

DEVELOPMENT OF A SMALL-BORE, HIGH-EFFICIENCY, HELICAL COIL ELECTROMAGNETIC LAUNCHER*

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Abstract

This investigation presents the design, development, and testing results of a small-bore helical coil electromagnetic launcher (HCEL) that is able to accelerate a 160 gram mass to 56 m/s with an efficiency of 3.3 %. The HCEL has a bore size of 15 mm, a length of 250 mm, and a projectile mass of 160 g. The measured inductance gradient of the HCEL is more than a factor of 100 times larger than a conventional railgun at 45 $\mu\text{H}/\text{m}$. The HCEL derives power from a capacitor-based PFN which typically provides 11 kA current at a charge voltage of 350 V. A numerical model of the HCEL launcher is constructed in PSpice. Theoretical and numerical predictions of launcher performance are compared with experimental measurements, including projectile velocity, projectile voltage, inductance gradient, and launcher current. The measured results are in good agreement with theoretical predictions.

I. INTRODUCTION

Helical coil electromagnetic launchers (HCEL's) have been investigated by many researchers in the past [1-3]. The basic HCEL geometry is shown in Fig. 1. The HCEL launcher geometry is attractive since it can potentially have inductance gradients many times larger than conventional or augmented railguns [4]. The HCEL will, therefore, provide more force than conventional railguns for a given current, since the propulsion force is proportional to the inductance gradient. Additionally, for a given efficiency, the large inductance gradient allows the HCEL to be scaled to smaller projectile diameters and to lower projectile velocities.

This investigation reports the results of initial tests to verify efficient (i.e., 3.3 %), high-gradient (i.e., 45 $\mu\text{H}/\text{m}$) HCEL with a small bore diameter of 15 mm. Measured projectile velocities were approximately 50 m/s. Experimental measurements show that remarkably good efficiency can be achieved at this scale. Experimental

results also show that erosion can be reduced to a manageable level. A PSpice [5] model of the HCEL was also constructed. Results show a good agreement between experimental measurements and numerical predictions. Based on these results, scaling the HCEL to larger bore diameters and lengths and to higher velocities appears practical.

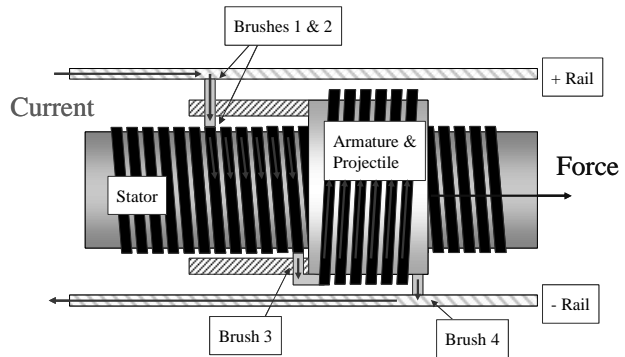


Figure 1. Basic HCEL geometry.

II. EXPERIMENTAL ARRANGEMENT

Fig. 2 is a photograph of the HCEL showing the various components and dimensions of the device. The stator is approximately 250 mm in length and is wound with 14 AWG OFHC square copper at a winding pitch of 12 threads per inch. The PFN that powers the HCEL is shown in Fig. 3 and consists of twenty 7700 μF , 450 V electrolytic capacitors. Typically, the PFN is charged to no more than 350 V and, under this condition, delivers approximately 11 kA to the launcher. A Westinghouse T9200100803D4 thyristor is used to switch power to the HCEL. A Stangenes current monitor (model SI-5009) is used to measure launcher current. Since the operating voltage of the HCEL is low, direct measurement of various voltages throughout the experiment are possible, although in-line 10X attenuators are often used to reduce voltage signal levels where needed.

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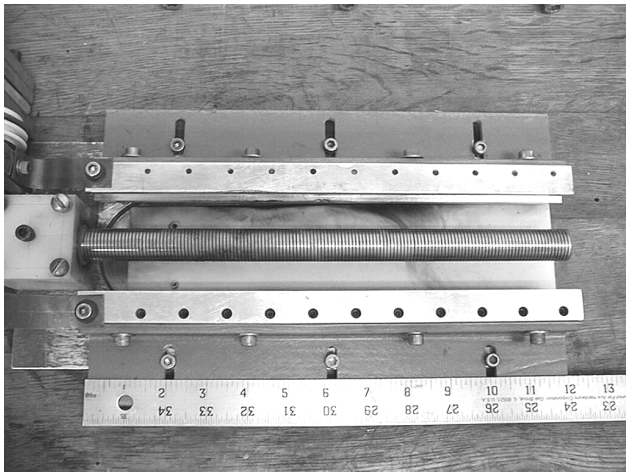


Figure 2. The experimental HCEL illustrating its components and dimensions (ruler shown is in inches).



Figure 3. The PFN and thyristor used to power the HCEL.

The HCEL projectile used in the experiment is, like the stator, wound with 14 AWG OFHC square copper. The total mass of the projectile is typically on the order of 160 grams. Table 1 is a breakdown showing the mass distribution of a typical projectile. From that table, approximately 40 % of the projectile mass is electrically related while 60 % is mechanically related.

Table 1. Projectile Mass Distribution (typical).

Component	Mass [g]
Stator brushes	37 g
Stator brush leads	10 g
Rail brushes and leads	20 g
Projectile housing	82 g
Brush tension mechanism	9 g
Total mass	158 g

A piezoelectric gauge was also constructed to provide a more direct measurement of the electromagnetic force produced in the HCEL. Fig. 4 illustrates the piezoelectric gauge constructed in this investigation. A piezoelectric material is “sandwiched” between two steel masses. The gauge is used in a “locked-rotor” test. The EM force compresses the piezoelectric material and generates a voltage signal.

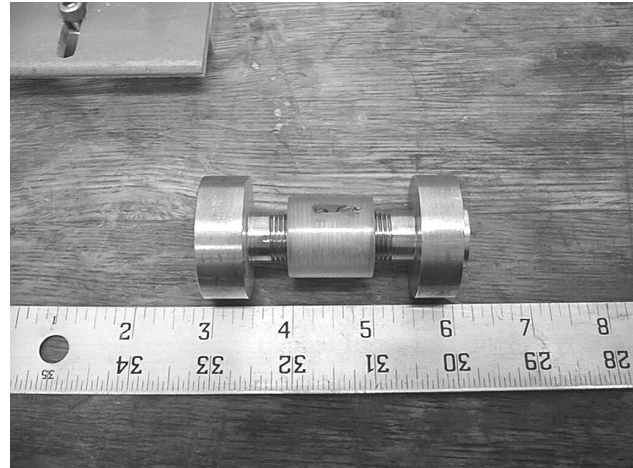


Figure 4. Piezoelectric gauge to measure EM force (ruler shown is in inches).

III. EXPERIMENTAL RESULTS

A. Inductance and Gradient

Fig. 5 illustrates a comparison between the theoretical and numerically predicted inductance values versus number of coil turns. Numerically predicted values are obtained using Grover’s tabulated methods [6]. The coil diameter is 15 mm and uses 14 AWG wire. As can be seen in that figure, there is good agreement between the two results.

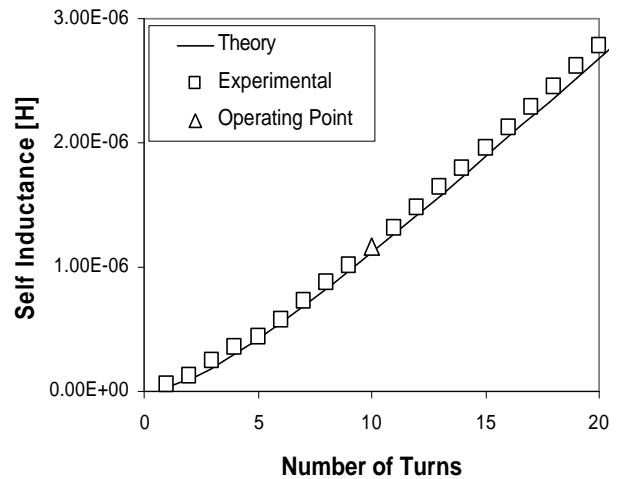


Figure 5. Theoretical and measured inductance

The HCEL inductance gradient that is of interest in this investigation is, more precisely, the gradient of the mutual inductance. Since a direct measurement of the mutual inductance is not possible, the leakage inductance is measured. For coupled coils, knowledge of the coil's individual inductances and the leakage inductance allows one to calculate the mutual inductance. Separating the coupled coils a small amount allows one to calculate the mutual inductance gradient. Figure 6 illustrates a comparison between the theoretical and numerically predicted values of leakage inductance. Again, numerically predicted values are obtained using Grover's tabulated methods [6]. Good agreement is noted to exist between these values.

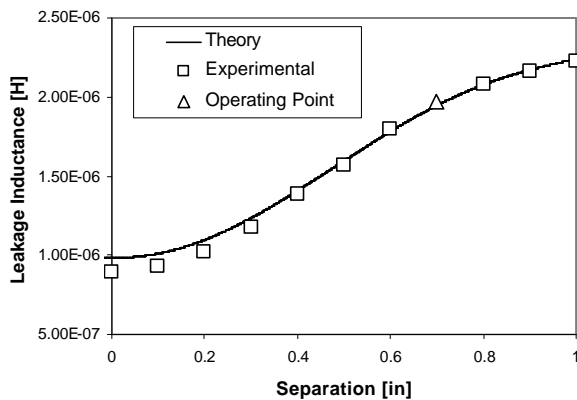


Figure 6. Theoretical and measured leakage inductance.

Based on self and leakage inductance measurements, the mutual inductance gradient was found to be approximately 45 $\mu\text{H}/\text{m}$. To the author's knowledge, this is the highest reported inductance gradient for a device of this size.

B. Electromagnetic Force

The piezoelectric (PZ) gauge was used as a more direct measurement of the electromagnetic force generated by the HCEL. Figure 7 illustrates a comparison between the theoretical and experimentally measured output of the PZ gauge. The data has typically shown that errors from 4 % to 12 % can be expected from this measurement.

C. Material Erosion

Quantitative erosion measurements were difficult for the HCEL in this investigation because the erosion was so small. The stator and rail brushes showed no significant signs of erosion in any form. Additionally, the stator endured more than 20 test firings with little erosion along the coil as well. However, at the end of the coil where the projectile would leave, there were signs of erosion due to current interruption. At interruption, the current was typically around 5 kA.

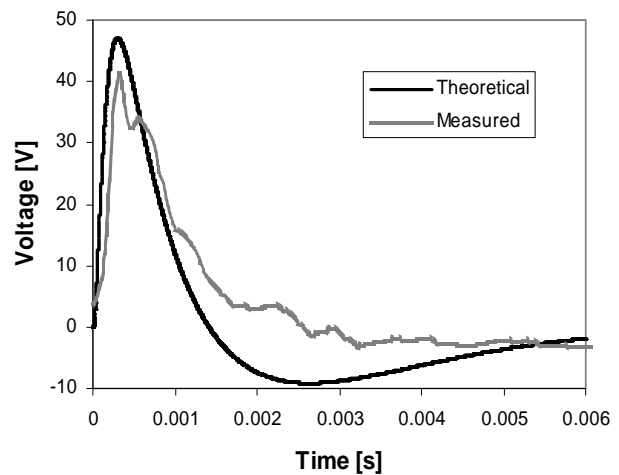


Figure 7. Theoretical and measured piezoelectric gauge output.

D. Velocity and Efficiency

Table 2 contains pertinent theoretical and measured parameters used to characterize HCEL performance. As can be seen in that table, there is good agreement between theoretical and experimental results.

Table 2. Typical HCEL Performance.

Parameter	Theoretical	Experimental
Velocity [m/s]	59.8	56.0
Mass [g]	166	166
M' [$\mu\text{H}/\text{m}$]	45	---
PFN voltage [V]	350	350
Peak current [kA]	11.3	11.3
taccel [msec]	5.1	5.7
Brush voltage [V]	9.1 (peak)	---
K.E. projectile [J]	297	258
Energy expended [J]	7768	7791
Efficiency [%]	3.8	3.3

IV. SUMMARY

This investigation has presented the theoretical and experimental results of a 15 mm diameter by 250 mm long HCEL launcher. The experimental results are in good agreement with theoretical and numerical predictions. The HCEL constructed and tested in this investigation accelerated 166 gram projectiles to 56 meters per second with an efficiency of 3.3 % using a small capacitive PFN charged to 350 V and delivering approximately 11 kA. The HCEL also showed little, or no, signs of material erosion on the stator and brushes. The HCEL is an efficient method of accelerating small caliber projectiles at low to medium velocities. With higher inductance gradient structures, the efficiency of the HCEL can be further increased. The HCEL also appears to be a practical candidate for larger caliber applications at medium to high velocity.

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