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Numerical and Computational Analysis on Two Stage Sounding Rocket

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Abstract- Extensive techniques of design have been proposed for two stage sounding rockets. The paper acquaints a theoretical and conceptual design for compact size 2 stage sounding rocket by focusing on structural optimizations at various levels. The aim of the paper is to develop a two-stage sounding rocket with overall length constrained to 1 meter. Based on the payload mass, structural design for rocket components is developed. The optimization helps to gain desired stability of the rocket body and achieve better aerodynamic characteristics. A comparative analysis of hatch series, power series and parabolic profile shape nose on rocket structure is discussed in the paper. Further modifications in design are made by analyzing the aerodynamic and structural characteristics.

Keywords: Two stage sounding rocket; design; analysis.

I. INTRODUCTION

Sounding rockets is getting extensively used for different kinds of space research and for probing the upper atmospheric regions. Since they are very affordable, they are also used for testing various kinds of prototypes of new components or subsystems intended for use in launch vehicles and satellites. They are lightweight and require less propellant to launch and can be easily restored for new projects.

Sounding rocket generally consists of a solid-rocket fuel motor and a scientific payload. The overall mass of this sounding rocket is 2853 g with length less than 1 meter and diameter of 51mm. Since the rocket does not have much weight, it does not need much propellant to work and glass silicon composite polymer provides an extra shielding from any kind of excess heat exposure.

CFRP has been used for the body part which makes the rocket very lightweight. Motor is always a major matter of concern while working on rockets as a rocket needs an efficient motor which can provide optimum performance and does not increase the weight. So, in order to increase the efficiency of the rocket without increasing the weight, a 15910-p motor has been used for the second stage which has high power efficiency whereas the J530-1M-15 motor has been used for the first stage to make the rocket lighter and more efficient.

The rocket can attain a maximum apogee of 7120 meter with transonic speed of 375 m\s and 1.11 mach. Three fins have been used for reducing the drag and to achieve more supersonic speed. Polymer is now widely used in manufacturing of almost all parts of rockets due to its lightweight, heat resistive, insulation and durability; so glass fibre and CFRP has been used to increase the performance and to decrease the weight of the rocket.

On analysis of linear stress and buckling stress at its body part, the rocket has shown low buckling stress in the range of 10 to 83.33 mm which is safe and efficient to use, making it very stable for usage.

Propellant always plays a significant role in designing of rocket, so it is one of the prime matters of concern while working on any kind of rocket as it will be responsible for the thrust and performance of rocket.

So in order to get better thrust and performance, a solid propellant is used for the design and it is a composite mixture of Aluminium, Ammonium Per chlorate and HTPB. The desired masses of propellant for first stage and second stage are 1.65 kg and 0.65 kg respectively.

II. LITERATURE REVIEW

Lucas de Almeida Sabino Carvalho et.al (2019) studied that the shape of the nose cone plays a critical role in reducing the aerodynamic drag of the sounding rocket. Different shapes of the nose cone were analysed on ANSYS Fluent with an objective to achieve minimum aerodynamic drag for a medium range Mach number 0.05 to 0.62 approximately. The study suggests use of ellipsoid shape as it produces 4.93% less drag compared to parabolic shaped nose cones. To further optimize the results, the paper suggests analyzing von Karman shape and Haach series shaped nose cones [1].

Simmons Joseph R III (2009) carried detailed analysis on one of the major causes of failure for fins, fluttering. Fluttering is oscillation of components due to aerodynamic effect and the fluttering velocity is the parameter used to define flutter. The fluttering velocity depends significantly on shear modulus of the fins structure, fin size and atmospheric conditions. The fins must have low thickness with comparatively large chord length and large taper ratio to minimize flutter. Comparative fin analysis of Falcon Launch V, Falcon Launch VI, Doe Low, and Doe High was studied and found that the flutter velocity decreases with decline in volume of the fin. The study recommends use of compact fins to reduce flutter [2].

Timothy W. Ledlow II et.al (2015) studied that the grid fins are modern design of fins that provide high stability as compared to simple planar fins. The grid fins are further optimised to increase stability and reduce the mass of the fins. However, large drag produced by grid fins is one of the major drawbacks and needs to be optimised. The volume and sweep angle of the fins can be adjusted to reduce the drag coefficient [3].

Joseph D. Vasile et.al (2020) analysed the fin design on lift to drag ratio and aerodynamic drag. The design used for the analysis is d=4 in, l/d= 10, ogive length of OAL=0.3 and the number of fins for subsonic flow is more as compared to supersonic flow to achieve high stability. The highest lift to drag achieved is around 3.1 approximately. The body trim angle is found to be efficient for the described system. Drag increases drastically in the transonic and initial supersonic flow region. The study suggests use of subsonic flow (Mach no. < 0.9) to reduce drag. The paper emphasizes analysing different fin shapes and material for optimization [4].

Naresh.K., et.al (2016) represents study on fibre reinforced polymers which have gained substantial popularity in the aerospace sector. Detailed strength analysis of CFRP, hybrid composite and GFRP were compared. The average tensile strength of CFRP is found to be more than GFRP and hybrid composites. However, increase in the strength of glass fibre reinforced polymer with increase in strain rate is comparatively more than CFRP and hybrid composites [5].

Yunfu Ou et.al (2016) has discussed the effect of temperature and strain rate on the tensile strength of CFRP using hydraulic testing apparatus. The tensile strength of CFRP gained by 21.4% from 2063 +/- 140 MPa to 2505+/- 109 MPa when strain rate was increased from 40 1/s to 160 1/s. Toughness increases by 46.6% with a strain rate increase of 25 1/s to 100 1/s but shows a gradual decline by 20.6% on increasing the strain rate from 100 1/s to 200 1/s. At 700° C, the strength of CFRP drops drastically which ultimately decreases the bonding strength of the composite. CFRP is found to have a tensile strength of 872 MPa at room temperature. However the tensile strength of CFRP decreased by 25.5 % from 50° C to 100° C [6].

Adam Okninskia (2017) investigated the design parameters for structural efficiency. The mass of the propellant decides the overall size of the rocket. Compact size rocket can be obtained by using high density composite solid propellant. Study found use of ammonia per chlorate with aluminium powder and HTPB as an effective composite propellant. The maximum altitude reached by the rocket can be optimised by increasing nose fineness ratio.

However for practical designs, a fineness ratio of 5 is recommended. The stage mass ratio gives a correlation of payload mass with rocket launch mass. If the value of stage ratio is less than 0.5, then heavy rocket design is obtained.

The paper suggests optimum value of stage ratio to be more than 0.6 for compact design [7].

Edward V. LaBudde et.al (1999) recommends some thumb rules for high altitude rocket design. The maximum altitude reached by the rocket is studied in correlation with fin size and launch length. Altitude of the rocket decreases with increment in fin span length. For stability the angle of attack must be ranging from 20-40 degrees. Low thrust engines with subsonic speed are found to be optimal for reaching higher altitudes. The launch length must be decided such that the angle of attack is below 15-20 degrees [8].

H.G.SEVIER* et al stated that if the fins bond structure is made up of shaped core truss grid to which the sheet aluminium skin facings are bonded with an aluminium nose block; this will enable the fin to have maximum aero elastic stiffness. [9].

Pankaj priyadarshi et al asserts that the aerodynamic stability of the rocket is dependent on the fins used which shall determine the position of the centre of pressure of the rocket rearward to the centre of gravity location. We also see a mention of the static margin (SM) values effect on stability, having a static margin of greater than or equal to 1.5 is a necessity in conceptual designing of the rockets. In order to get a greater SM value, we can increase the size of the fins or move the C.G value towards the nose. If we have a cruciform set of fins, then the bending deflection will not be a grave concern.

While designing the fins we have to note the maximum torsion occurring at the tip of the fins which may lead to the altering of the angle of attack of the fin. And to give it a more gyroscopic stability we need to provide an intentional spin to the rocket which can be done by changing the orientation angle of the fins, constraining the maximum tip torsion angle making sure that strength and stiffness of the fin are not compromised while also keeping in mind the minimum factor of safety [10].

Fiona Kay Leverone* states that the fineness ratio of the nose cone is the ratio of its length divided by its diameter and the bluffness ratio is the ratio of tip diameter to base diameter. If we increase the nose cone length, it increases the fineness ratio while decreasing the drag at supersonic speeds. It was seen that the conical shape gave the least subsonic coefficient of drag and it had the under most mass because it required less material for consistent thickness [11].

INVICTUS I, used the parabolic configuration for the nose, as it was a simple design to manufacture and it rendered less weight, so they could use a less impulse motor for the rocket. In order to avoid the fin fluttering problem they developed a rigid nose cone design with G10 glass fibre laminate, Toray T300 carbon fibre laminate with sandwich panel laminate , while they used Nomex honeycomb (two ply face sheet) in the core so that weight reduction with strengthening is possible [12].

Seffat Mohammad Chowdhury (2012), says that in order for a rocket to be considered as stable it should have a good longitudinal stability, in order to prevent problems like spilling of liquid fuels. We consider the rocket to be longitudinally stable, if it tends to return to its longitudinal mode after the disturbance and have a zero pitch, which is possible if the centre of pressure of the rocket is oriented more towards the hind part of the centre of moment. It is also necessary that at all times the centre of pressure remains at 1-2 calibres hind of centre of mass.

Gyroscopic stability can be ensured by providing an intentional spin to the rocket to combat orientation changes and to make it more stable. We can face problems of wind destabilization, if the design has a lesser thrust to weight ratio, which also slows down the acceleration. Fineness ratio for the fuselage is given by the ratio of its total length to its biggest diameter. The transonic drag experienced by the rocket can be reduced if the diameter is the same for all sections of the rocket [13].

Ted W Bohrer*(2017), mentions different materials used for the body and the nose cone of the rocket along with their pros and cons. He mentions about cardboard, blue tube, fibreglass and carbon fibre. Carbon fibre has good strength and is lightweight. It also possesses a problem of intervention with the radio transmission, so the next best choice would be to use fibreglass.

G-12 filament winded tube would be a good choice for its carbon fibre counterpart replacement, which will give us a good strength because of the multilayer arrangement and keep the wind angles between 30 to 45 degrees. The next choice of the material was blue tube, which is strengthened with cardboard, as it is low in cost and density but with good strength.

If only cardboard was used, zipper phenomenon would occur, which is the sudden tear of the material at higher longitudinal loads, thereby causing damages to the structure, which can be avoided if fibreglass, Carbon fibre and blue tube are used.

Cardboard when wetted lose their structural strength but resins and composites are waterproof. For nose cone, tangent ogive configuration gives more space to incorporate more payloads [14].

III. METHODOLOGY

The design of the outer structure of a sounding rocket is initiated by deciding payload mass. For a compact system, the payload mass is chosen to be 0.5kg. Based on the empirical formulas, the desired mass of propellant required for the first and the second stages of the rocket are calculated. The values of the structural ratio and payload ratio of 0.1 and 0.18 are found to be optimum. The desired masses of propellant for first stage and second stage are 1.65 kg and 0.65 kg respectively.

The solid propellant used for the design is a composite mixture of Aluminium, Ammonium Per chlorate and HTPB.

1. Ablative Material:

Since the overall length of the rocket is constrained to 1m, the inner diameters of the ablative material for both the stages are calculated using the total volume occupied by the propellant mixture of respective stages. The diameter for both the stages is kept equal.

The material used for the ablative structure based on comparative analysis is silicon glass reinforced polymer. The inner diameter obtained from calculations is 44mm by considering a cylindrical profile. Using the thin shell concept, thickness of the ablative material derived is 1.5 mm.

2. Body Frame:

The inner diameter of the body frame is selected by providing some allowance to the ablative structure. The carbon fibre reinforced polymer provides excellent strength at higher temperatures and also reduces the mass of the system due to its low mass density. CFRP is used for body frame structure. Using the concept of thin shells, the thickness of the frame is worked out. The thickness of the body frame for both the stages evaluated to 2 mm.

3. Fins:

Two sets of three fins are used for both the stages. The dimensions of the fins for both the stages are obtained by trial and error basis. The correlation of the fin dimensions with the diameter of the body frame derived in the paper is found to be effective. The material used for the fins is fibre glass since the material is found to reduce aerodynamic losses.

4. Nose Cap:

Nose of the rocket bears a huge amount of drag and heat which is generated due to the aerodynamic friction between the air layers and the nose tip. The profile of the nose cone analyzed for the design is the parabolic series. Based on the analysis, the Haack series shape cone is found to give a higher apogee.

5. Motor:

The motors used for the given design constraints for the first and the second stages are J530-IM-15 and 159WN-P respectively. The design and the rocket characteristics obtained from Open rocket software is as follows:

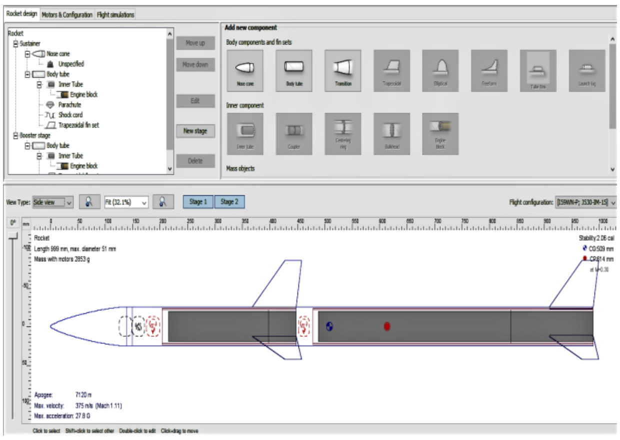

Fig 1. 2-D rocket design in Open Rocket software.

The 3D design modelling of the rocket was done in Solid Edge software. First the inner tubes and the engine blocks were done, then the first and second stage were done and finally the nose cone was designed. All were done separately, to enable any last minute changes and then assembled together. While designing, all clearances were kept in mind and made sure the design was in the allowable error limit.

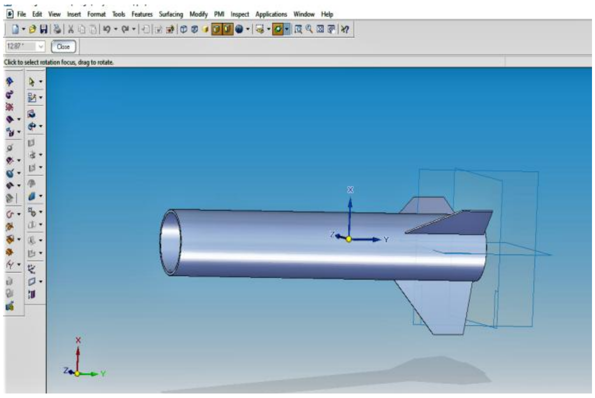

Fig 2. Body tube with fins in Solid Edge software.

IV. RESULT AND DISCUSSION

The results obtained were as follows:
The design was simulated in Solid edge for buckling and linear stress and the analysis of altitude versus time and altitude versus drag was done in Open rocket.

Fig 3. Buckling stress analysis.

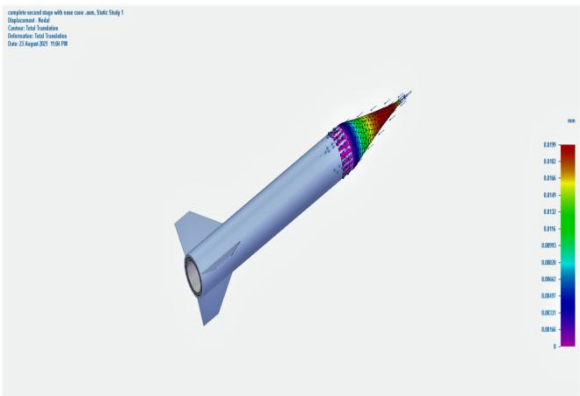

Fig 4. Linear stress of nose cone.

Since the maximum altitude reached by the rocket would be of 7 Km from the sea level and 11.31 PSAI (77979 N/m^2) which would be the pressure experienced by the rocket at its highest altitude, it was subjected to 11.31 PSAI pressure force for buckling stress and the results obtained showed that the buckling stress were low and in the range of 10 to 83.33 mm.

Fig. 4 shows the linear stress experienced by the nose cone when it reaches the apogee and it shows that the maximum stress experienced by the nose cone would be at its tip and the least stress experienced would be at the nose cone shoulder.

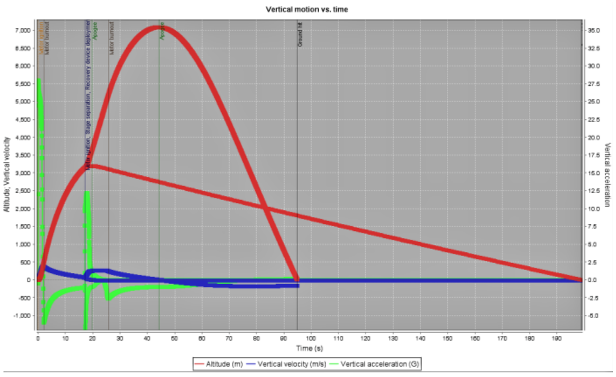

Fig 5. Altitude versus drag graph.

Fig. 5 shows the plot for altitude versus time, which depicts for the given design. It has a linear vertical velocity through the flight and descent time. Altitude first drops from 7 Km and then reaches to around 5.4 Km when the first burnout happens and it continues to drop to 3.4 Km when the first parachute is released.

Vertical acceleration first reaches around 27.8 and then decreases. The fig. also shows that after the first burnout, the apogee reached is around 3.5Km.

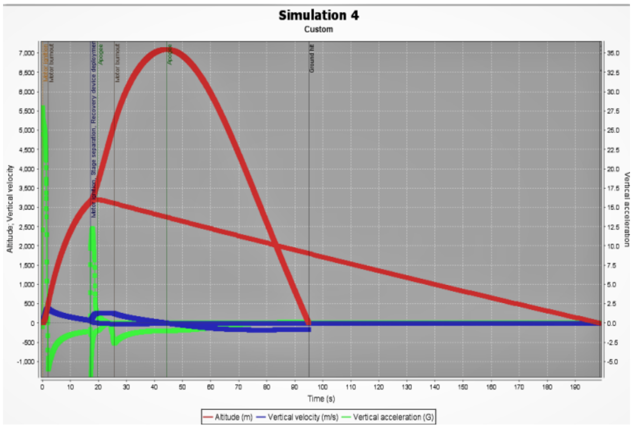

Figure 6: Altitude versus time graph.

Fig. 6 shows the plot for altitude versus time, where altitude, vertical velocity and vertical acceleration are shown after each stage.

V. CONCLUSION

The conceptual design for a two stage sounding rocket has been proposed with buckling and linear stress analysis. The rocket can attain the maximum apogee of 7120m with maximum velocity of 375m\s. According to Fig.3, linear and buckling stresses are in the range of 10 to 83.33 mm when it was subjected to 11.31 PSAI pressure force and has low buckling stress.

The linear stress for the nose cone has been studied in Fig.4 and it turned out to be smoothly distributed which makes it more efficient. The linear stress in the nose cone of the rocket is high at its tip when the rocket attains maximum apogee. Fig. 5 shows that the altitude of the first stage increased after the separation and velocity after the motor ignition also increased making it very stable and efficient to use.

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