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Design and Simulation of a Light Gas Gun

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ABSTRACT: Development of a device or a machine or a vehicle needs lots of steps to achieve the desired results. One of them is to design the final product and to analyze the same using computer simulations. The process of design and simulation of a product on software reduces the cost of making a real time prototype for analysis and modification based on the problems which arise after that. The idea of launching an object to space dates back to Jules Verne and even before that when man tried to catch the flying birds with the help of a pin (as a projectile) and a wooden pipe (launch tube). So this paper describes about the process of simulating a light gas gun design which is proposed to launch projectiles to the Low Earth Orbit. The Light gas gun design adopted is of the distributed injection type. Instead of using one high pressure charge at the breech of the gun, the charge is distributed at regular intervals to have a constantly refreshed pressure at the base of the projectile. This results in a better performance than the breech fed guns. The projectile is said to achieve a muzzle velocity of $8.2 \text{ (kms}^{-1}\text{)}$ on the basis of the computerized simulations. Also the acceleration loads on the projectile is kept below 9000 G's .

KEYWORDS: Distributed hydrogen injection, hypervelocity, light gas guns, pressure.

I. INTRODUCTION

Rockets are being used for transporting astronauts and small to very large payloads for a long time since 1950s and they will continue in service for some more years to come until other launch methods are fully developed and operationally realized. But their complexity and high costs made us think about other cost effective methods for many other purposes. The emerging trend of launching many small satellites to the Low Earth Orbit (LEO) is one of the reasons for considering other methods which are cost effective. Nowadays many launches to space are meant to be commercial and more developing nations want to launch their own satellites and also to experiment their capabilities in space. Many researchers and students have started to book a place for their satellite in the rocket launches. Many of them are said to be small and experimental satellites, some of them can operate in groups as a constellation. The 66 satellite Iridium constellation [1] was a better example of this scenario, which had provided “cell phone in sky” service worldwide and the trend continues.

As the space race to access the LEO is getting faster, too many launches with payloads in the range of 10 – 100 kilogram in a year will be the level next. This demands a new fully developed and functional method for cost effective launching. Several R&D programs are already underway to develop a cost effective method of launching payloads. One of them is the gun launch technique. A gun to launch payload might sound crazy, but it is an attractive and a cost effective way for launching. A gun is simple in design, reusable, and more launches per year are possible. When compared to rockets weight is not an issue for a terrestrial mounted or an ocean based gun. Thus their parts can be closer to the industrial grade than aerospace grade which makes them relatively inexpensive. The gun launch techniques are also having some disadvantages which are substantial and are to be eliminated if they are to be considered for launching payloads. The vehicle or the projectile launched from a gun should withstand the high acceleration loads. Many of the electronic components couldn't withstand high acceleration loads more than $1,00,000 \text{ G's}$ (Gravitational constant for acceleration). Moreover it will make the projectile to undergo large aerodynamic heating which may cause severe damage to the projectile and the

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payload components. They should survive these aerodynamic heating associated with trans-atmospheric flight at hypersonic speed. If these problems are solved, a gun launcher would be a nice choice for launching small satellites to LEO.

There are several other factors like politics and policies of each country and the researchers' mindset about the gun launch technique. There are several gun launch techniques available today and to name a few are the Blast wave accelerator, Light Gas Gun, Rail Gun, Ram Accelerator, etc., In this paper we consider the reduction of the acceleration loads for a better design tolerance and to achieve the orbital velocity using a light gas gun for launching communication payloads with little or no G hardening needed.

First efforts to launch a projectile from a barrel gun began as early in world war – I. In the first world war Germans used a gun called as 'Wilhelmgeschuetze' (vengeance weapon) or simply 'Paris kanonen' (Paris gun) which were built by the Krupp company for delivery of explosives to Paris from positions near the German front lines [2]. They have attacked Paris from 113 kilometer away with a modified naval gun. More serious efforts to develop a gun launch system for launching payloads to space were made in the early 1960s under the High Altitude Research Project (HARP) [3]. The HARP produced cannon launch altitude records that are yet to be broken. They achieved an apogee of 180 km, which was up to date the highest by any gun launch system and that too not just once, but 15 times during a four-day period in 1966.

The rocket shaped projectiles launched from the barrel in the project High Altitude Research Programme (HARP) had mass of 100kg and they attained the altitude of 180 (km), and the muzzle velocity was 2100 (ms^{-1}). More than this velocity they hadn't ventured due to high molecular weight of the propellant charges. Whereas in a light gas gun as the name indicates, a light molecular weight gas such as hydrogen or helium would be used to propel the projectile to hyper-velocities. The high 'G' loads were also a problem with this gun.

II. CONCEPTUALIZING THE DESIGN

Light gas guns are used for research in laboratories for more than 40 years. They have proven track record of launching projectiles to more than 8kms⁻¹. They're used for space debris impact testing, testing materials at hypersonic speeds, studying the equation of state of a material [4],[5],[6]. Light gas guns are more commonly used in laboratories around the world than any other gun launch technique due to their varied applications.

There are several designs for the light gas guns, which are classified by their number of stages. One stage light gas guns are used in the laboratory experiments such as to study the real gas behavior of light gases such as hydrogen and helium under testing conditions [7]. Two stage light gas guns are used for many purposes such as for plasma fuelling, space debris impact tests and for studying propellant behavior, etc., [8], [9], [10]. They are also anticipated to put the payloads to the orbit [11].

There are also three stage light gas guns which were also used for hypervelocity impact tests [12]. During the 1980's and 1990's, researchers at U.S.A, who were involved in the Super High Altitude Research Programme (SHARP), developed a new method of launching payloads with a light gas gun [13]. They had designed a gun with many stages. Their design included a conventional two stage light gun design and distributed injectors of hydrogen in pairs. With that design they were able to launch a scramjet test projectile at Mach 8. They have also described about the process of heating hydrogen to high temperatures on the order of 1500(K) – 2000(K) with a particle bed heating system, an electric arc heating system, etc. Heating the gas to such a high temperature is to increase the velocity of the gas as shown by [4], [14]. The velocity of a gas, is said to increase with the root of its temperature as defined by the following equation

$$C = (\gamma RT)^{1/2} / M \dots (1)$$

Where is the temperature of the compressed gas, 'M' is the Molar mass of the gas, 'R' is the universal gas constant and ' γ ' is the ratio of specific heats.[4] shown that the reason to choose Hydrogen as the working fluid is to have the highest efflux velocity and the corresponding projectile can be achieved by the gas with the smallest molecular weight.

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$$2C / (5/3-1) = 3C \dots (2)$$

These relations stress the need for heating the gas and we propose to use the existing systems such as particle bed heating, particle reactor bed heating [13]. [15] Shown that a multi valve launcher is more feasible than a two stage gun for launching payloads to the orbit. [16] Their feasibility study shows that a distributed injection system for a light gas gun is the most possible solution to reduce the 'G' loads to get a convincing design for the satellites or the payloads.

III. DESIGNING THE VIRTUAL MODEL

The design of this gun is supposed to be based on the results of above inputs and we have zeroed in on the distributed injection light gas gun over the other design concepts.

A. Constructional Details of the Projectile

The design of this gun is based on the projectile design. Hence designing the projectile first will add sense to the concept. The projectile is based on the low drag configuration concept. [17], [18] & [19] had shown that the power law shape ($r=Ax^{0.65}$) for the projectile suits the best which needs a low drag configuration. The power law shape with a base flare of 7.5° is used by [16] & [19]. This ensures both the low drag and the passive stability of the projectile. Based on these results, the projectile is said to be designed as shown in the figure 1.

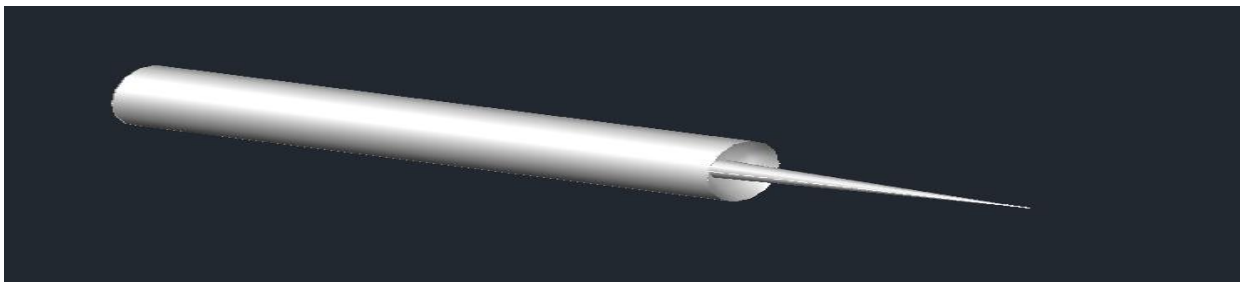


Fig.1. Sabot containing the projectile. The cylindrical part is the sabot and the conical one is the projectile.

The sabot as shown in the fig1, is to hold the projectile inside the launch tube. This is to hold and to protect the projectile from high G loads inside the launch tube. The sabot is necessarily made of carbon composite and is said to be of the baseline of mass fractions set by [17]. So the projectile package is of 1000(kg), of which a 166 (kg) of payload can be included for a density of $665 - 670 \text{ (kgm}^{-3}\text{)}$. But this value can be improved by having a projectile density more than $1000\text{(kgm}^{-3}\text{)}$. The projectile geometry based on the current configuration has a length of 883.58 cm and a diameter of 80.33cm, the sabot which is said to house the projectile is said to have a diameter of 96cm. The remaining mass in the package is dedicated to an aero shell to protect from aerodynamic heating, an aerospike in front of it to reduce the drag. These features dictate the launch tube parameters which are as follows.

B. Constructional Details of the Launch tube, chamber and the valves.

The Launch tube is said to have a diameter of 1m. The chamber or the reservoir has a diameter of 5m and a length of 6m. The outer diameter of the chamber is said to have a diameter of 6.8m and the chamber is of co axial design. The valves used here are of the chamber seal type. A total of 18 injector pairs are used and all of them are said to be having identical valve design. The valves has the dimensions as the flow coefficient of 45% and a seat diameter of 63(cm)The launch tube has a length of 830(m) along which the side injector pairs are placed at an angle of 20° as predicted to be advantageous by [16]. A 3 - dimensional view of the light gas gun is shown in fig 2, which is shown below

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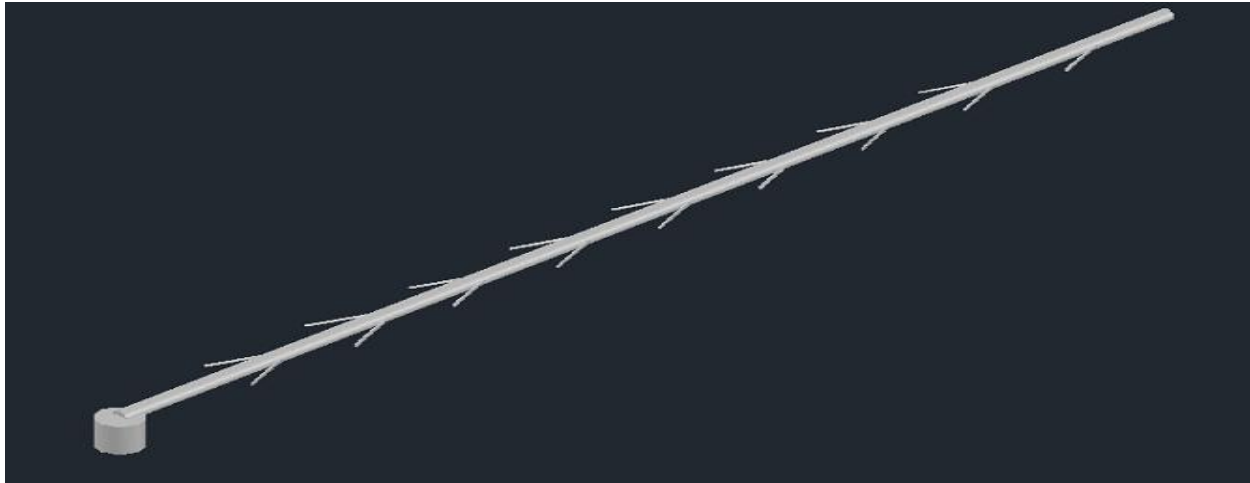


Fig.2. Light Gas Gun with distributed injection of hot hydrogen.

IV. RESULTS

The projectile is said to have been attached with an Attitude and Orbit Control System (AOCS), a solid rocket motor for sustaining the velocity to reach the orbit. We have made the calculations with a reference of launching from 3000(m) above sea level. This is to take the advantage of reduced atmospheric drag [20]. The operating pressure is set at 30000 (psi). The temperature of the gas is raised to 1550K, because at this temperature the velocity of the gas will be $3002 \text{ (ms}^{-1}\text{)}$ which can be calculated from equation 1.0 and the molar mass of hydrogen is 2.01588 [21]. With these values if the projectile launch has been simulated with a simulation tool GGDT[®], which is especially dedicated to the design of light gas guns. The projectile is said to have a more or less linear increase in velocity with the time. The projectile is said to exit the muzzle in a time of 236(ms) with a velocity reaching $8280.5 \text{ (ms}^{-1}\text{)}$, which is enough for a payload to enter into the LEO orbit.

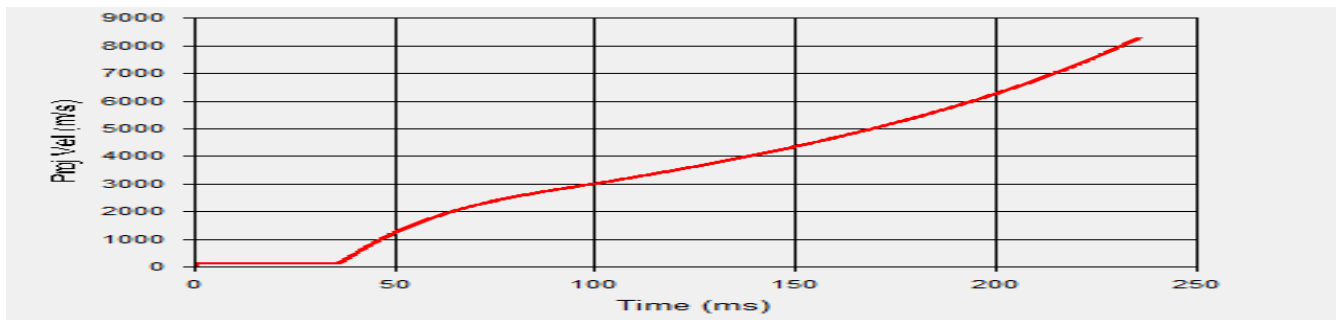


Fig3. Time (s) Vs. Projectile Velocity

The main objective of the paper is to reduce acceleration loads on the projectile which is also achieved by the current design from the results of the simulation and the graph is shown below in fig. 4

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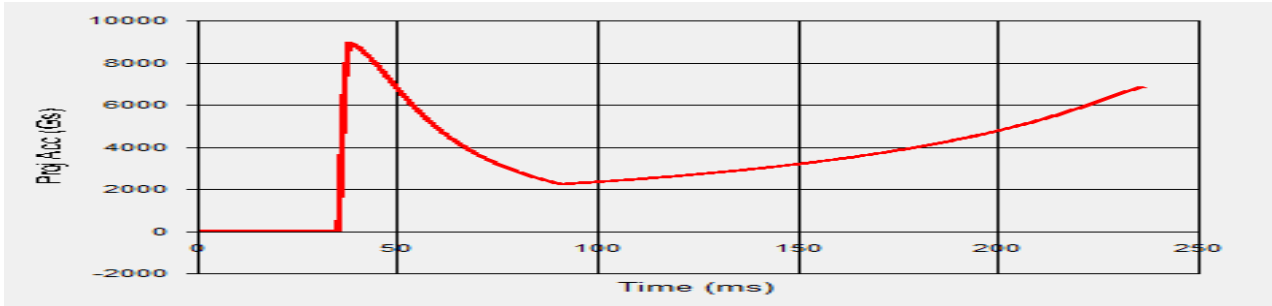


Fig. 4. Time (s) Vs Projectile Acceleration (G's).

The barrel is initially fed with the high temperature gas (hydrogen) to fully pressurize the system before launching. The barrel temperature is then refreshed with pairs of injectors which also has the temperature gas but as more energy was lost to the walls as it approaches the muzzle, the barrel temperature goes up and down which is shown in the graph shown below in fig 5.

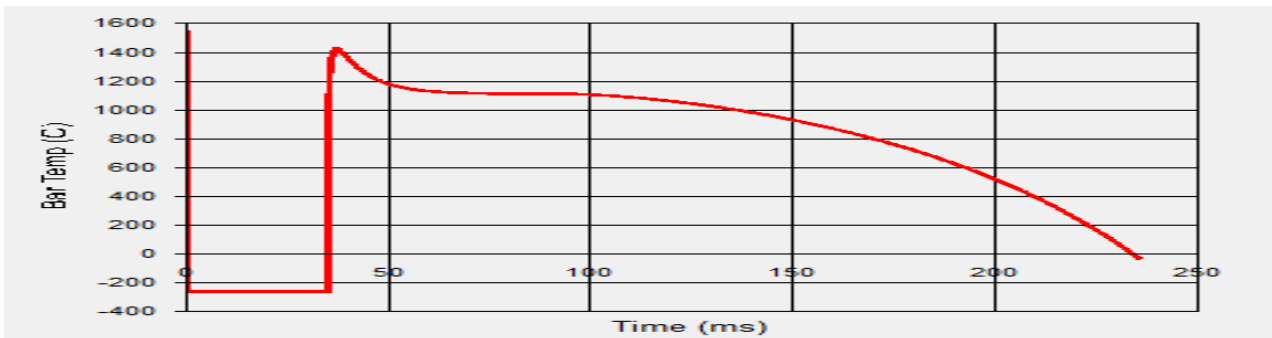


Fig 5. Time(s) Vs. Barrel temperature (°C)

The barrel pressure is said to increase then decrease and then increase, and goes on decreasing as it approaches the muzzle as the gas behind each stage of injector is said to be recovered by the fast acting shutter valves. The values are shown in fig 6.

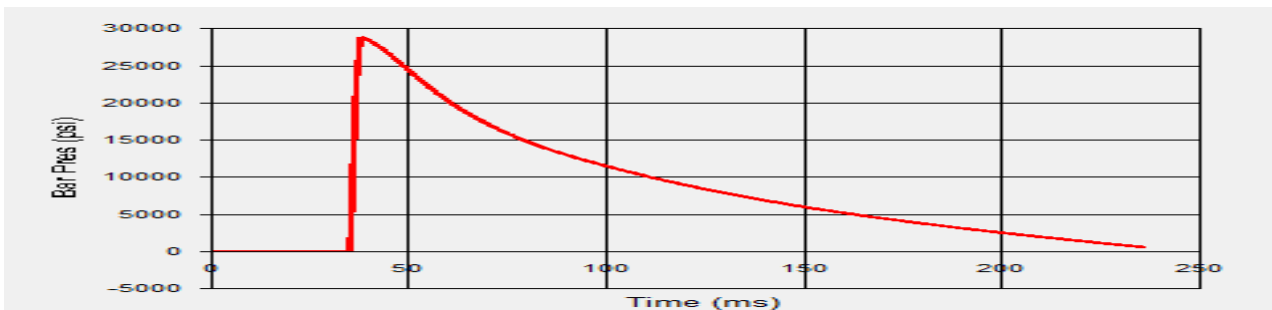


Fig 6. Time Vs Barrel pressure (psi)

Once again looking at the projectile acceleration and comparing it with the projectile position gives us a curve as given below in the fig. 7. The projectile acceleration is said to small rather than steep rise seen in breech fed guns. The accelerations show that the sensitive payloads which could withstand only 10's of thousands of G loads could be easily

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launched without any hassle.

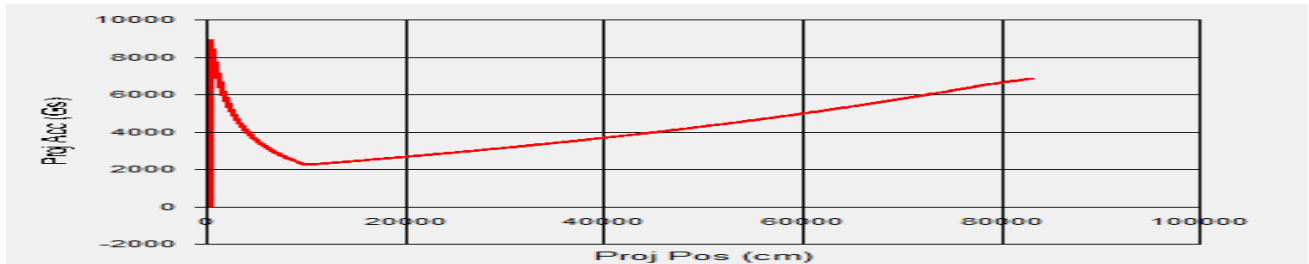


Fig.7. Projectile Position (cm) Vs Projectile Acceleration (G's).

V. BALLISTICS CALCULATION

From the results and the graphs obtained we can think that the payload gets into the orbit, but there's another drawback in the name of aerodynamic drag and the gravitational pull. These factors tend to pull back the payload or anything back to earth. If the trajectory of the projectile is calculated, it can reach an apogee of 58.465(km) after which it starts to decelerate. But in our design we are having a solid rocket motor, which can act like an apogee kick motor to further to increase the velocity and to sustain it until it escapes the dense layer of the atmosphere and enter into the orbit. Thus the design is safer for the trans atmospheric flight.

VI. CONCLUSION

An optimized design based on the distributed injection technique for the light gas gun is made for achieving the orbital velocity required to reach Low Earth Orbit. As a suggestion, the atmospheric drag can be further decreased by improving the projectile design and to incorporate techniques such as super cavitation for the projectile by some means like Magneto Plasma Dynamics and to improve the payload mass fractions by improving the density of the projectile with an optimized geometry.

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