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Optimization Design of Rocket Nosecone for Achieving Desired Apogee by Empirical Research and Simulation-Based Comparison

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Abstract: Morgan State ARROW team seeks to design a Liquid Propellant Rocket (LPR) that should reach an apogee of 13,000ft. Component design such as Nose Cone (NC), Fins, Boat Tails are all crucial in achieving the desired apogee. Of all these components, the rocket NC is the first to interact with the air and it also houses the payload. The aerodynamic design of the NC section is key to the overall success of the rocket. The drag is the aerodynamic force that opposes the aircraft's motion through air, so it is essential to minimize the drag in order to achieve a higher altitude. The choice of materials and NC shape are also crucial to proper design and minimizing the drag. Hence, this paper focuses on investigating the effect of NC materials, size, and shape on achieving the desired apogee. OpenRocket software was used in simulating the apogee reached by varying the NC design factors. The simulated data were analyzed using General Factorial Design method to investigate the effect of design factors on the rocket apogee. Furthermore, a 2D and 3D model and Finite Element Analysis (FEA) were performed on the optimum NC parameters using Solidworks. On analysis, the results indicated that NC shape, length, diameter, and materials have significant effects on the apogee of the rocket. The maximum altitude of 8163ft was observed at 30-inch length, 6.15-inch diameter, fiberglass material and ogive shape of NC. The FEA simulated result yielded average values of 116.64KPa, 306.64K, 485.63ft/s and 256.02N for the pressure and temperature distribution, velocity, and drag of the NC respectively. The simulated results show a greater performance measure of the NC design. The result of this research will benefit the MSU Arrow team in designing the overall LPR.

Keyword: Nosecone, Fiberglass, Liquid Propellant Rocket, Openrocket, Apogee, Simulations

1. Introduction

Last year, Morgan State University (MSU) received a grant award from BASE 11 to establish the first rocket research and education program at an HBCU (historical black college and university) in the USA (Base 11, 2020). One task of this program is the design and development of a Liquid Propellant Rocket (LPR) to be launched in January-March of 2021 to an apogee of 13,000 feet. This rocketry team, named as Aerospace Rocket Research for Opportunities in the Workforce (ARROW), is working hard to develop this LPR, aimed at completing the structural and analysis design model of the LPR in this summer. The concept of using a liquid propellant in a rocket engine is not new. It has been around for over 100 years. However, its actual implementation and construction only began in 1921 and was only possible because of Robert H. Goddard, an engineer, and a professor. He received credit for being the first one to successfully launch the world's first LPR on March 16, 1926, ushering in an era of space flight and innovation (Sutton, 2005). The complexities provided by the LPR resulted in innumerable specific driven research, and one of the complex components of an LPR is the NC. Asides being the forwardmost section of a rocket to interact with the air, it also houses the payload, which can be a satellite, a GPS tracker, humans, animals, or cargo. In war missions, the NC carries the instruments used in tracking enemy aircraft. The aerodynamic design of the NC section of a rocket is key to the overall success of the rocket. The major aim of the design is to minimize the total drag of the rocket. The drag is the aerodynamic force that opposes the aircraft's motion through the air and so it is essential to minimize the drag in order to achieve a higher altitude. Choice of materials and shape are also key to proper design and minimizing of drag. Hence, this paper focuses on investigating the effect of materials, size, and shape on achieving the desired apogee.

1.1 Nose Cone Shapes

A wide variety of studies suggested that the geometrical shapes such as conical, ogive, and parabolic on a rocket's NC profoundly affect its performance (Suresha et al., 2015; Sreenivasula and Keerthi, 2017). Additionally, several experiments conducted on how the comparison of different NCs, such as its length and diameter, will influence the transonic region in order to find the most optimal and efficient design to reduce aerodynamic drag (Chalia and Bharti, 2016). Furthermore, aside from investigating the impact of shapes and fitness ratio of NCs, other several factors must also be considered in order to provide factual and concrete data. Figure 1 shows different NC shapes – (a) Conical, (b) Ogive, (c) ellipsoid, (d) Power series, (e) Parabolic series, and (f) Haack series, which are available in the OpenRocket Simulator.

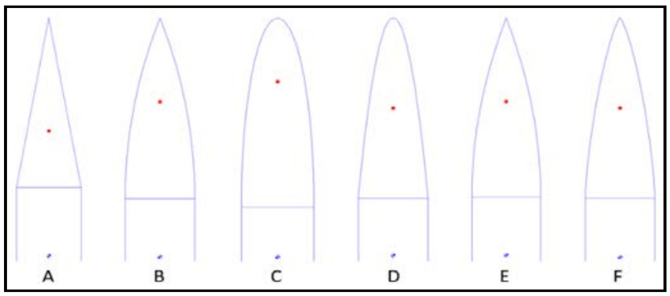

Figure 1. Nose cone Shapes in OpenRocket Simulator

1.2 Nose Cone Materials

Material selection for the NC also depends on its function. The NC needs to resist the extreme heat and pressure since the NC of a rocket undergoes a head-first atmospheric re-entry. Therefore, the material of the NC must be constructed of heavy heat-sink and shielding materials. Alternative materials for the NC included fiberglass, carbon fiber, and aluminum. As shown in Table 1, the comparison of alternative materials properties showed that fiberglass has high heat resistance, low thermal conductivity, and density. Many student rockets teams among national universities, such as UAkron (Tombazzi, 2018), the University of Michigan (Buccellato et al., 2018), and the MIT (Lozano et al., 2010) selected fiberglass for their rockets' NCs.

Table 1. Comparison of Alternative Material Properties for the NC

Material	Density	Thermal Conductivity
G-10 fiberglass	1.91 g/cm^3	0.288 W/m-K
Carbon Fiber	1.93 g/cm^3	21-180 W/m-K
Aluminum	2.7 g/cm^3	167 W/m-K

1.3 Nose Cone Dimensions

The magnitude of NC drag is not only dictated by its shape but also fineness ratio, which is the ratio of a NC's length to its base diameter. In summary, shape, material, length, and diameter of NCs are critical design factors to determine the rocket performance.

1.4 Design of Experiments (DOE)

This is a tool utilized by engineers and scientists for product design and development in the product cycle as well as process development and improvement in a variety of disciplines, which will substantially reduce development lead time and cost, leading to processes and products that perform better, and have high reliability than other approaches [15]. General model of a process or system as shown in Figure 2, the process transforms some input to an output that has one or more observable response variables. Some of the process variables X_1, X_2,…, X_p are controllable, whereas other variables Z_1, Z_2,…, Z_p are uncontrollable. The main objective of the experiment is to determine which variables are most influential on the response, even you can set the influential factors that response is near the desired nominal value with small variability, and reduce the effects of uncontrollable factors (Montgomery, 2005). The objective of this study is to investigate the effect of NC design factors on the rocket altitude in a simulation-based environment using DOE.

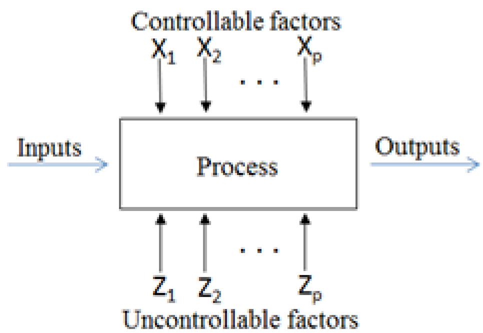

Figure 2. General Model of a Process or Systems (Montgomery, 2005)

2. Methodology

2.1 Open rocket Simulation

This study utilized OpenRocket Simulator to design a constant generic rocket design in terms of the airframe, motor, and fins and which has a total length of 136 inches. Both upper and lower airframes were modeled using aluminum material which has a density of 1.56 oz/in^3. In addition, the fins that are used in this model are trapezoidal fin set with a root and tip chord of 12 and 4 inches, respectively. Furthermore, the height is 6.25 with a sweep length of 7.58 inches and a sweep angle of 50.5 degrees. Lastly, the motor that was used in this model was the L1115 due to its characteristics such as its total impulse of 5017 Ns, an average thrust of 1116 N, a maximum thrust of 1713 N, and a burn time of 4.47 seconds. As observed in Figure 3, the stability of the rocket in this model is 1.7 cal. In this study, the stability of the rocket's design is of paramount importance. Thus, both static and dynamic stability played a vital role during the design phase.

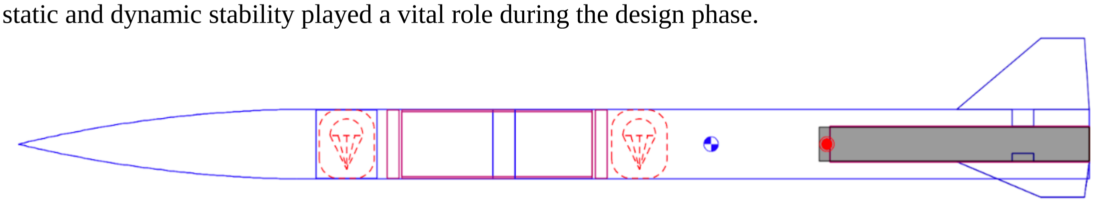

Figure 3. Rocket Model for Simulation

2.2 Statistical Analysis Using DOE

From the simulation results in OpenRocket, the highest apogee was observed at Ogive NC shape. A general factorial analysis was performed for the Ogive NC shape to study the effect of operating factors (NC material (density), NC length and NC diameter) on the altitude of the rocket as shown in Table 2.

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Table 2. Design Factors and Level

Factors	Levels					
NC Material (Density)	3	CarbonFiber (1.03oz/in^3)	Fiberglass (1.07oz/in^3)	Aluminum (1.56 oz/in^3)		
NC Diameter	3	6.15in	6.2in	6.25in		
NC length	5	30in	32in	34in	36in	38in

3. Results and Discussion

3.1 OpenRocket Results

The NC was simulated by varying its shape, materials, diameter, and length and recording the corresponding altitude and weight. For this study, 3 levels of NC diameter (6.15 in, 6.2 in, and 6.25 in), 5 levels of length(30 in, 32 in,34 in,36 in and 38 in), 6 levels of NC shapes (Conical, Ogive, Ellipsoid, Power Series, Parabolic, Haack series, Power series) and 3 levels of materials with their density (Carbon Fiber- 1.03 oz/in^3 , Fiberglass, 1.07 oz/in^3 and Aluminum 1.56 oz/in^3 were considered and the results are shown in Figure 4 below. The data show that the highest apogee of 8163ft was reached at ogive NC shape, fiber glass NC material, 30in NC length and 6.15in NC diameter. The effect of NC length, NC diameter, NC Material is being examined for the Ogive NC shape using Analysis of Variance (ANOVA) at 95% confidence interval as shown in Table 3.

		Nose Cone Length = 30			Nose Cone Length = 32			Nose Cone Length = 34			Nose Cone Length = 36			Nose Cone Length = 38		
Nose Cone Shapes	Materials	Base Diameter = 6.15	Base Diameter = 6.20	Base Diameter = 6.25	Base Diameter = 6.15	Base Diameter = 6.20	Base Diameter = 6.25	Base Diameter = 6.15	Base Diameter = 6.20	Base Diameter = 6.25	Base Diameter = 6.15	Base Diameter = 6.20	Base Diameter = 6.25	Base Diameter = 6.15	Base Diameter = 6.20	Base Diameter = 6.25
Conical	Fiberglass	7808	7771	7723	7796	7777	7694	7823	7805	7704	7812	7772	7746	7808	7781	7722
	Carbon Fiber	7821	7763	7732	7795	7762	7703	7850	7786	7710	7858	7791	7752	7858	7797	7756
	Aluminum	7650	7581	7541	7651	7589	7540	7635	7602	7551	7623	7594	7541	7645	7573	7527
Ogive	Fiberglass	8163	8064	8001	8106	8041	7996	8093	8043	7990	8067	8051	7960	8021	8008	7923
	Carbon Fiber	8139	8129	8046	8096	8108	8012	8111	8085	8051	8080	8011	8025	8040	8017	7952
	Aluminum	7909	7825	7795	7849	7830	7741	7835	7784	7727	7772	7727	7722	7753	7716	7647
Ellipsoid	Fiberglass	7430	7381	7333	7414	7365	7317	7388	7339	7290	7368	7319	7271	7346	7298	7249
	Carbon Fiber	7441	7392	7343	7424	7376	7329	7401	7351	7302	7381	7332	7283	7360	7311	7263
	Aluminum	7296	7247	7198	7271	7222	7174	7237	7187	7137	7207	7158	7109	7177	7127	7078
Power Series	Fiberglass	7709	7662	7613	7681	7633	7586	7653	7604	7556	7624	7575	7528	7595	7547	7500
	Carbon Fiber	7720	7671	7624	7691	7644	7596	7664	7616	7567	7636	7587	7539	7608	7560	7512
	Aluminum	7581	7532	7484	7546	7498	7450	7511	7462	7412	7474	7425	7377	7439	7390	7341
Parabolic Series	Fiberglass	8152	8105	8059	8099	8057	8005	8065	8069	7993	8059	8006	7970	8009	8015	7928
	Carbon Fiber	7220	8093	8049	8138	8082	8020	8121	8054	8063	8078	8050	8026	8061	8002	7963
	Aluminum	7901	7855	7813	7861	7812	7784	7849	7784	7739	7813	7750	7700	7768	7690	7669
Haack Series	Fiberglass	8130	8080	8040	8112	8037	8038	8119	8042	8010	8054	8026	7698	8032	8048	7931
	Carbon Fiber	8142	8114	8079	8144	8073	8050	8124	8062	8042	8075	8017	8033	8055	8056	7970
	Aluminum	7947	7888	7840	7874	7852	7797	7820	7775	7755	7786	7761	7707	7757	7701	7681

Figure 4. Simulated Data for Rocket Altitude

Table 3. Analysis of variance for Ogive Shape

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	28	890239	31794	80.56	0.000
Linear	8	879755	109969	278.65	0.000
NC Material	2	745434	372717	944.43	0.000
NC Diameter	2	70425	35213	89.23	0.000
NC Length	4	63895	15974	40.48	0.000
2-Way Interactions	20	10485	524	1.33	0.285
NC Material*NC Diameter	4	2305	576	1.46	0.260
NC Material*NC Length	8	4038	505	1.28	0.320
NC Diameter*NC Length	8	4142	518	1.31	0.306
Error	16	6314	395		
Total	44	896554			

The NC material, diameter and length are all significant factors that affects the altitude of a rocket as shown in Table 3. In the 2-way interaction, all the NC factors combinations were insignificant on the altitude of NC Ogive shape with p-value > 0.05. The optimal parameters (Ogive NC shape, 30 inch NC length, 6.15 NC diameter and fiberglass NC material) were used in obtaining both 2D and 3D designs as shown in Figure 5.

Figure 5. NC Shape 2D and 3D Diagram

Furthermore, the parameters were used for simulating NC performance in SolidWorks. The material chosen for this simulation was fiberglass and the gas defined in this flow simulation is air to display the effects on the design. The velocity chosen for this simulation was 540 ft/s in the Y-axis with earth's gravity at 9.81 m/s^2. The simulation is set to calculate total temperature, total pressure, drag, and the average velocity (y-axis). A total of 90 iterations were performed and the last 21 iterations is used as its analysis interval for calculations. The results were placed in an Excel spreadsheet providing the user with the value to use for calculations, the averaged value, the minimum value, and the maximum value for each selected output calculation is shown in Table 4.

Table 4. Summary of Simulation Data

Goal Name	Unit	Calculation Value	Average Value	Minimum Value	Maximum Value
Average Total Pressure	[kPa]	116.64	116.63	116.61	116.64
Average Total Temperature	[K]	306.64	306.64	306.64	306.65
Average Velocity (Y)	[ft/s]	485.63	485.34	484.79	485.63
Average Drag	[N]	256.02	255.99	255.63	256.29

4. Conclusion

The effects of NC length, diameter, shape, and material selection on rocket engine apogee have been studied in this research paper. Choice of materials and shape has been observed to be a key component to proper design and minimizing of drag which opposes the aircraft's motion through the air. From the simulations performed in an OpenRocket software, the highest rocket apogee of 8163ft was recorded at 30-inch length, 6.15-inch diameter, Fiberglass material type and Ogive shape of NC. The analysis of variance performed on each NC shape shows that all the design parameters – NC material, length, and diameter, have significant effect on the rocket apogee. A 2D and 3D design and simulations were performed on the optimum NC parameters using Solidworks to determine its total temperature, total pressure, drag, and the average velocity. The simulated result yielded average values of 116.64KPa, 306.64K, 485.63ft/s and 256.02N. Thus, showing a greater performance measure of the NC design. The result of this research will benefit the MSU Arrow team in designing the overall LPR.

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