total mass of propellant increases with reduced valley angle, hence sliver fraction increases with higher valley angle.

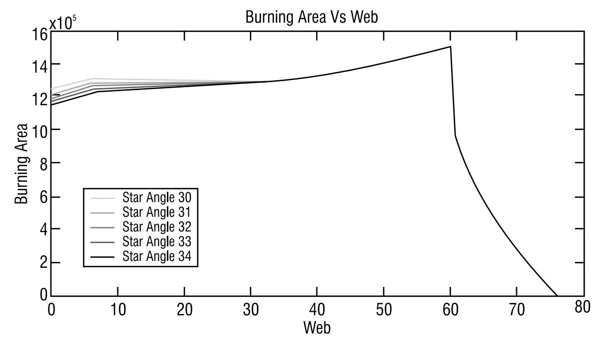

Figure 4. Effect of valley angle on neutrality and sliver fraction

Effect of Grain Outer Diameter

Fig. 5 shows the effect of changing the grain outside diameter on the burning area evolution. It can be seen that at higher values of star grain outer diameter, the burn area vs web profile becomes comparatively neutral. Thus neutrality reduces with increase in star outer diameter. However, a sharp rise in burn area curve indicates rise in peak pressure with increase in grain outer diameter which may be undesirable. On the other hand, tail-off duration also increases with outer diameter which is also not favorable. Normally there is very less margin of grain outside diameter for the solid rocket motor designer to take advantage. Outside diameter of grain cannot exceed the predefined diameter limits. Any variation in outside diameter towards the lower side will lead to less amount of propellant that may not be sufficient to provide adequate amount of energy required. Hence outside diameter is set fixed considering the insulation requirements for the specific grain configuration and other parameters are varied for evaluation of optimal solution.

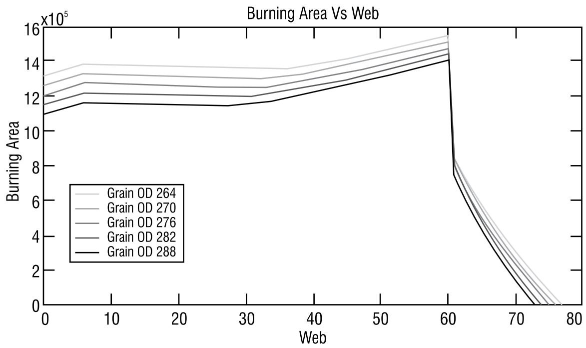

Figure 5. Effect of grain outer diameter on neutrality and sliver fraction

Effect of Density of Propellant (ρ_p)

In addition to studying the effect of star grain geometry, effect of different propellant densities was also investigated. For a particular star configuration, the propellant density values were varied from 1700 Kg/m^3 to 1780 Kg/m^3. The pressure time curve for this investigation is shown in Fig. 6. It can be noted that higher propellant density results in higher pressures. At lower density, both neutral and peak pressures are lower with minor increase in burn time but neither the neutrality nor the tail-off factor has any variation because of same amount of sliver fraction.

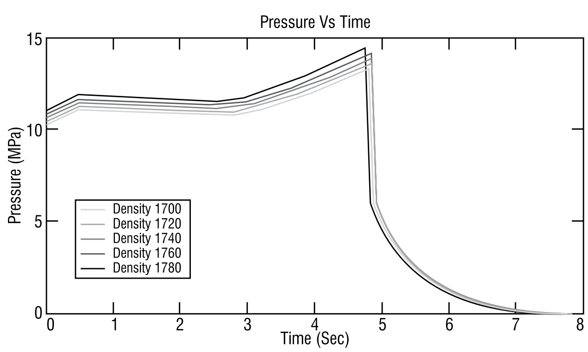

Figure 6. Effect of propellant density on neutrality and sliver fraction

Effect of Characteristic Exhaust Vel (C*)

The characteristic exhaust velocity value is varied in an arbitrary range of 1500 m/s to 1700 m/s. The pressure-time curve for these values shown in Fig. 7 highlights that increase in C* value causes a rise in the pressure level. However, this increase in pressure level does not affect the neutrality since all curves are parallel to each other. Also the sliver fraction remains the same for all C* values, since sliver is a function of star grain geometry. However, increase in C* reduces tail-off factor and total burn time but sliver fraction remains the same.

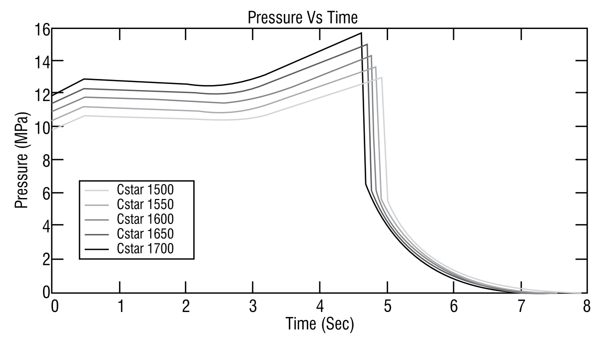

Figure 7. Effect of characteristic exhaust velocity on neutrality and sliver fraction

CONCLUSION

In this research, a selected star configuration was analyzed to generate parametric design data to qualitatively evaluate various star configuration, particularly the tradeoffs between sliver and neutrality.

The results of this parametric study showed that each of the analyzed variables of star configuration has a bearing on neutrality and sliver fraction. For good neutrality, higher angular fraction (€) and star angle near to neutrality must be maintained. Sliver fraction depends upon the star geometry and can be reduced by decreasing angular fraction leading to reduced tail-off. However, higher value of characteristic exhaust velocity (C*) will reduce tail-off. Thus neutrality and reduced tail-off cannot be achievedsimultaneously. Hence, each star that is ‘best’ in onerespect is far from the ‘best’ in another respect. Therefore, an analysis of a suitable range of star configurations which satisfy the requirements will guarantee an optimum design.The computer program developed is a comprehensive package for carrying outsuch analysis.

REFERENCES

1. Biblarz, O. and Sutton, G.P., 2011 “Rocket

Propulsion Elements", Wiley

2. *Dauch, F. and Ribereau, D,. 2002 "A Software for SRM Grain Design and Internal Ballistics Evaluation, PIBAL", 38th AIAA/ ASME/ SAE / ASEE Joint Propulsion Conference & Exhibit, Indianapolis, Indiana*

3. *Johannsson, M. 2012 "Optimization of Solid Rocket Grain Geometries", MS Thesis, Kungliga Tekniska Högskolan/DLR-SART*

4. *Hartfield R, Jenkins, R., Burkhalter, J., and Foster, W,. 2003 "A review of analytical methods for solid rocket motor grain analysis", 39th AIAA/ ASME/ SAE / ASEE Joint Propulsion Conference & Exhibit, Huntsville, Alabama*

5. *Lefebvre Antoine, 2000 "Burning analysis of star configuration", Retrieved from http://rocketwork-bench.sourceforge.net/ on 8/11/2014*

6. *Brooks, W, 1980 "Application of an analysis of the two-dimensional internal-burning star grain configuration", 16th AIAA, SAE, and ASME, Joint Propulsion Conference, Hartford, CT*

7. *RICCIARDI A, 1989 "Complete geometrical analysis of cylindrical star grains", 25th AIAA, ASME, SAE, and ASEE, Joint Propulsion Conference, 25 th, Monterey, CA*

8. *NASA/SP-8076, 1972 "Solid Propellant Grain Design and Internal Ballistics", NASA Space Vehicle Design Criteria (Chemical) NASA Lewis Research Center (Cleveland, OH, United States)*