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Ballistic Performance of Solid Rocket Motor with Various Propellant Grain Configurations

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Abstract:-The initial phase of the development of the solid propellant rocket motor is characterized by a series of parametric studies that are carried out to fulfill the rocket's mission. Throughout the process of evaluating feasible solutions for propellant shape, engine configuration and type of propellant, production issues, specific engine performance requirements, and operating conditions are considered. After several preliminary project studies, and practical assessments of possible solutions, an optimal construction is selected. It is then sent for detailed analysis. During this analysis, the motor has to satisfy the necessary parameters for a stable solid propellant rocket motor design for which the propellant type, geometry of the propellant grain, and motor structure are critically tested. The main objective of this project is to define and produce a propellant grain that will fulfill the required thrust - time profile, impulse and needed for a successful rocket mission considering the other limitations (envelope, mass, etc.). In this article, different grain configurations of solid rocket and their burning rates are studied. A direct modelling is involved in the design process of the grain geometry in CAD software using various features. The numerical results from the CAD are used to derive the performance of the propellant grain using MATLAB Programming. The procedure we have followed here can be applied to any complex geometry in a simpler way for preliminary designing of grain configuration.

Keywords: *Solid Rocket motor, Propellant grain, Thrust profile, Grain Geometry*.

1. Introduction

In the field of solid rocket propulsion, the ongoing challenge lies in achieving optimal performance within defined constraints. One crucial element in this domain is the design and fabrication of propellant grains that not only generate the requisite thrust over a defined period but also comply with limitations such as envelope dimensions and mass restrictions. The importance of propellant grain design cannot be undermined, as it directly impacts the success of rocket missions, influencing aspects like trajectory accuracy and payload delivery. Traditionally, the process of propellant grain design has been a multifaceted endeavor, requiring detailed analysis of various grain configurations and their respective burning rates and thrust profiles. With the help of computational tools and modeling techniques, there emerges an opportunity, rendering it more efficient and precise.

This article explores the complexities of designing propellant grain for solid rockets, delving into various configurations and how they impact performance metrics like Action time, thrust-time profiles and Total impulse. Our method focuses on incorporating direct modeling techniques into computer-aided design (CAD) to meticulously shape and evaluate propellant grain geometries.

Furthermore, we emply MATLAB programming to utilize the numerical data from CAD simulations, enabling a thorough evaluation of propellant grain performance under various design parameters. By merging CAD modeling with computational analysis, our methodology not only spped up the design iteration process but also enhances the accuracy of performance predictions.

The framework developed here for a singular rocket mission provides us a blueprint for preliminary propellant grain design across diverse applications. This methodology aims to offer a potent toolset for navigating the complexities of grain design, thereby fostering advancements in rocket propulsion technology.

2. Objectives

The objectives of this article are to investigate various configurations of solid rocket propellant grains and analyze their burning rates to achieve the required thrust-time profile and impulse for successful rocket missions. With constraints such as envelope and mass taken as consideration, the article aims to demonstrate a methodical approach using CAD software for the design process, integrating numerical modeling to assess performance with MATLAB. The proposed procedure provides a simple systematic framework applicable to complex geometries for preliminary grain configuration design, providing insights for future rocket propulsion system development.

3. A. Solid Rocket Motor

A solid rocket motor is a simple propulsion system with no moving components. It includes an outer cylindrical casing, solid propellant with a hole (known as “grain”), an igniter to ignite the propellant, and a nozzle to exhaust the combustion gases. Typically, the shell is made of thin metal with insulation to prevent propellant burn-through, housing the propellant within this protective layer.

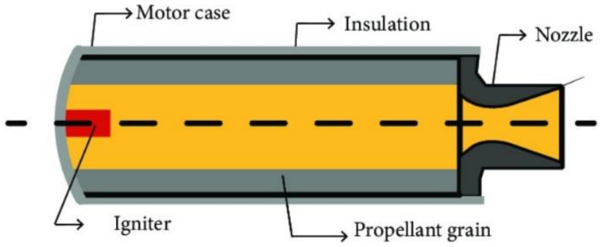

Fig 1. Schematic Diagram of Solid Rocket Motor

While most of the motors have a hollow core, others need ignition at the base to allow combustion to progress gradually from end to end, consuming only the propellant's outer layer. However, hollow-core designs boost thrust by enlarging the burn surface area, leading to faster and more powerful combustion. Once ignited, combustion continues until either the propellant is used up or the combustion conditions become unsustainable. Many propellant cores have a star shape to enhance the burning surface area even more. Positioned at the rocket's rear, the nozzle aids in expelling hot expanding gases. Consisting of a throat and an exit cone, the nozzle speeds up gas release, thus contributing to the overall thrust.

B. Propellant Grain

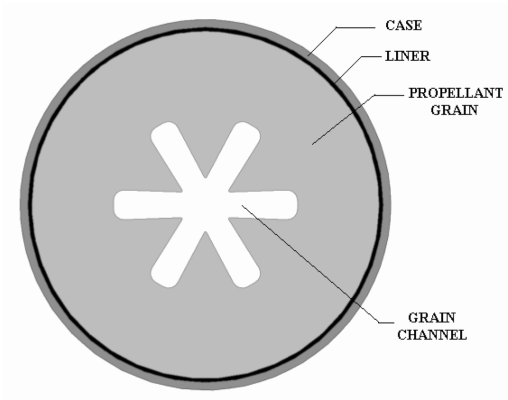

Fig 2. Propellant Grain

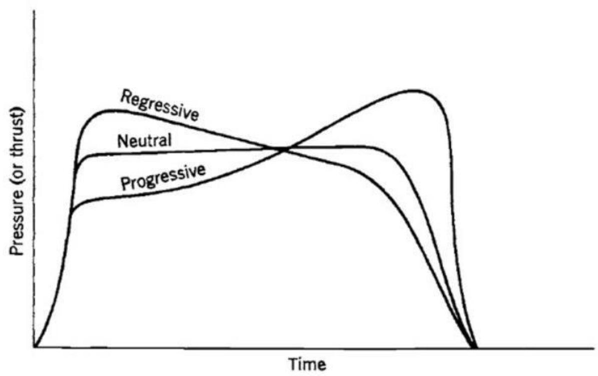

Fig 3. Types of Burns

The solid propellant mass that has been processed inside the rocket motor and given a specific shape is referred to as the grain. Typically, about 96 percent of the entire mass in a solid rocket motor is composed of this propellant grain. This grain mass is usually poured as a liquid into the pre-insulated casing. Configuration of the grain is a critical aspect of solid rocket motor design.

Depending on the starting grain geometry, a variety of thrust profiles can thus be achieved, three categories of thrust profiles/Burns are commonly referred to

1. Progressive burning thrust - thrust, pressure and exposed grain surface area increases
2. Neutral burning thrust - thrust, pressure and exposed grain surface area remain generally within %
3. Regressive burning thrust - thrust, pressure and exposed grain surface area decreases.

Main types of grain cross-sections often used in Space launcher applications are stars, cylindrical tubes, or a combination of both. The advantages of these shapes compared to others are their ease of manufacturing, inherent structural support with minimal leftover propellant, known as 'slivers'.

Grain Geometry:

Coming to the geometry of the grain, the Thrust-Time curves of the well-known shapes are given below.

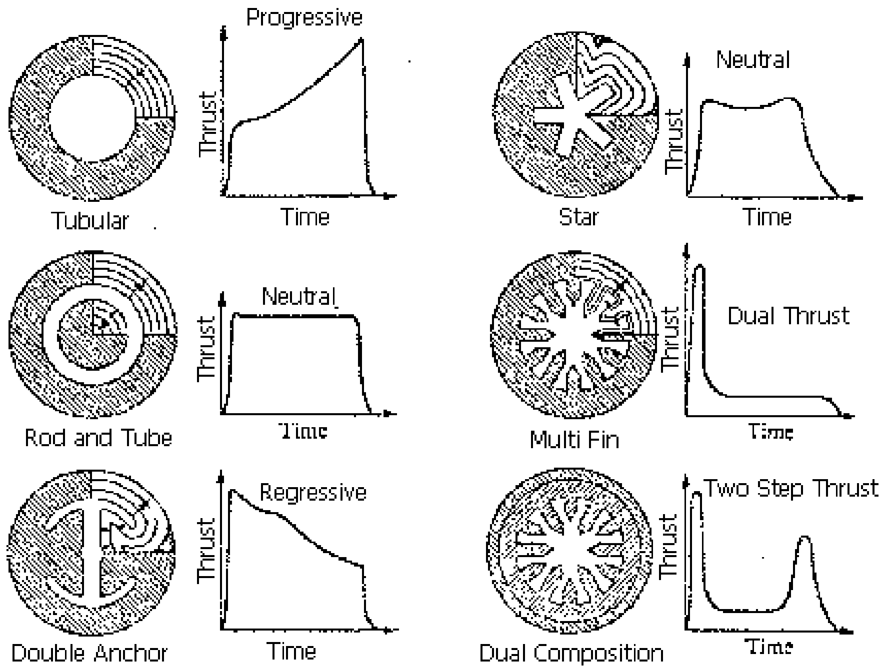

Fig 4. Thrust – Time Curves of known grain shapes

4. Methodology

Using CAD Software different grain geometries were designed for determining the performance and the burn parameters of the grain.

Data:

Propellant Mass (M_p) = 1 ton

Structural Mass (Ms) = 3 tons

Specific Impulse (I_{sp}) = 260 seconds

Final Velocity (V_f) = 2500 m/sec

Diameter of the motor = 2.00 m

Length of the motor = 2.2m

From BEM Firing:

Observed Burn rate data = 6 mm/sec @ 45 Ksc

1. Final Velocity

$$Vf = Isp.g.ln(\frac{Mp + Ms + Mf}{Mp + Ms})$$

$$\frac{2500}{260 \text{ x } 9.81} = ln(\frac{Mp+Ms+Mf}{Mp+Ms})$$

$$\frac{4 + Mf}{4} = 2.665$$

$$Mf = (4 * 2.665) - 4$$

$$Mf = 8 \; tons$$

2. Total Impulse

Total Impulse = Mf x Isp

$$= 800 * 260$$

$$= 2080 \; ton - sec$$

Thus, the required thrust > 24 tons

Action time > 86 sec

Calculation of Burn Surface Area from CAD Model:

Length of the grain = l

Perimeter (length of web) = P

Burn surface area = length of the grain x perimeter = l x P

Calculation of Chamber Pressure & Mass flow:

The relationship between the Ab profile, pressure and thrust profiles are similar to that of the relationship between the burn rate of the propellant and mass flux. The steady- state burn rate (m/s) simply is

$$r_b = \frac{\Delta x}{\Delta t}$$

If the web difference, Δx, is known all that is needed is the burn rate to find change in time, Δt. The propellant burn rate is found as follows:

$$r_b = aP_c{}^n$$

Where *a* and *n* are empirical constants. This propellant burn rate is directly related to the internal pressure of the motor. The mass flux of the grain is found using

$$\dot{m}_b = r_b \rho_b A_b$$

Where *ρb* is density and *Ab* is the burn surface area. The mass flow through the throat is defined by

$$\dot{m}_t = \frac{P_c A_t}{c^*}$$

Here, Pc = chamber pressure ; At = throat area

c* = characteristic velocity (constant for a particular propellant mix)

Under steady state conditions, $\dot{m}_b = \dot{m}_t$

This assumption is valid except during motor start up and tail-off where transient effect effects become significant, however this causes only negligible error in the results. It can be shown after some manipulation that

$$P_c = \left(\frac{a \, A_b \rho_b C^*}{A_t}\right)^{\left(\frac{1}{1-n}\right)}$$

Action time can be found by dividing the web step by the burn rate. This method corelates A_b web thickness profile to the pressure-time profile thus determining the pressure profile in the respective Solid Rocket Motor.

5. MATLAB Programming

```
clear all
clc
W = input ("[]");
A = input ("[]");
A*2200;
rho = 1780/10^9;
cstar = 1560;
Dt = 250;
At = (pi.*(Dt^2))./4;
P0 = 45*9.81/100;
n = 0.4;
rdot = 6;
Wb = 0;
a = rdot/P0^n;
P(1) = 0.8;
delT = 1;
r(1) = a*(P(1))^n;
i=1;
while Wb<=540
   Ab = interp1(W,A,Wb);
   mdot(i) = rho*Ab*r(i);
   i=i+1;
   r(i) = a*(P(i-1))^n;
   P(i) = rho*Ab*r(i)*cstar/At;
   Wb = Wb+(r(i)*delT);
end
thrust = mdot.*2800/10000;
mean_thrust = mean(thrust)
MEOP = max(P)
Im = thrust.*delT;
Total_Impulse = sum(Im)
Action_time = i*delT
```

Table I. Parameters Defined

ρ	Density	**P**	Pressure
A_b	Burn Area of the grain	**P_0**	Ambient Pressure
A_t	Area of the throat	**r_b**	Burn rate
C*	Characteristic velocity	**T**	Time
Dt	Diameter of the throat	**Thrust**	Thrust
g	acceleration due to gravity	**W**	Web thickness
mdot / ṁ	mass flow rate of the propellant	**Wb**	Web thickness at every point
ρ	Density	**Finocyl**	Cylindrical grain with fins as cross-section

6. Results

i. Finocyl with 4 Fins

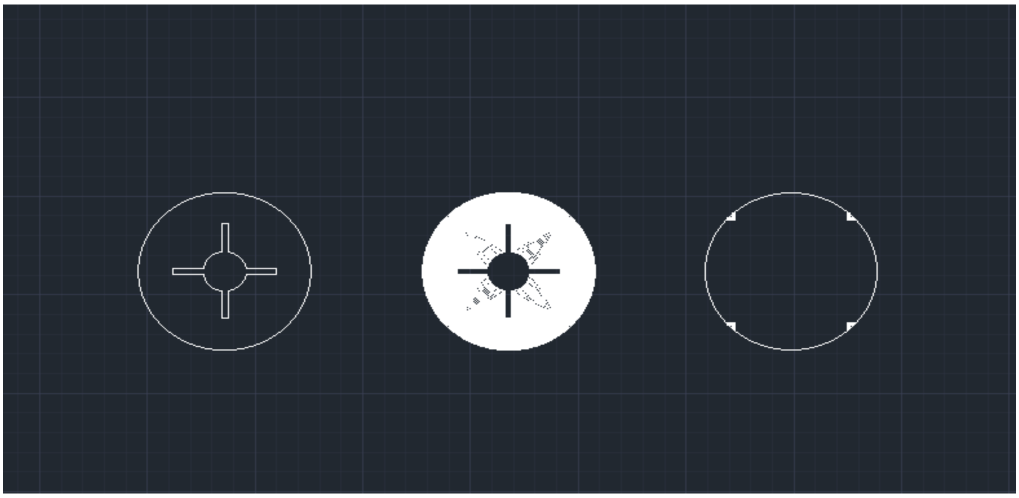

Fig 6.1a. Progressive burn pattern of finocyl grain (4 fins) configuration

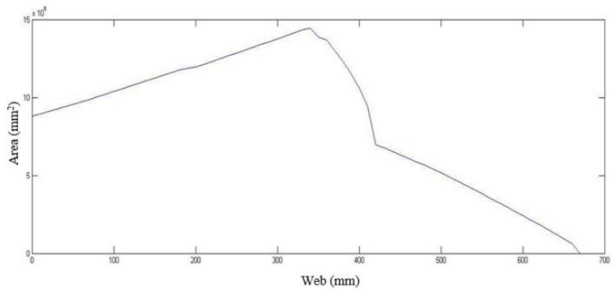

Fig 6.1b. Web vs Area

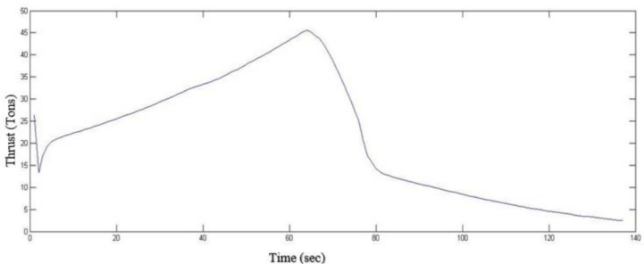

Fig 6.1c. Thrust vs Time

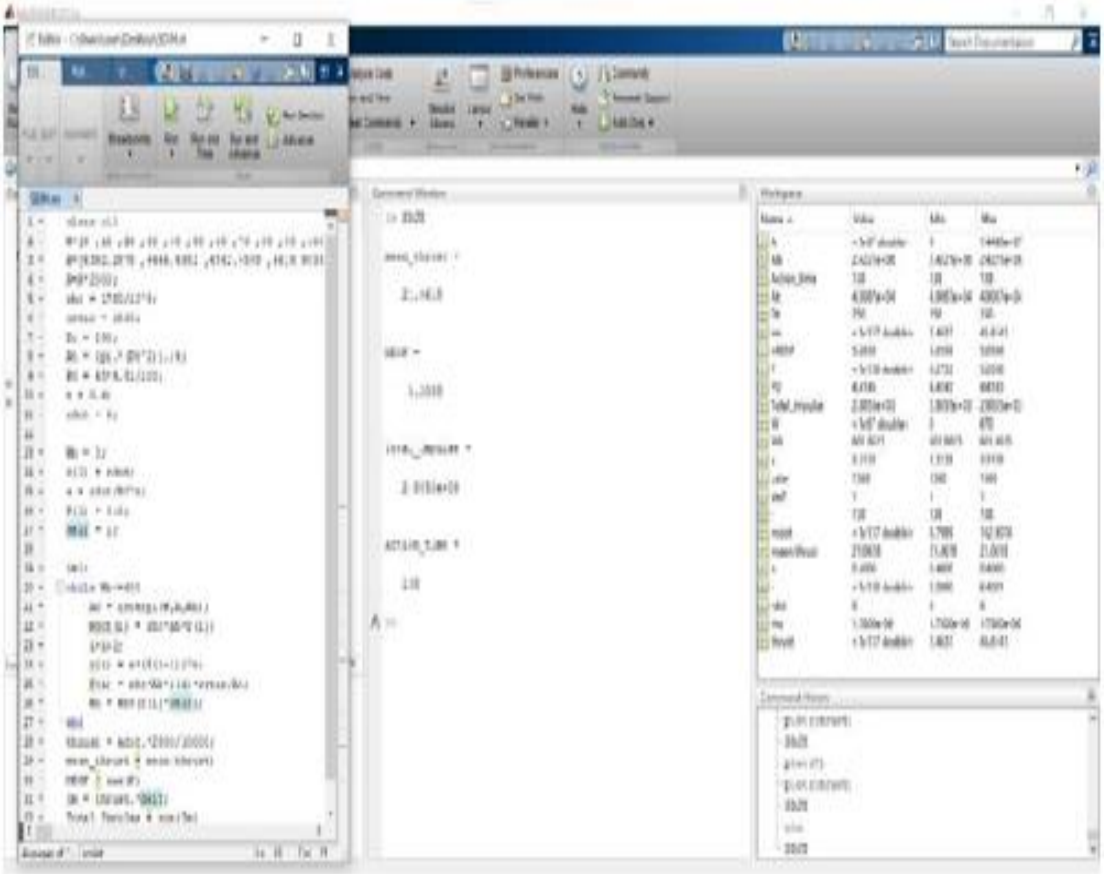

Fig 6.1d. MATLAB Output

ii. Finocyl with 6 Fins

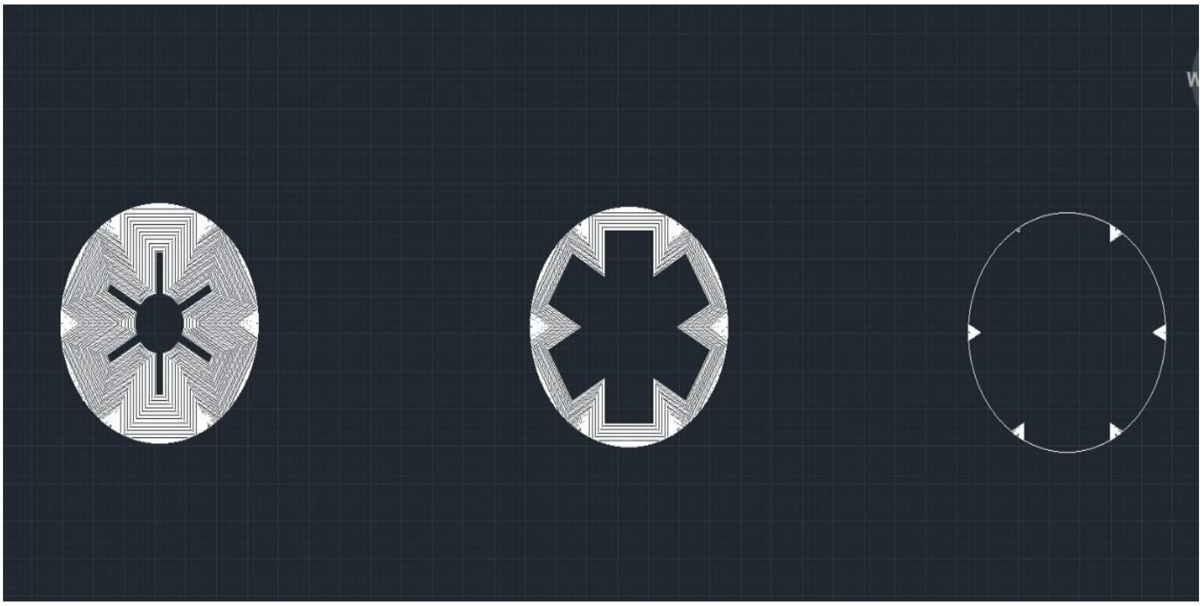

Fig 6.2a. Progressive burn pattern of finocyl grain (6 fins) configuration

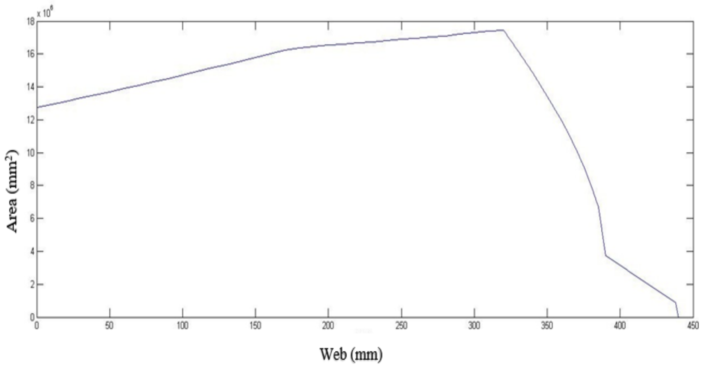

Fig 6.2b. Web vs Area

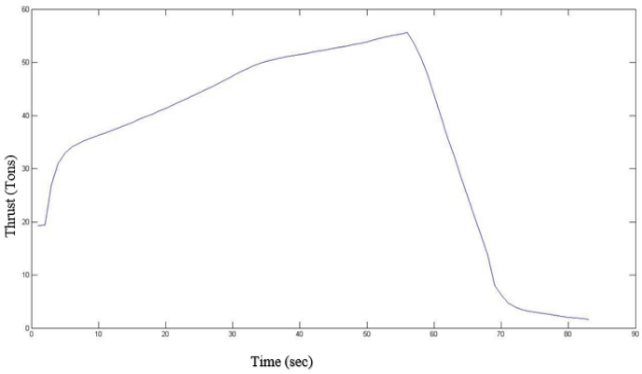

Fig 6.2c. Thrust vs Time

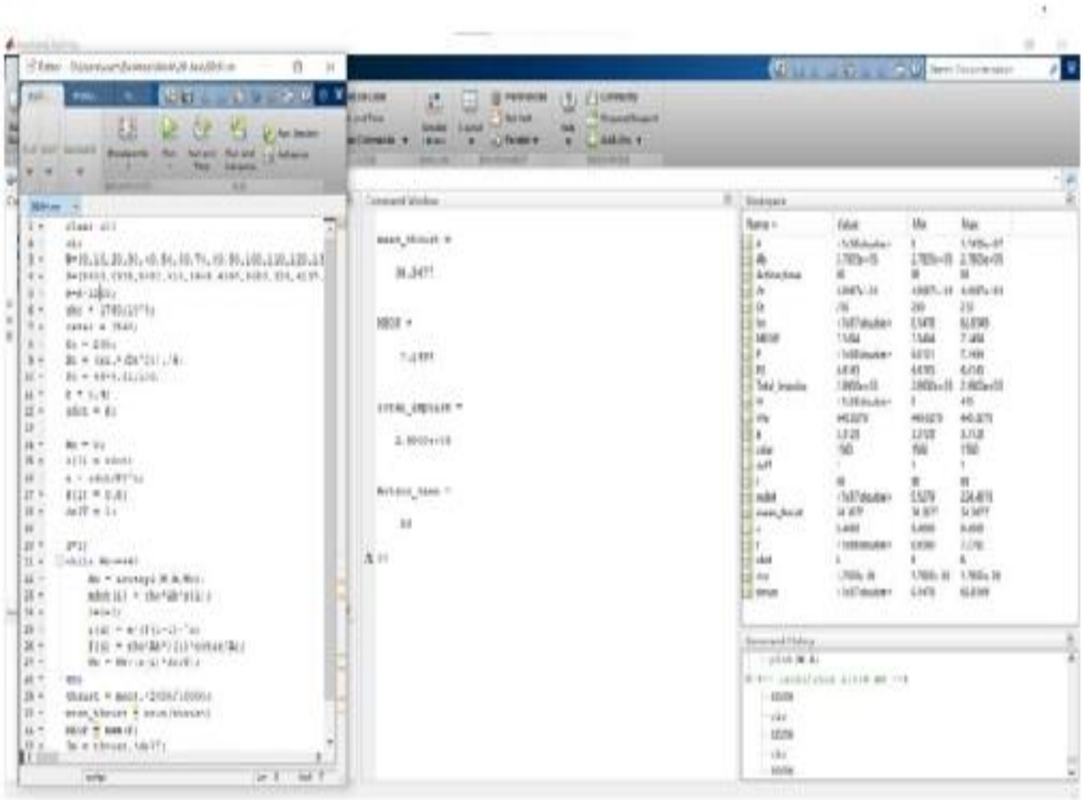

Fig 6.2d. MATLAB Output

iii. Finocyl with 8 Fins

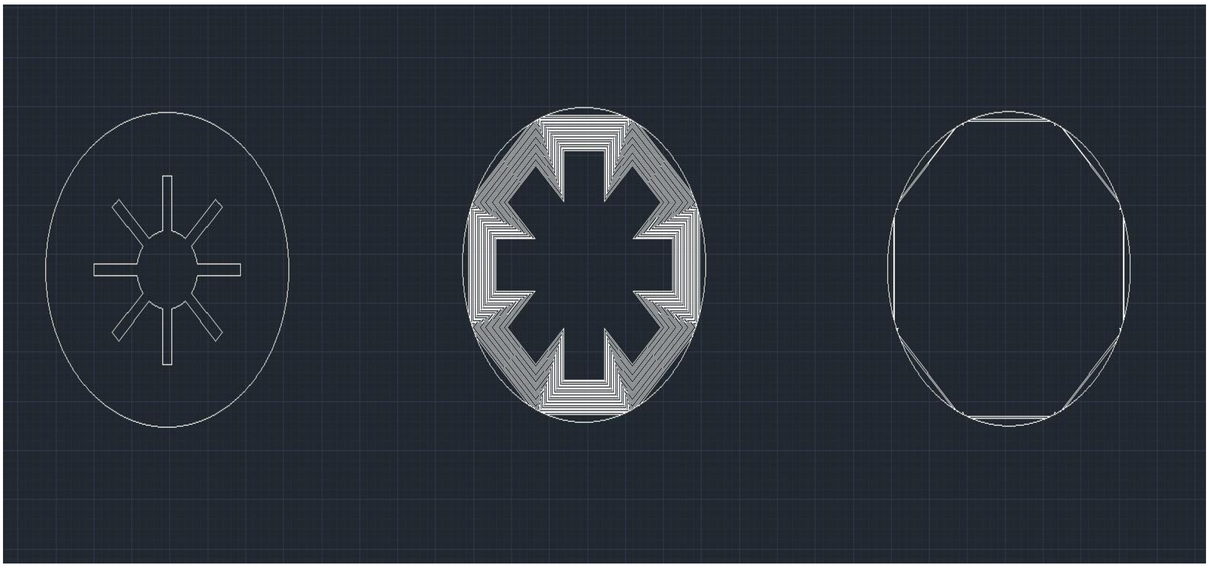

Fig 6.3.1. Neutral burn pattern of finocyl grain (8 fins) configuration

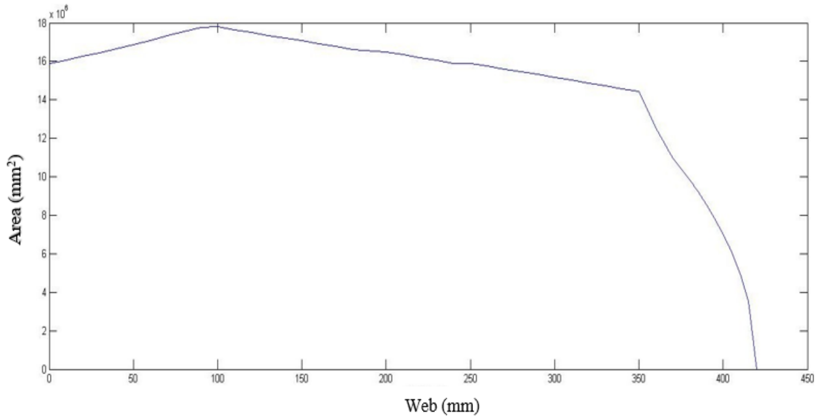

Fig 6.3b. Web vs Area

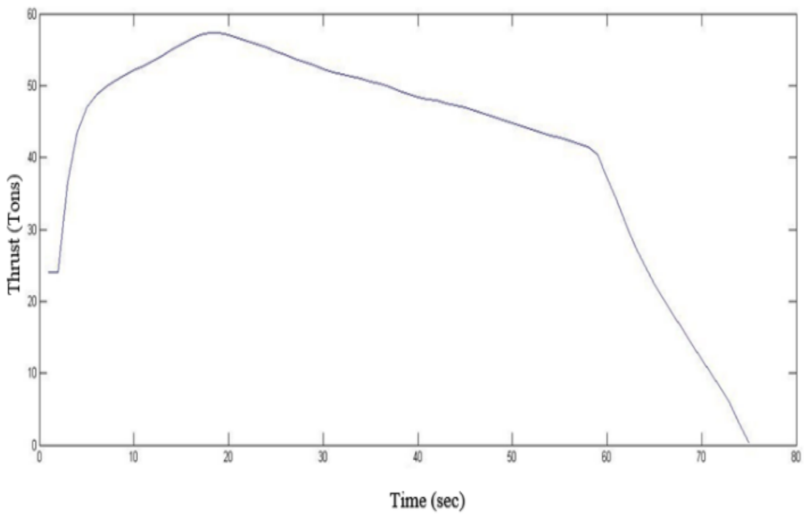

Fig 6.3c. Thrust vs Time

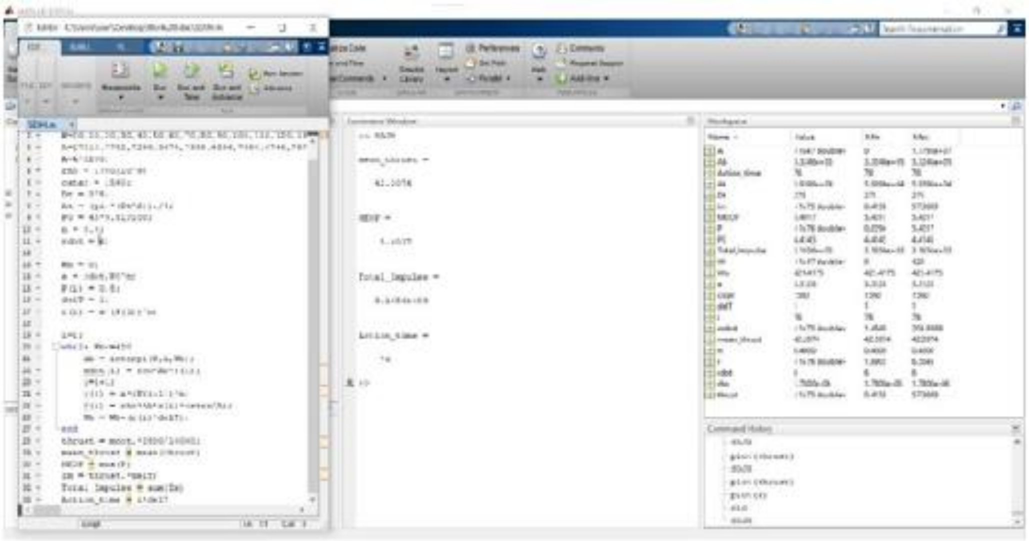

Fig 6.3d. MATLAB Output

iv. Star with 350mm diameter circumscribed circle

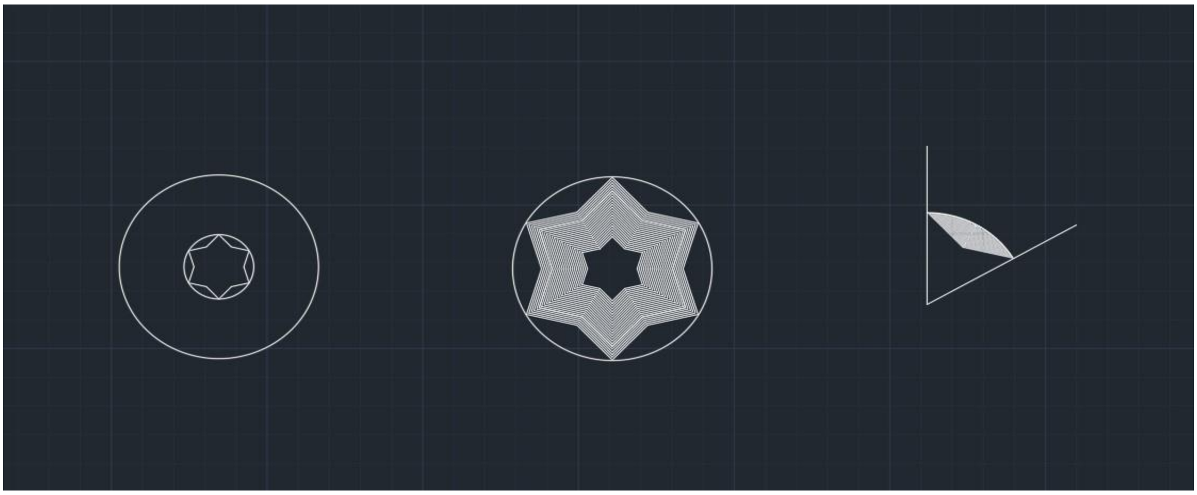

Fig 6.4a. Regressive burn pattern of finocyl grain configuration

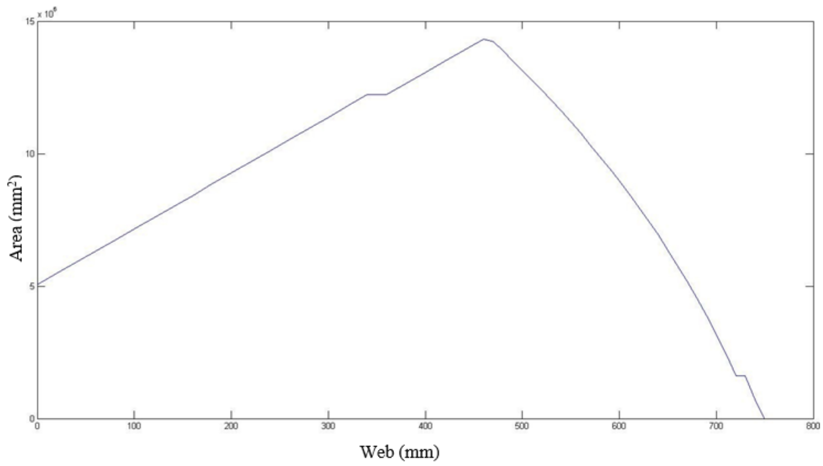

Fig 6.4b. Web vs Area

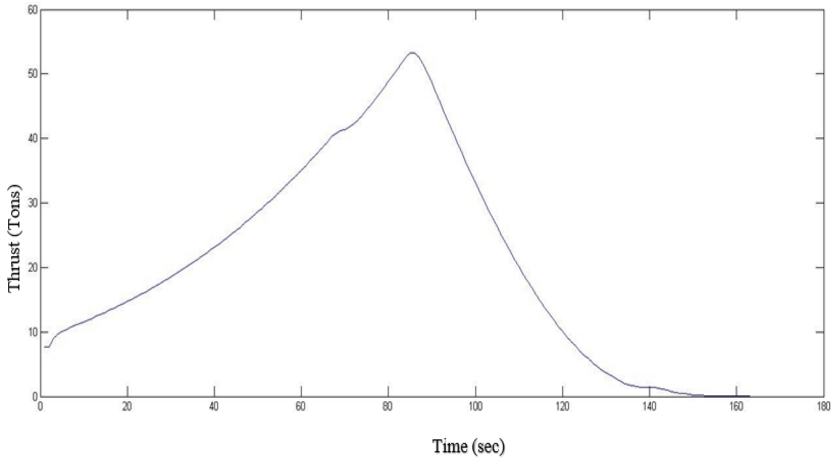

Fig 6.4c. Thrust vs Time

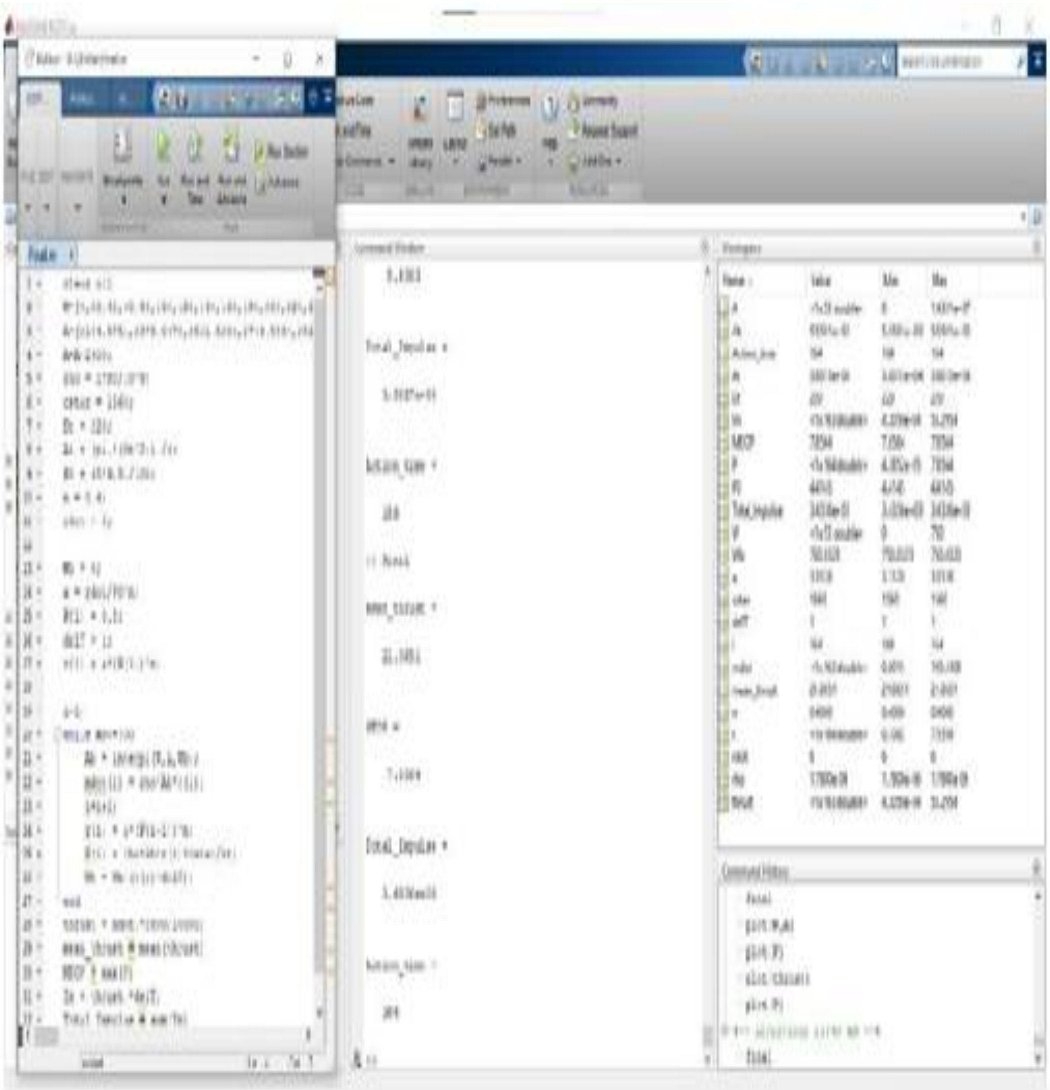

Fig 6.4d. MATLAB Output

v. **Star with 500mm diameter circumscribed circle**

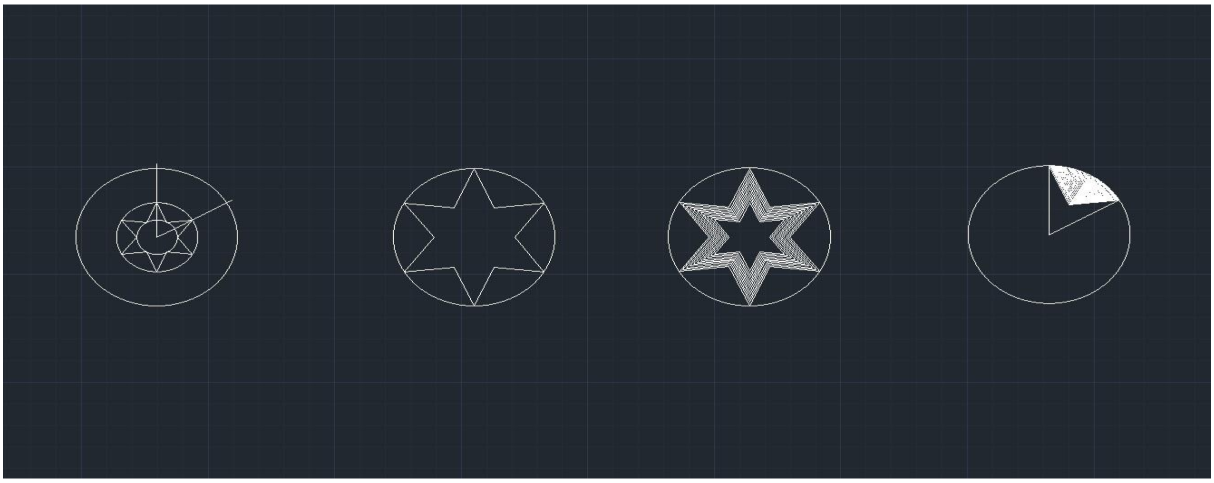

Fig 6.5a. Regressive burn pattern of finocyl grain configuration

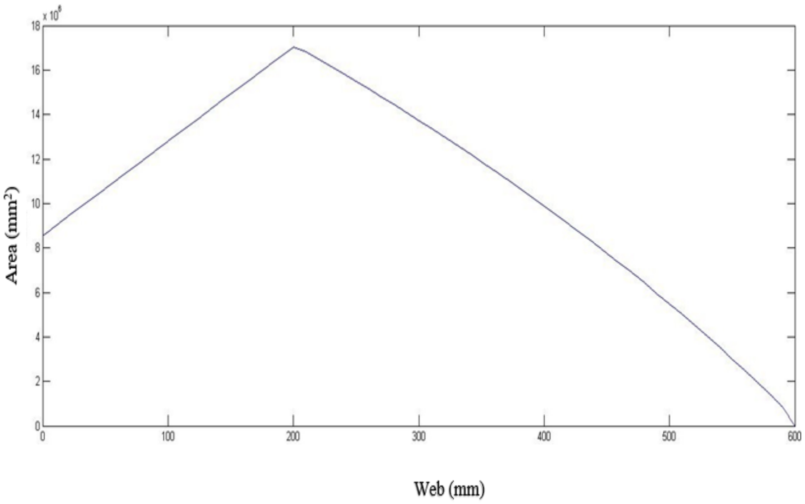

Fig 6.5b. Web vs Area

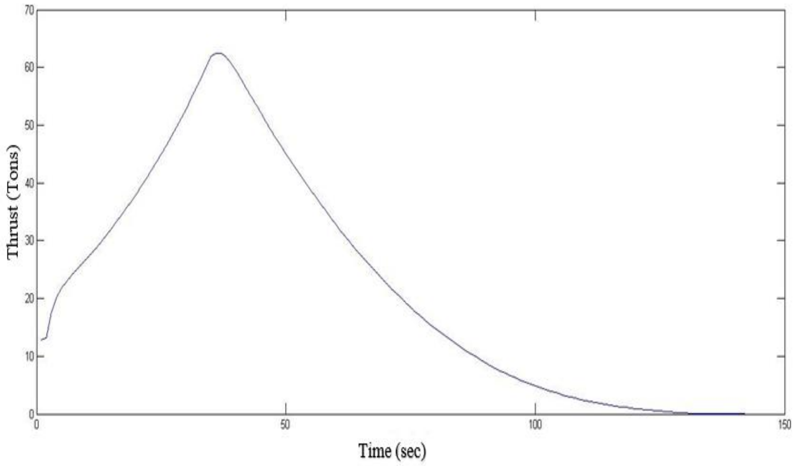

Fig 6.5c. Thrust vs Time

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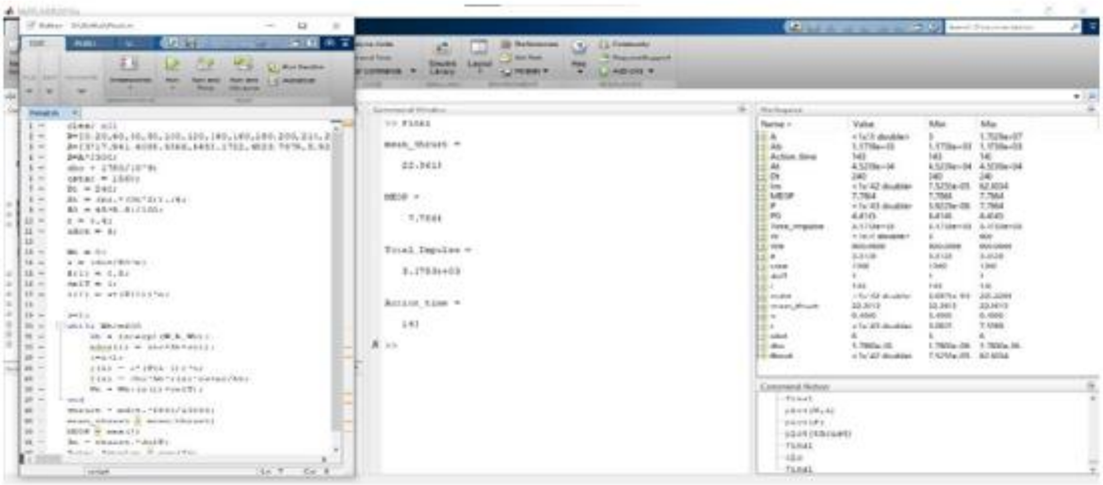

Fig 6.5d. MATLAB Output

vi. **Star with 650mm diameter circumscribed circle**

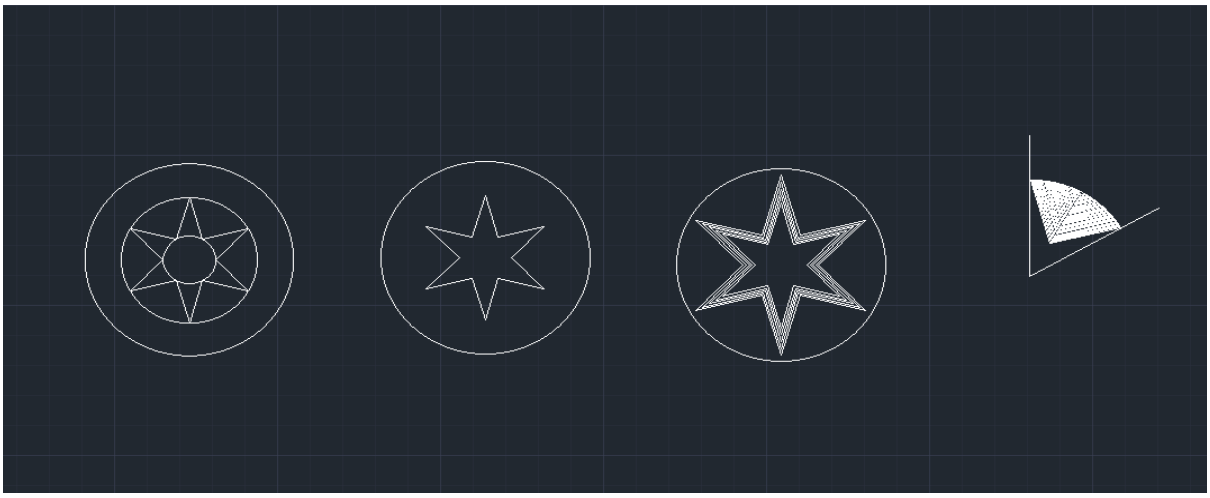

Fig 6.6a. Regressive pattern of finocyl grain configuration

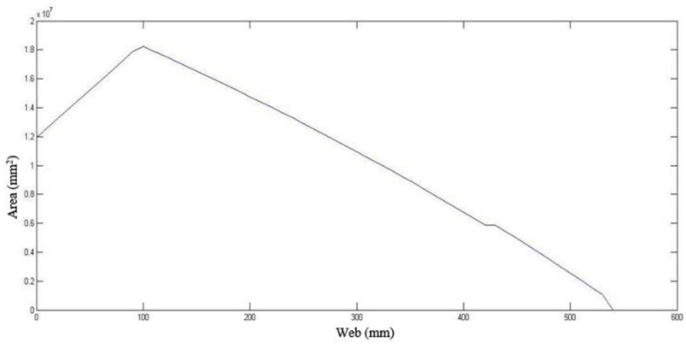

Fig 6.6b. Web vs Area

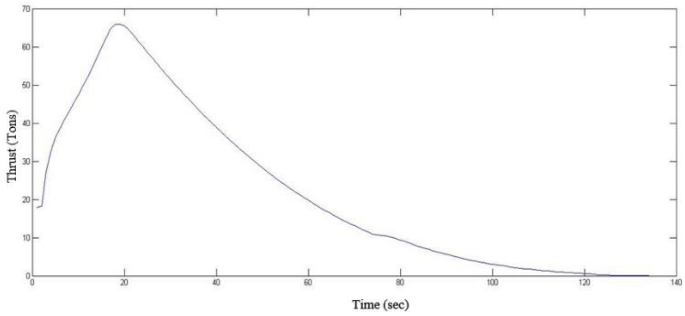

Fig 6.6c. Thrust vs Time

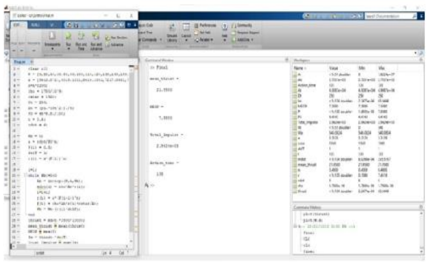

Fig 6.6d. MATLAB Output

7. Conclusions

Different grain geometries and their performances using CAD modelling and MATLAB are obtained. AutoCAD and SolidWorks were used for producing different grain designs and MATLAB is for plotting web vs area, pressure and thrust profiles.

Different solid propellant grains are designed and their respective thrust-time profiles are evaluated. The grain performance evaluation is the one of the most important steps of solid rocket motor design. After considering grain design parameters, we have concluded that:

(a) For a neutral burning – Finocyl with 8 fins is preferable

(b) For a regressive burning – Star with 650 mm diameter circumscribed circle

(c) For a progressive burning – Finocyl with 6 fins is preferable

Solid propellant grain can be designed for particular parameters i.e., For a given P-T profile, grain design can be obtained by integrating AutoCAD with MATLAB. These data are very important for overall flight performance of a launch vehicle/rocket system accurately.

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