KSC-13597

The Feasibility of Railgun Horizontal-Launch Assist

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Railguns typically operate for a few milliseconds, supplying thousands of G's of acceleration to a small projectile, resulting in exceptional speeds. This paper argues through analysis and experiment, that this "standard" technology can be modified to provide 2-3 G's acceleration to a relatively heavy launch vehicle for a time period exceeding several seconds, yielding a launch assist velocity in excess of Mach 1. The key insight here is that an efficient rail gun operates at a speed approximately given by the system resistance divided by the inductance gradient, which can be tailored because recent MOSFET and ultra-capacitor advances allow very low total power supply resistances with high capacitance and augmented railgun architectures provide a scalable inductance gradient. Consequently, it should now be possible to construct a horizontal launch assist system utilizing railgun based architecture.

***Index Terms*—Electromagnetic Launching, Railguns, Linear Motor, Supercapacitors**

I. INTRODUCTION

NASA studies have argued that next generation launch systems, composed of an air breathing hypersonic vehicle launched off of a high speed rail, could substantially reduce the cost of placing payload into earth orbit [1]-[4]. Recent discussions have concluded that advantages in airframe weight, engine type, and engine scale could be realized if this vehicle were launched well past Mach 1, preferably in the Mach 1.5 to Mach 2 range [5]. Yet, to date, most studies and prototype launch assist systems have proposed using linear synchronous motors [2] or linear induction motors [6] neither of which, to this author's knowledge, have been demonstrated at speeds above Mach 1.

An alternative motor technology that might provide a supersonic launch assist capability is a modified railgun system. Railguns have routinely launched small projectiles at velocities in excess of Mach 6 [7], so the desired speeds are achievable. Also, the fundamental design is based on rails that would be less expensive than the coils required by other linear motors. But, typical railguns launch their projectiles in millisecond time scales whereas a launch assist system might require 20 seconds or more to reach launch speed (500 m/sec launch speed at 3 G's acceleration). Also, even a prototype hypersonic vehicle plus sled combination might weigh 1000 kg, far more than the typical projectiles used in rail guns. And finally, rail guns operate most efficiently at very high speeds and it needs to be determined if a lower speed version, operating in the 50-500 m/sec range, can be designed with reasonable performance.

This paper will begin by developing a railgun model to provide expressions from which efficiency and performance estimates can be made. Then, a demonstration system will be described, showing partial system feasibility along with estimated values for the model. The analysis section uses these estimated values, along with the model expressions, to develop a proposed first stage for a rail launcher. The conclusion section discusses future work.

II. RAILGUN MODEL

Railgun theoretical models have been previously published [8], [9] in a variety of forms but we have chosen to develop our own model for three reasons. First, due to the very rapid nature of projectile launch, effects such as friction and ohmic heating are usually neglected in the published literature, but in our application these are important and must be included. Second, much of the literature deals with constant current power supplies, whereas our system is better described using a constant voltage supply. The distinction is important since the total system resistance plays an important role in the performance. And third, in order to efficiently operate the system at relatively low speeds, an augmented railgun design is needed, as shown in Figure 1, and these are not typically modeled (though [8] and [10] do address these). Multiple passes along the rails and sled provide an increased magnetic field for a given current and also result in a larger inductance gradient, improving the performance of the system at lower velocities as described below.

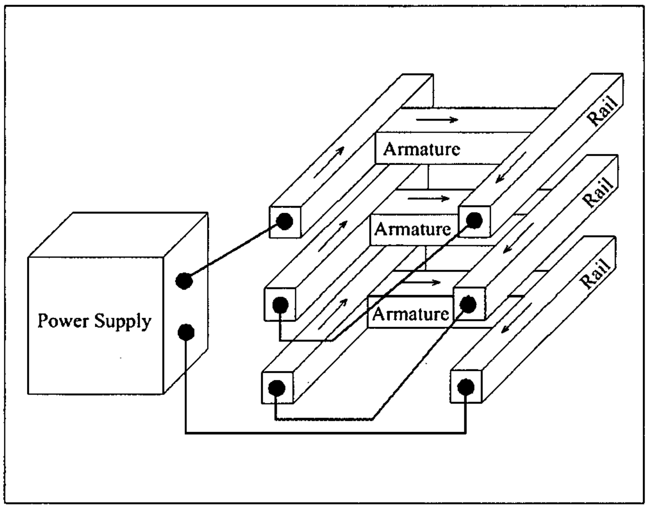

Figure 1. An augmented railgun schematic showing three sets of armatures and rails. The three armatures would be tied together to form a sled for a launch assist system.

The Lorentz Force Law provides an expression for the force on the sled;

$$F(t) = nw_s i(t)B(t)\,, \tag{1}$$

where w_s is the width of the sled, $i(t)$, is the current, $B(t)$, is the magnetic induction, and n is the number of loops, or passes that the current makes, in the augmented rail system. It has been assumed that the magnetic induction has been averaged spatially so that it is only a function of time. The Faraday Induction Law then provides an expression for the total emf across the sled,

$$\begin{aligned} V_e(t) &= -n\frac{\partial}{\partial t}(B(t)A(t)) \\ &= -nw_s x(t)B'(t) - nw_s B(t)x'(t) \end{aligned}\,, \tag{2}$$

where the area, $A(t) = w_s x(t)$, is over a single loop and where $x(t)$ is the position of the sled on the track as a function of time. Newton's force law relates the force on the sled to its acceleration after subtracting friction, F_f, i.e.

$$F(t) = m_s x''(t) + F_f\,, \tag{3}$$

where m_s is the mass of the sled.

Ohm's Law states that

$$V(t) = i(t)R + L_0 i'(t) - V_e(t)\,, \tag{4}$$

where $V(t)$ is the applied voltage, L_0 is the induction of the total system, including the power supply, before the sled starts moving, and R is the total system resistance. The magnetic induction is proportional to the current, so set them equal with a proportionality constant, L_g, such that

$$B(t) = L_g i(t)/(nw_s)\,. \tag{5}$$

Combining equations (1) through (5) to eliminate the force, $F(t)$, the magnetic induction, $B(t)$, and the emf, $V_e(t)$, yields two coupled differential equations with two unknown functions, the position of the sled, $x(t)$ and the current $i(t)$.

$$\begin{aligned} &L_g i(t)^2 = m_s x''(t) + F_f \\ &V(t) = (L_0 + L_g x(t))i'(t) + (L_g x'(t) + R)i(t) \end{aligned} \tag{6}$$

Equation (6) can be solved numerically to find the current and position functions and from these the other functions can be determined.

Recall that the power delivered to the system is given by the voltage times the current. Using the two expressions in (6) to express this product yields the power expression

$$\begin{aligned} V(t)i(t) = \;& (L_0 + L_g x(t))i(t)i'(t) + \\ & m_s x'(t)x''(t) + x'(t)F_f + Ri(t)^2 \end{aligned}\,. \tag{7}$$

The first term describes the energy being stored in inductance, both static and time varying (L_g is seen to correspond to an inductance per unit length of the track). The second term shows the mechanical energy being delivered to the sled, and the final two terms describe the power required to overcome frictional and Joule heating, respectively. Integrating this expression then provides total energy values from which the railgun efficiency, total mechanical energy divided by total electrical energy, can be found.

If the friction and the inductive (i.e. $i'(t)$) terms can be neglected and if we let the applied voltage be constant, then insight into the mechanical power delivery to the sled, $m_s x'(t)x''(t)$ can be obtained. Equation (7) above becomes

$$Vi(t) - Ri(t)^2 = m_s x'(t)x''(t)\,. \tag{8}$$

By taking the derivative of this and setting it equal to zero, it is found that the maximum power delivery to the sled occurs when the current drops to a value of $V/(2R)$. Then using simplified versions of (6) and (2) it can be shown that this corresponds to a sled velocity of R/L_g and an emf of $V/2$. This is not unexpected. Typical motors show peak power delivery when the emf is half the applied voltage. Now, a typical rail gun might have an L_g value of 0.4 microHenries/meter and a resistance of 4 mΩ, yielding an approximate optimal velocity of 10 km/sec. This result is only an approximation, but it is clear that a launch assist system will require larger inductances and smaller resistances than this in order to operate efficiently in the 10-500 m/sec range.

III. EXPERIMENTAL SYSTEM AND RESULTS

There are three goals of the experimental effort; demonstrate that a multi-second power supply for a rail gun is feasible, work towards a design that would operate efficiently for velocities between 10 m/sec and 500 m/sec,, and hopefully obtain ranges of values for the parameters shown in (6) that could lead to a feasible launch assist design.

The multi-second power supply requirement can be met by the use of ultra-capacitors [11]. Maxwell Technologies supplies 3000 Farad capacitors that can be charged to 2.7 volts and have an equivalent series resistance (ESR) of 0.24 mΩ. Maxwell Technologies also supplies kits allowing these capacitors to be configured in series allowing higher voltage operation. We chose to use 24 of these 3000 Farad capacitors—3 banks of 8—to achieve a 1125 Farad, 21.6 volt energy storage system (0.26 MJ capacity). The measured total ESR for this 24 capacitor configuration is only one milliOhm including cabling (See Figure 2). Such a system can supply current for several seconds into a load of a few milliOhms, so the desired time constant is possible, though it still needs to be determined if the current being supplied will be adequate.

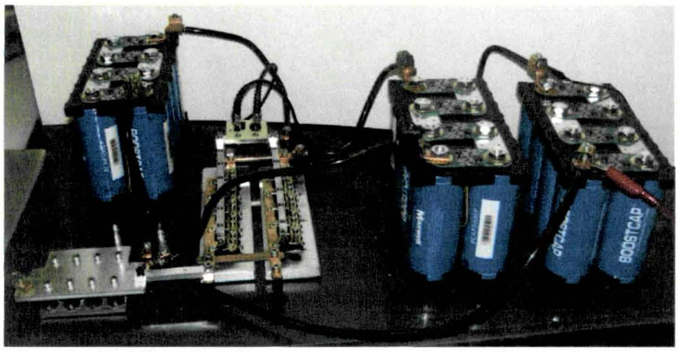

Figure 2. This is the power supply used to drive the augmented railgun. It consists of an 1125 Farad capacitor bank that can be charged to 21.6 volts with a bank of ten low-impedance MOSFETs, fly-back diodes, and transient voltage surge protection for the MOSFETs.

One advantage of this capacitor configuration is that it operates at low voltage and allows MOSFETs to be used as switches. Fortuitously, during this effort the IXYS Power MOSFET IXFN520N075T2 became available, with only 1.9 mΩ resistance (at 25 C, 4 mΩ at 175 C) and capable of handling 500 Amps when switched on for less than 0.1 seconds. Ten of these were installed in parallel with a MOSFET driver to achieve a switch capable of handling 5000 Amps for up to 0.1 seconds. Longer times can be reached by adding more MOSFETs or by using a different device, such as the International Rectifier HEXFET IRF1324S-7PP.

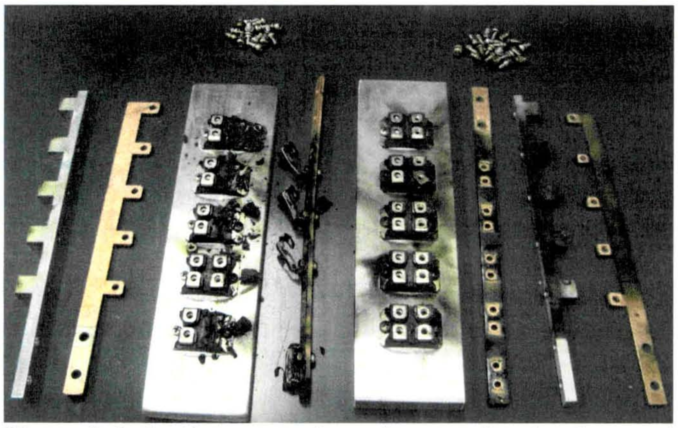

Figure 3. Inductive surges from the capacitor bank caused all ten MOSFETs to fail destructively. Transient Voltage Suppressor (TVS) diodes were used to prevent this from occurring again.

Several power fly-back diodes were installed to absorb inductive surges from the augmented rail, but this proved to be insufficient. Unknown to us there was significant induction in the capacitor bank causing the entire rail and diode assembly to reach the breakdown voltage of the MOSFETs each time the system was fired, eventually destroying the entire MOSFET bank (see Figure 3). To prevent a reoccurrence we installed ten 15 kW, 24 volt, Transient Voltage Suppressors (TVS) (Littelfuse 15KPA24CA) across the ten MOSFETs.

The power supply has a total internal resistance of only 2 mΩ (one from the capacitor bank and one from the MOSFET bank and cabling), and can supply up to 5000 Amps (limited by the MOSFETs) with a maximum voltage of 21.6 volts (limited by the capacitor bank) in 0.1 second pulses. This is substantially less current than typical railguns use, but proved to be adequate for the augmented railgun design used in this demonstration. As mentioned in section II, by designing a railgun with multiple loops, the inductance goes up substantially (as the number of loops squared) and so does the force delivered for a given current. Our demonstration railgun has three isolated pairs of aluminum rails with three corresponding, conductive, aluminum sleds as shown in Figure 4. The three sleds weighed (total) 0.32 kg and the kinetic frictional force (measured by pulling them down the track) was 13 Newtons. A 3 inch diameter, ¼ inch thick rare earth magnet was installed under the sled starting location to provide a kick-start to the sleds, helping to overcome static friction and minimize welding.

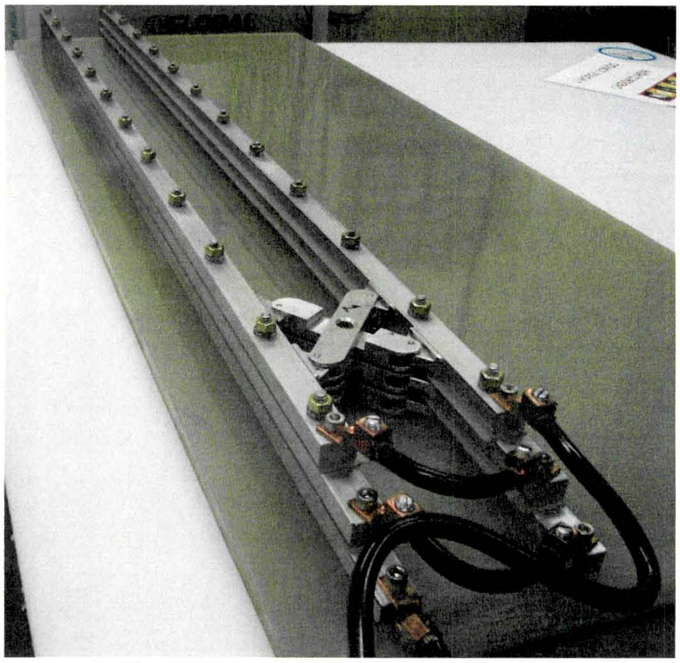

Figure 4. The augmented railgun consists of three isolated pairs of aluminum rails connected as shown to provide current across the three-tier sled. Each sled is spring loaded with pads on axels to ensure solid contact.

This system was fired with 0.1 second pulses on a variety of occasions and performed well. For example, on one test a 3900 Amp (average) pulse was sent through the rail and the sled accelerated (as determined from camera images) at 12 G's. This corresponds to 39 Newtons of acceleration force, or 52 Newtons total including that needed to overcome friction. Calculations based on an ideal rail geometry predict 58 Newtons, in reasonable agreement with that seen. The measured resistance of the rail and sled configuration varied with the amount of damage that accumulated on the pads and rail surface, but a typical resistance was 2 mΩ, i.e. the total system resistance was 4 mΩ, 2 mΩ from the power supply and 2 mΩ from the rail and sled.

The time constant of the system is over 4 seconds (1125 Farads, 0.004 Ohms), indicating that substantial thrust could be generated for more than 1 second, potentially accelerating the sleds for tens of meters to a moderately high velocity. This shows that a larger scale system, capable of accelerating a vehicle for several seconds, may be feasible, meeting the first goal of the experimental work. In addition, the inductance per unit length, L_g, is about 4.6 microHenries and the total resistance is 4 mΩ, so the optimal speed for this demonstration track is approximately 870 m/second, which is still too fast, but indicates that a lower optimal speed may be possible by further reduction of the resistance and adding more loops to the track, supporting the second goal listed at the start of this section. The third goal has also been met since parameter values for a full scale system can now be approximated.

IV. ANALYSIS

In this section a railgun design will be proposed with parameters based on insight from the above discussion. The goal is to show that a full scale launch assist system based on railgun is feasible. This is not meant to be an optimized design, nor even a proposed design, but only an argument that this technology development has promise and should be continued.

The hypersonic community has indicated that a future vehicle might weigh over 10,000 kilogram, could be accelerated at 3 Gs, and would be several meters in width and length. So assume four augmented rail systems, similar to the small one shown in Figure 4 but substantially larger, are laid down parallel to each other to provide a stable platform for the vehicle. Each individual rail system only needs to provide 3 G's of acceleration to 3000 kilograms (~90000 Newtons) to demonstrate feasibility. Also, each rail system will be constructed in segments—to minimize resistive loading down a track that could be several kilometers long—but at present, the details of that rail and power supply segmentation will not be discussed. Instead, the immediate question to be addressed is, "can an average of 90000 Newtons thrust be developed with a reasonable arrangement of ultra-capacitors and an augmented rail over a one second time period?" This corresponds to providing 1.3 MegaJoules of kinetic energy to the sled and vehicle.

The most important insight gained from the analysis and experimental work is that the total system resistance is a key parameter in determining performance and consequently, feasibility. It not only affects the current and thus the net force, but also strongly impacts the optimal sled speed and the system efficiency. The resistance comes from two sources, the power supply—mainly the ESR in the capacitors—and the rail itself. From the experimental work good approximations for the power supply resistance can be made, but the rail resistance is difficult to estimate. The tabletop system shown in Figure 4 has a resistance of 0.7 mΩ per loop. Scaling this system by roughly a factor of eight in width and height and by 16 in length (to 20 meters) should significantly lower the resistance. Not only are the rails larger, but the sled pads become more than a hundred times larger in area. In addition, it might be possible to distribute the capacitors down the track to reduce the rail resistance. So with this in mind the analysis will assume a resistance of only 0.07 mΩ per loop, a factor of 10 reduction from the lab bench version [12].

Another decision required before an analysis can be made is, "How many 3000 Farad capacitors can be used and in what arrangement should they be configured?" In the experimental system 24 were used, 3 parallel banks of 8 in series. It was seen that adding banks increases the capacitance and reduces the system resistance, but adding capacitors in series raises the voltage. Each 3000 Farad capacitor can store 11 kiloJoules, so 120 are required to accelerate the sled/vehicle if the system were 100% efficient and if all of the power could be accessed. Neither of these is the case, but the analysis shows that half of the power can be accessed and that 20% of that can be converted to kinetic energy during this first second, so about 1400 of the Maxwell 3000 Farad capacitors are assumed to be available.

In addition to the above parameters it was assumed that the force of friction would be 10000 Newtons, that there was 1 microHenry of static inductance, that the track has $0.5 * n^2$ microHenries/m of inductance per unit length, and each capacitor has 0.3 mΩ ESR (this is higher than stated by the vendor, but is consistent with our measurements and includes the MOSFET switching banks). Using these parameters as inputs, Equation (6) can be solved for the position and current functions, and from these velocity, acceleration, power, and energy plots can be derived. After that the free parameters can be varied to find an acceptable system configuration.

A reasonable result was obtained by configuring 1408 capacitors into 44 banks of 32 in series. This yielded a fully charged operating voltage of 86.4 volts (the same as some modules available from Maxwell Technologies) and a total capacitance of about 4000 Farads with a net ESR of 0.225 mΩ. It can then be shown that there should be at least 4 loops in track to meet the system goals. Using 5 or 6 loops does not increase the final sled/vehicle velocity appreciably, but reduces the necessary current, increasing the system efficiency. Considering the low cost of electricity it probably is not cost effective to add more loops, so 4 loops were used in the evaluation, resulting in a total system resistance of about 0.5 mΩ.

The predicted velocity after one second is 32 m/sec with the sled having moved about 20 meters down the track. This is a promising result and averages about 3 G's, but the acceleration curve (see Figure 5) is not acceptable. The acceleration exceeds 7 G's at start and then rapidly decays due to the accumulation of emf and capacitor voltage drop. This is not acceptable, but by segmenting the track and controlling the switching of the capacitor banks it should be possible to smooth this profile.

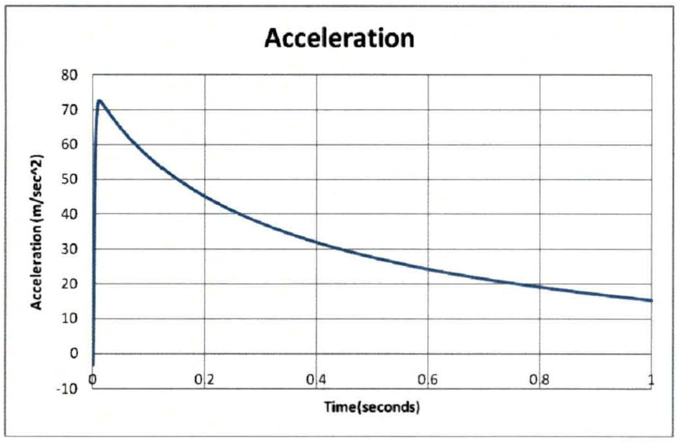

Figure 5. This is the acceleration of the sled/vehicle for the feasibility study case described in the text.

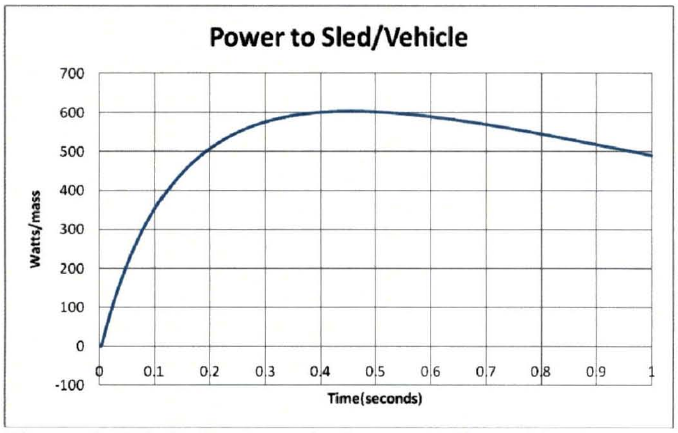

Figure 6. This is the power/unit mass delivered by the rail to the sled/vehicle versus time.

Figure 6 shows the power/unit mass delivered to the sled/vehicle for the first second. This curve peaks between four and five seconds, corresponding to a velocity of about 21 m/sec, but the optimal velocity, discussed earlier, for this track is 63 m/sec. This significant discrepancy occurs because the capacitor bank discharges substantially during this time (the RC time constant is only 2 seconds). If more capacitors were available the time constant could be lengthened and the power delivery extended.

Efficiencies will improve for sections further down the track where the velocities are higher. The capacitor banks can be rearranged to yield higher voltages in order to overcome the emf and lower time constants to correspond to the higher velocity of the sled. Microprocessor control of the MOSFETs should provide better control of the acceleration profile helping to minimize stress on the airframe.

V. CONCLUSIONS

This work has demonstrated that constructing a launch assist system using railgun technology is possible. There are significant design issues still to be addressed, but the basic architecture described above should be able to accelerate a full sized vehicle at 3 G's. In addition, MOSFET technology is advancing with new ultra-low impedance components becoming available monthly. Also, ultra-capacitor research is progressing [13], [14] with claims made of lab achievements 100 times higher than the Maxwell capacitors used in this project. With these advances, low voltage railgun, or Lorentz force, type linear motors may find applications in numerous areas, including that of hypersonic vehicle launch assist.

ACKNOWLEDGMENT

We would like to thank Curtis Ihlefeld and Stephen Simmons for helpful discussions on the power supply design. This work was supported in part by the NASA Innovative Partnerships Program.

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