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SHORT COMMUNICATION

Modelling of Burning Surface Regression of Taper Convex Star Propellant Grain

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ABSTRAC'

The burn area calculation of a propellant grain with taper convex star port is discussed and a software developed, using a new zoning definition of the star cross-section, is elaborated. The evolution of lengthwise conditions, inclusion of a coupled sustainer mode, real-time calculations and calculation for sliver burning part make this software a versatile tool for propellant grain design and parametric studies.

1. INTRODUCTION

The star-shaped configuration in propellant grains is widely used in solid rocket applications because of their ability to produce all the three modes of burning, namely, progressive, neutral and regressive. In addition, suitable combinations of various star parameters can give several peculiarities like long tail-off, strong regression at the beginning, regression-neutral combination, etc. A representative star grain configuration (Fig.1) with convex tip points is defined by seven independent geometric parameters, viz., grain radius (r_g), ray length (r_l), number of star points (n), angular fraction (ε), star angle (α), fillet radius (r_f), and tip radius (r_t). For solid propellant grain designer, the prime objective is to evolve a thrust-time profile consistent with mission requirements. So, the geometrical analysis of grain becomes a fundamental requirement. Most of the analyses for star grain configuration are based on the formulation given by Barrere[1], *et al.*, but sliver burning part after complete consumption of propellant web (w) is not included in that formulation and only fraction of the initial volume left at the time of consumption of w is evaluated. In addition, taper port configuration cannot be analysed by this formulation. Ricciardi[2] has developed a program STAR to generate web verses burning area profiles. He has defined nine zones of star cross-sections during burning of a convex tip star grain configuration, and mathematical expressions for all possible combinations are given here. His definition of zones is valid for a particular cross-section only, and no treatment is given to create various zones along length in course of burning. Brooks[3] has compiled all the works of scholars in the area of geometrical analysis of star grain burning and has confined himself mainly to configuration optimisation with reference to volumetric loading, sliver formation and achievement of neutrality conditions. Krishnan[4] has also confined his study to neutrality condition only. This article is aimed to elaborate algorithm for a computer program developed to predict pressure-time and thrust-time profiles of star port grains.

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2. STAR PARAMETERS & ZONE DEFINITION

The seven basic geometrical parameters (r_g, r_l, r_f, r_t, n,α,ε) univocally define the star configuration, but in some cases additional star parameters, from which basic star parameters can be computed, are also considered. Some of them are: w, star outer diameter (D_o), star inner diameter (D_l), etc. The following relations can be derived in relating these parameters to basic star parameters:

$$r_{\,} \qquad (1)$$

$$D_{\,} \quad 2\times(r$$

$$D_l \quad 2\times \quad r_l\times\sin(\alpha-\varepsilon\pi/n)/\sin(\alpha)\}$$
$$+\{(r_{\,} \; +r_t)/\sin(\alpha)\}-r_t] \qquad (3)$$

In case of burning every cross-section of grain regresses and for any cross-section, the following cases are observed [Fig. 2(a)]:

(a) When burning is progressing through web and complete star is intact (*case* 1).

(b) When w is completely consumed but propellant grain is not consumed. In this case, sliver burning is observed (*case* 2).

(c) When grain is completely consumed (*case* 3).

Practically, star grain configuration is obtained by casting and curing propellant slurry around a star-shaped mandrel (core). As core needs draft taper for easy extraction, actual grain configuration has a taper star port always. If the above-mentioned cross-sectional conditions are applied along length of the taper star port propellant grain, the following six conditions can exist:

When *case* 1 exists at both ends of the propellant grain [Fig. 2(b)] (*condition* 1). Star is intact at both ends and burn area calculation needs, averaging grain perimeter of both ends and its multiplication by the length of the grain.

When *case* 1 exists at one end and *case* 2 at another end [(Fig. 2(c)] (*condition* 2).In this situation, there exist two types of cases. Up to some length from second side star is intact, whereas rest has sliver burning. In addition to calculation of burn perimeters at ends, this parameter is calculated at the section of length, where case transition is taking place. Burning area is calculated separately for both lengths and are added up.

When *case* 1 exists at one end and *case* 3 at another end [(Fig. 2(d)] (*condition* 3). In this situation, effective grain length is less than the original grain length and two transition zones exist. First, where star-to-sliver transition occurs and second, where sliver-to-complete consumption of propellant is observed. Calculation of burn area is similar to *condition* 2 but with reduced effective length.

When *case* 2 exists at both the ends [(Fig. 2(e)] (*condition* (4). In this situation, both ends of grain are undergoing sliver burning phase and treatment in this case is similar to that of *condition* 1 except for the perimeter calculation at both the ends.

When *case* 2 exists at one end and *case* 3 at another end [(Fig. 2(f)] (*condition* 5). In this case also, effective length of the grain is less than the original grain length, and burn area is calculated from burn perimeter at first end and effective grain length.

When *case* 3 exists at both ends (*condition* 6). This condition shows complete consumption of grain, and calculation has to be terminated if this condition is attained. Burn area calculation is mainly confined to perimeter calculation at various cross-sections. For star configuration, half-petal repeats itself to generate a full star. So calculation of perimeter is carried out for half-petal only. Every half-petal can be divided into the following four zones for ease in calculation (Fig. 3):

Zone created by star outer radius (*zone*

Zone created by star slant length (*zone* 2)

Zone created by r_t (*zone* 3)

Zone created by r_f (*zone* 4)

The calculation of star half-petal lengths for these zones is possible by geometrical means. The

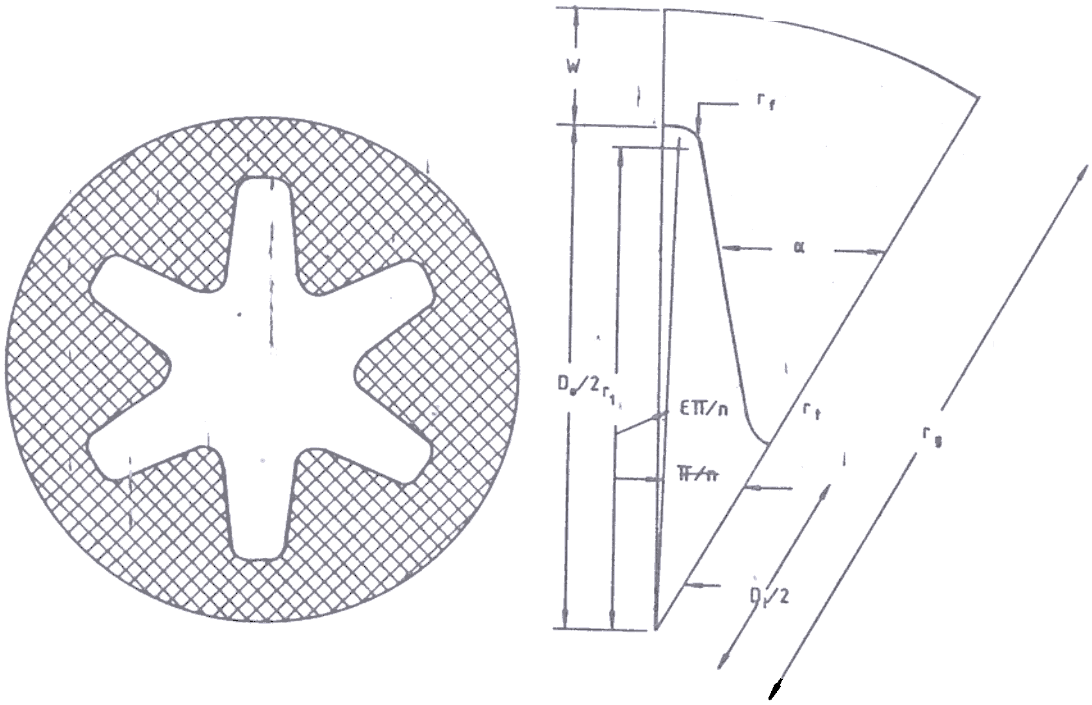
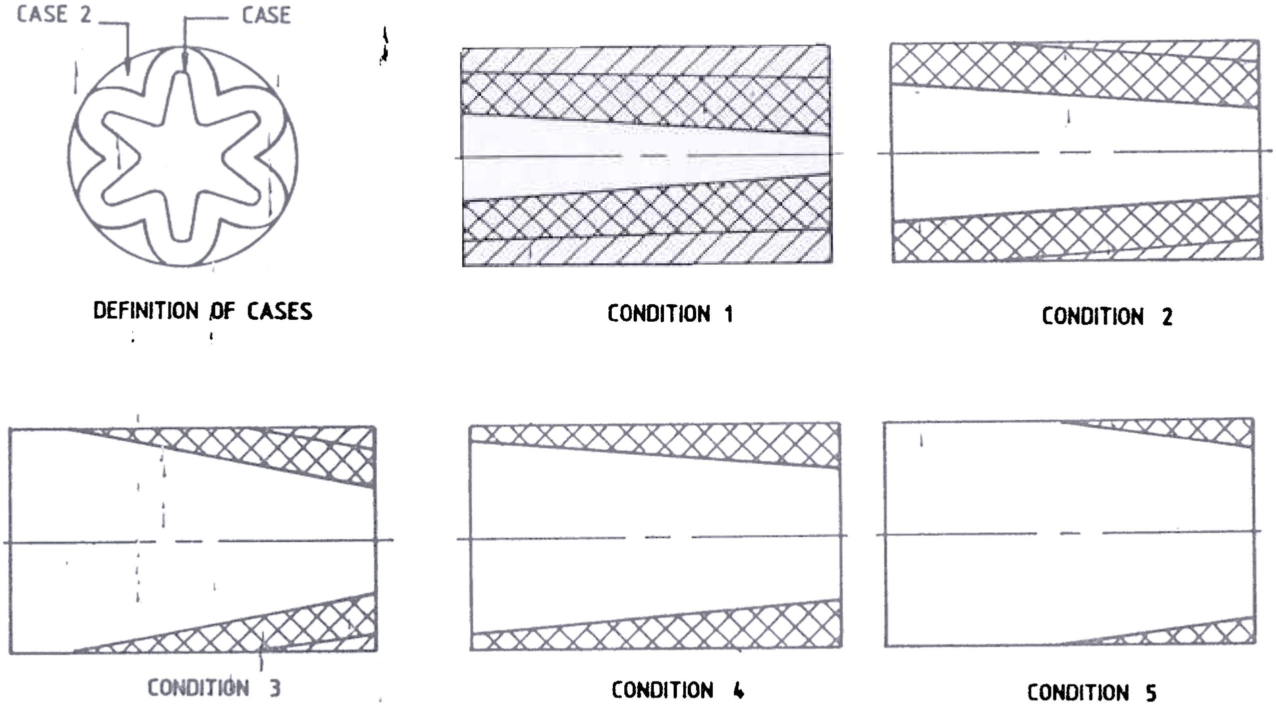


Figure 1. Star grain configuration parameters



DEFINITION OF CASES

CONDITION 1

CONDITION 2

CONDITION 3

CONDITION 4

CONDITION 5

Figure 2. Conditions for star grain during burning: (a) definition of cases, (b) *condition* (1), (c) *condition* (2), (d) *condition* (3), (e) *condition* (4), and (f) *condition* (5).

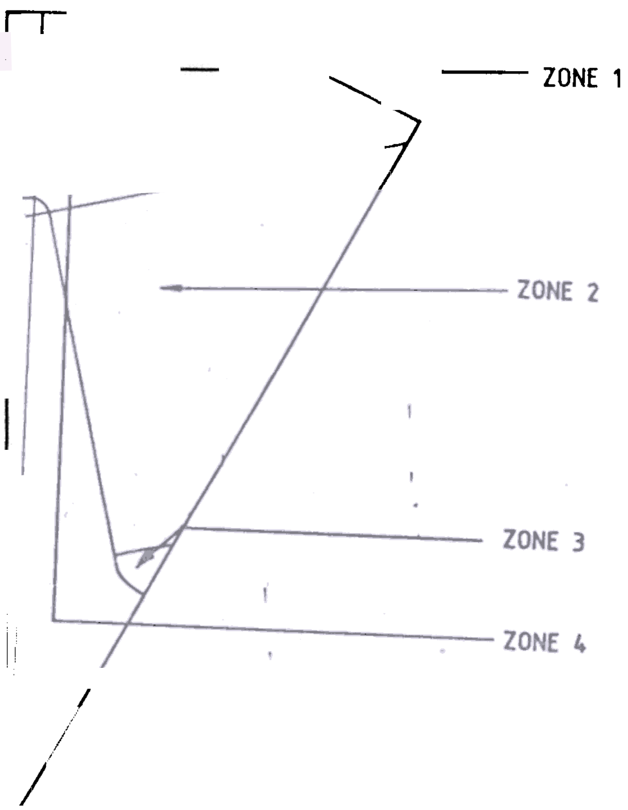


Figure 3. Zones of star grain cross-section

part of the star perimeter lying in *zone* 1, is an arc with constant central angle, radius of which increases with progress of burning. In *zone* 2, a straight length is realised, which decreases with propellant burning and its instantaneous length is dependent on star angle and initial slant length. Star perimeter in *zone* 3 area is again an arc of constant central angle whose radius decreases with time. *Zone* 4 region contains an arc of constant star angle in the beginning, but this star angle reduces, when either *zone* 1 star perimeter and/or *zone* 3 star perimeter is consumed. The reduction in star angle can be calculated for a given burnt web, using trigonometrical relations. This type of zone creation helps in modular algorithm development. The above-mentioned conditions are applied to each of these zones and results are integrated to obtain burning perimeter for any typical cross-section.

3. SOFTWARE VALIDATION & FEATURES

A software is developed to calculate burn area corresponding to various web burnt. In conjunction with propellant properties, this software calculates chamber pressure, thrust and time elapsed after ignition using the following relations:

$$P \quad [\{C^* \times A_b \times a \times \rho\}/\{A_t \times g\}]^{(1/(1-n))} \tag{4}$$

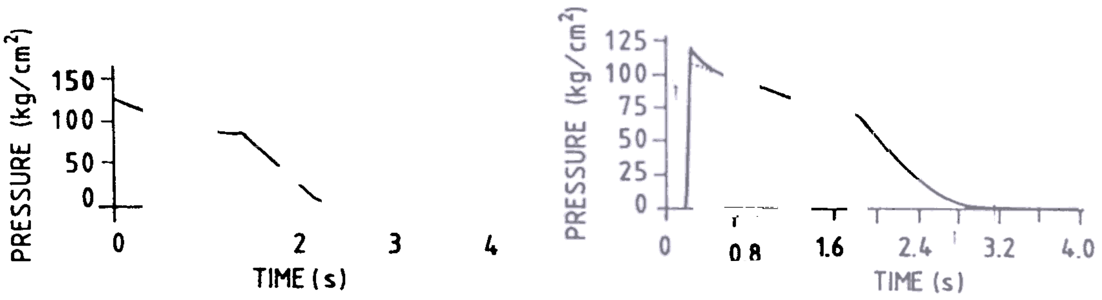
$$F \qquad \times P \quad A \qquad (5$$

$$w/(a \times P \tag{6}$$

This software was validated for six, seven and eight-petal star port grain, and actual pressure-time profile and software-predicted pressure-time profile exactly matched. A comparison of typical seven-petal star-shaped grain is shown in Fig. 4.

The main features of the software are:

(a) The software has a modular approach and each module does distinct jobs like checking star condition, calculation of star half length, calculation of effective length, etc.



PREDICTED CURVE

ACTUAL FIRING CURVE

Figure 4. Pressure-time profile for seven-star grain

(b) It is independent of number of star points, and variable angular fractions along the length of the grain can be analysed.

(c) Input parameters and control conditions are fed in free format, while formatted output is obtained from the program.

(d) Coupled sustainer mode and variable end inhibition condition can be analysed by this software.

(e) The software is not terminated at the point of web consumption, but it continues till complete consumption of the propellant.

(f) It does real-time calculations, i.e., instantaneous time and web burnt are calculated, star configuration is updated and corresponding burn rate, pressure and thrust data are generated.

(g) It is a faster design tool for propellant grain with taper convex star port and is a good tool for studying effect of various star parameters on output performance of the grain and configuration.

4. CONCLUSION

The software is a general purpose design tool for propellant grains with star configuration and is useful in developing solid propulsion systems. The new zoning concept (4 zones) and evolution of lengthwise configuration conditions has made the software complete in all respects. The software integrates the ballistic and mechanical design of the grain for its faster realisation.

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Contributor

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