On the Design of a Coilgun as a Rapid-Fire Grenade Launcher

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***Abstract*: Two electromagnetic grenade launcher designs for armored vehicles are described. Both are based on the specifications for a conventional launcher, the Mark 19, which uses an M430 projectile. The first launcher has a muzzle velocity of 241 m/sec, as does the conventional one. For the second, the muzzle velocity was increased to 700 m/sec. Because of the large difference between the two velocities, the two designs had to be based on different energy considerations. The effects of variations of barrel parameters such as the pole pitch, the number of sections, and the thickness of the coils, are examined. For the projectile, the sleeve length parameter is varied. General guidelines are presented for the design of grenade coilguns.**

I. INTRODUCTION

We consider here the design of electromagnetic grenade launchers for use with armored vehicles. The launchers were chosen to be similar to the U.S. Army Mark 19, which uses a 3/4 lb. (0.34 kg) M430 projectile, and has a caliber of 1.636 inches (0.0416 m). We describe several coilgun launcher designs.

At the Polytechnic, since 1986, we have worked on the development of an electromagnetic launcher of the coilgun type called a Linear Induction Launcher (LIL) under contracts with SDIO/IST and BMDO/IST [1,2]. In 1993, our experimental prototype accelerated a 137-gram projectile to a muzzle velocity of 476 m/sec in a two-section, 60-cm-long barrel with an average acceleration of 19 kGee's [3]. The projectile was well-centered (fully levitated) during its transit of the barrel. The fact that this launcher performed as planned, according to design specifications, is evidence that both our design approach and our simulation code are valid.

The barrel of the LIL consists of an array of discrete coils energized by multi-phase excitation. The currents in these coils generate a magnetic traveling-wave energy packet. In turn, this induces additional currents in a conducting cylinder (sleeve) which houses the projectile. The interaction of these currents produces strong propulsion and centering forces.

The sketch of Fig. 1 suggests more clearly how the launcher is constructed and the mechanism by which the projectile is propelled. Currents in the drive coils, indicated by large arrows, establish a magnetic field, represented by the outer set of $N-S$ poles, which moves to the right at a speed proportional to the frequency of the current oscillations. These currents induce a second set of currents (smaller arrows) in the sleeve, which in turn establishes an inner set of N - S poles. This set of projectile current-generated poles is displaced a short distance to the right of the set of barrel poles. Since like magnetic poles repel, and unlike poles attract, the projectile moves to the right. In addition, inward directed forces suspend, or center, the projectile within the barrel.

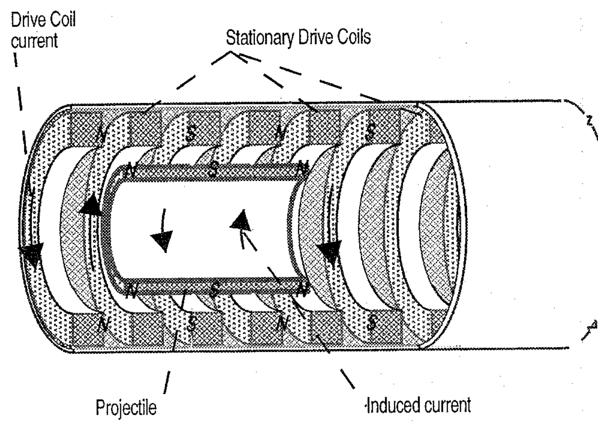

Fig. 1: Construction of the linear induction launcher (LIL)

Here, in this paper, two different launchers are considered. In the first, the muzzle velocity of the projectile is 241 m/sec, as in the conventional one. In the second, the muzzle velocity has been increased to 700 m/sec. Because of this large difference in velocity, the energy considerations upon which the two designs are based had to be different. In the low velocity, and hence low-energy, launcher, the barrel consists of a single section. This limits the efficiency. In a first design, a short pole pitch equal to half the length of the sleeve is chosen. In a second design, the length of the pole pitch is increased by a factor of four, to twice the length of the sleeve.

In the high-energy launcher, the barrel consists of three sections energized at increasing frequency, so that the speed of the electromagnetic wave (the synchronous speed v_s) is only slightly higher than the

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velocity of the projectile. The resulting small slip of the latter causes the losses in the sleeve to be low. Also, the pole pitch is made equal to twice the length of the sleeve [4].

The projectile is inserted at the breech; then, it is picked up and accelerated to the required velocity by the magnetic traveling wave. The launch rate is limited mainly by the speed of the mechanism which feeds the projectiles into the barrel.

Each section of the grenade launcher is energized by a separate flywheel motor/generator set (Fig. 2). Prior to a shot burst, the flywheel energy store is "charged" by bringing it up to full speed, with the synchronous machine operating as a motor fed by an adjustable frequency supply. During a shot burst the flywheel kinetic energy is "discharged," with the synchronous machine operating as a generator.

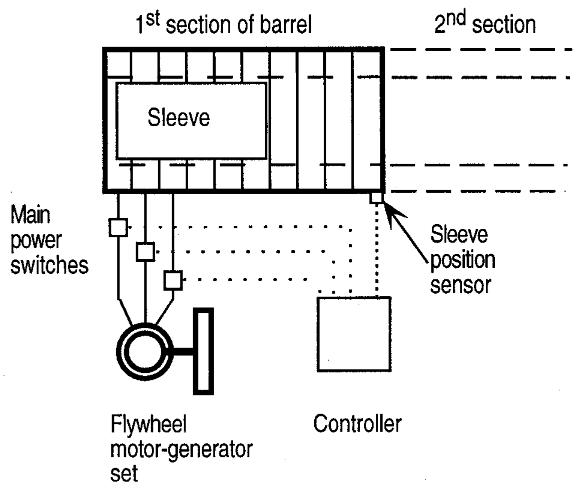

Fig. 2: One-section schematic of the grenade launcher system

The control of the main power switches (Fig. 2) is a function of the sleeve position, and it is accomplished by the Controller. A firing scheme was devised to allow operation of separate generators in each section [5]. The timing of the energization of a section has a significant effect on the performance of the launcher. Either a pre-set time delay, or alternatively the initial position of the sleeve, can be used to set the time when to energize the next section, in order to achieve the best performance. In the design stage, this is done by computer simulation.

Designs with different thicknesses of the barrel coils are compared. The effect of lengthening the sleeve is also considered. Only very preliminary designs are presented and no attempt was made at optimization. This was done purposely, in order to accentuate the differences in performance. The main dimensions of the launcher are determined using a closed-form method of steady-state analysis previously reported [6]. The force and velocity profiles are calculated, taking into account transient phenomena by computer simulation.

The designs for the low-energy launcher are presented in the next section, and those for the high-energy launcher in the third section. The last section contains conclusions, and suggestions for better designs. A preliminary design for the flywheel motor/generator set to energize the launcher is included as Appendix A.

II. DESIGN OF THE LOW-ENERGY LAUNCHER

Design parameters, based on the specifications of the Mark 19 launcher, follow:

Muzzle velocity = v_m = 241 m/sec.
M430 projectile mass = m = 3/4 lb. = 0.34 kg.
Caliber = 1.636 in. = 0.0416 m.
Barrel length = l_b = 16.26 in. = 0.413 m.
Kinetic energy = E_{kin} = 9.87 kJ.
Rate of fire: 325 to 375 per min.

Assuming that the projectile has a diameter D = 0.040 m, and an average density $\xi_{pr} = 5 \times 10^3$ kg/m^3, we get a projectile (and sleeve) length

$$l_s = \frac{m}{\frac{\pi D^2}{4} \cdot \xi_{pr}} = 0.0541 \text{ m.}$$

For a first design, we choose the pole pitch to be $\tau = 0.5 l_s = 0.027$ m. Since the barrel length must equal an even number of pole pitches, we increase the barrel length to 0.432 m to get exactly 16τ. The average value of the propelling force is then

$$<F> = \frac{E_{kin}}{l_b} = 2.28 \times 10^4 \text{ N}$$

corresponding to an average acceleration

$$<a> = \frac{1}{2} \cdot \frac{v_m{}^2}{l_b} = 6.72 \times 10^4 \text{ m/sec}^2\text{; or } 6.85 \times 10^3 \text{ Gee's}$$

The average force density, calculated by dividing the average force $< F >$ by the sleeve surface area $l_s \pi \cdot D$, is found to be $< f_s > = 3.35 \times 10^6$ Pa. It is noted that, if $< F >$ were to act on the rear of the projectile, as in a conventional cannon, then the force density would be 1.814×10^7 N/m^2, or 5.4 times greater.

Next, we calculate the efficiency, which we define as "kinetic energy" divided by "kinetic energy + i^2R losses in the barrel and sleeve". If we assume a synchronous speed of v_s = 250 m/sec; a sleeve thickness a_s = 0.005 m; an aluminum sleeve conductivity $\gamma = 2.7 \times 10^7$ S/m; and a barrel coil thickness a_b = 0.01 m, then the efficiency is only 6% ([6], and Appendix B).

In general, v_s is chosen to be slightly higher than the specified muzzle velocity. This leads to lower slip, lower losses, and higher efficiency. Exactly how these quantities are affected by the choice of v_s is revealed by simulation.

For a second design, we keep the dimensions the same, and the parameter values the same, but we relax the condition that $\tau = 0.5\ l_s$; instead, we select $\tau = 2\ l_s$ = 0.1 m. The result is that the efficiency is tripled to 18%. The reason is that, with a short pole pitch, very little magnetic field penetrates from the barrel into the sleeve, so that high excitation (magnetizing) currents are needed in order to generate the specified propelling force.

This very large magnetizing current is the main cause for the low efficiency of the first design. In the second design, the longer pole pitch results in a greater penetration of the magnetic field into the sleeve, in a corresponding reduction of the magnetizing currents, and in lower losses in the coils of the barrel. The higher efficiency, however, comes at a price, because a sleeve shorter than twice the length of the pole pitch is exposed once to the peak and once to the minimum of the electromagnetic wave amplitude, resulting in fluctuations in the profile of the propelling force vs. time.

For additional insight, re-consider the simplest case, that of the first design, in which the spacial period of the inner-directed, barrel-produced magnetic field, 2τ, also equals the length of the sleeve. In the sleeve, there flow induced circumferential currents, whose amplitudes per unit length vary along its length, but with the same spacial period, 2τ. Ideally, these two distributions travel at the same speed along the barrel; i.e., are at rest with respect to one another. Thus, even though these distributions are seen by the sleeve to move forward "slowly", at slip speed, the total force $< F >$ acting on the sleeve remains constant. (At any given location on the sleeve, the local propulsive force "slowly" fluctuates, at twice the slip frequency.) Also, since the longitudinal force per unit length varies along the sleeve, there exist longitudinal compressive and elongative stresses along the sleeve, which also vary at twice the slip frequency. As for the inward-directed centering forces, the total force (per unit of circumference) is constant, but its distribution along the sleeve also varies in the same way as do the other force distributions.

III. DESIGN OF THE HIGH-ENERGY LAUNCHER

As was already mentioned, the barrel of this launcher is divided into three sections in order to keep the value of the slip (and hence the losses) low, with consequent improvement in the efficiency. The lower losses also keep the temperature rise of the sleeve within allowable limits. While the higher efficiency is beneficial from the system point of view, because it reduces the size and cost of the power supply, it also comes at a price. The main problem, with more than one section in the barrel, occurs at transitions between one section and the next, which is at higher frequency. If the timing of the energization of the next section is not chosen accurately, so that there is a near match between the phase of the current in the barrel with that persisting in the sleeve, the propelling force may change sign and become a braking force. Accurate timing is determined at the design stage and requires the installation of special sensors which effectuate the energization when the sleeve has reached the desired position.

The projectile dimensions for the 700 m/sec launcher are taken to be the same as for the previous one, with $l_s = 0.5\ \tau$. This raises the kinetic energy to 83.3 kJ from 9.87 kJ. Assuming that the lengths of the three sections of the barrel are l_{b1} = 0.2 m, l_{b2} = 0.4 m, and l_{b3} = 1.0 m, with a total length l_b = 1.6 m, the average propelling force becomes $< F > = 5.21 \times 10^4$ N, corresponding to an average acceleration $< a > = 1.53 \times 10^5$ m/sec^2, or 1.56×10^4 Gee's.

Considering that the average force is now more than double that of the low-energy launcher, so that higher currents are needed, the thickness of the barrel coils was doubled to 0.02 m. The length of the pole pitch was chosen to be τ = 0.1 m. The exit velocities in each section are v_1 = 247 m/sec, v_2 = 428 m/sec and v_3 = 700 m/sec and the synchronous speeds are v_{s1} = 255 m/sec, v_{s2} = 435 m/sec, and v_{s3} = 712 m/sec.

The efficiency in the first section is η_1 = 26.8%. This value must be compared with the 18% for the single-section low-energy launcher which had comparable muzzle and synchronous velocities, but double the length of the barrel and half the thickness of the coils. This, together with the doubling of the power output, accounts for the improvement in efficiency. The efficiency in the second section is η_2 = 49%. The higher efficiency is due to the higher power developed with higher power factor and with smaller currents, despite the fact that the conductivity of the aluminum sleeve has decreased from 2.7×10^7 S/m to 2×10^7 S/m because of the rise in its temperature [6].

In the third section, the conductivity of the sleeve material is further reduced to 1.26 S/m, and the efficiency is η_3 = 42%. This decrease in efficiency is caused by the larger losses due to the greater length of the section, the lower conductivity of the sleeve material and the higher current densities.

In an attempt to increase the efficiency, the thickness of the coils is now increased to 0.03 m. The resulting efficiency of the third section η_3 then becomes 44%. A thicker coil leads to lower losses, but it decreases the coupling between the barrel and the sleeve, accounting for the meager gain in efficiency. In view of this small gain in efficiency, it is doubtful that it is worthwhile to increase the thickness of the barrel coils, and therefore their weight and cost.

Next, we relax the condition that the length of the sleeve equals the presumed length of the payload. As the sleeve length is increased, its thickness is decreased, in order to keep the total weight of the projectile more or less the same. First, we consider a sleeve length equal to the pole pitch length of 0.1 m. Letting the dimensions of the various sections of the barrel be the same as in the previous case with a coil thickness of 0.02 m and a sleeve thickness of 0.002 m, the efficiencies of the three sections become η_1 = 47%, η_2 = 64% and η_3 = 60% (overall η = 59%). A comparison with those previously obtained, η_1 = 26.8%, η_2 = 49% and η_3 = 42% (overall η = 41%), shows that there is a clear advantage to increasing the sleeve length, thereby increasing the surface of interaction between the barrel and the projectile, even at the cost of increasing the sleeve resistance.

To check this conclusion, the sleeve is made still longer, equal to twice the length of the pole pitch, or 0.2 m, and its thickness is reduced to 0.00165 m. The resulting efficiencies are η_1= 44.8%, η_2= 71.3% and η_3 = 69% (overall η = 65%). As can be seen, the efficiency is decreased in the first section and is increased in the other two. Therefore, although the overall efficiency has still increased, it appears that no dramatic advantage can be gained by making the sleeve longer. It has to be noted that extending the sleeve beyond the payload may require mechanical strengthening. That adds to the total weight of the projectile.

Some additional design details are shown in Table 1, below.

The performance of the launcher was simulated using our computer code. Each phase was connected separately with the correct phase delay, chosen to eliminate the dc components of the barrel currents as much as possible [7]. The propelling force and the velocity profiles as functions of the distance traveled by the projectile are shown in Figs. 3 - 6 for the last two designs. How the force on the projectile decays as the sleeve exits one section, and how it increases as the next section is energized, is clearly evident at the distances 0.2 and 0.6 m. The jagged shape of the force is due to the end effects, because of the finite lengths of both the barrel sections and the sleeve. Although the force oscillations are very strong, the velocity profiles of Figs. 4 and 6 are relatively smooth due to the inertia of the projectile.

Table 1: Design details for high energy grenade launcher

Parameter	Symbols	Dimensions		
Barrel length	l_b	1.6 m		
Barrel ID	ID_b	0.043 m		
Barrel OD	OD_b	0.083 m		
No. of Sections		3		
Section lengths	l_{b1}, l_{b2}, l_{b3}	0.2, 0.4, 1.0 m		
Pole pitch	τ	0.1 m		
No. of phases		3		
Total no. of coils	N_c	48		
No. of coils/section	N_1, N_2, N_3	6, 12, 30		
No. of turns/coil	N_t	4		
Barrel coil width	w_c	0.033 m		
Barrel coil thickn.	a_b	0.02 m		
Sleeve OD	OD_s	0.041 m		
Sleeve length [m]		$0.5\times\tau$	τ	$2\times\tau$
Sleeve thickn. [m]	a_s	0.005	0.003	0.00165
Sleeve weight [kg]	w_s	0.076	0.0916	0.1
Payload weight	W_p	0.264 kg		
Proj. weight [kg]		0.34	0.3556	0.364
Ph. voltages [kV]	V_1	3.5	3	2.5
	V_2	8	7.1	5.6
	V_3	34.4	26	18
Proj init. pos.* [cm]	d_1	1.5	1.1	1
	d_2	−3	−4.1	−2.7
	d_3	1.5	0.7	1
Synchro. speeds	v_{s1}, v_{s2}, v_{s3}	255, 435, 712 m/sec		
Freq's $(v_s/2\tau)$	f_1, f_2, f_3	1275, 2175, 3560 Hz		

* The "initial position" is zero when the back of the projectile corresponds with the beginning of the section; it is positive when it is entirely within the section; negative when part of it is outside.

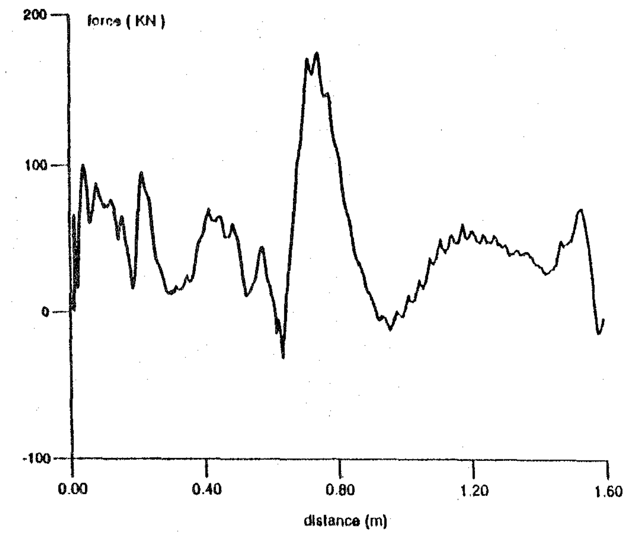

Fig. 3: Force vs. distance ($l_s = \tau = 0.1$ m)

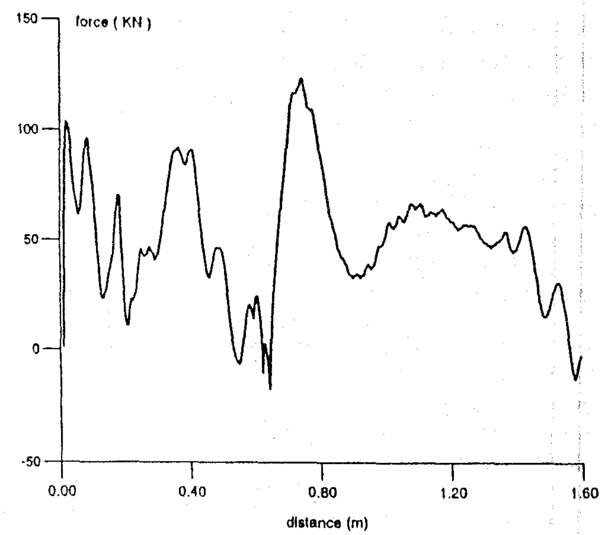

Fig. 5: Force vs. distance ($l_s = 2\tau = 0.2$ m)

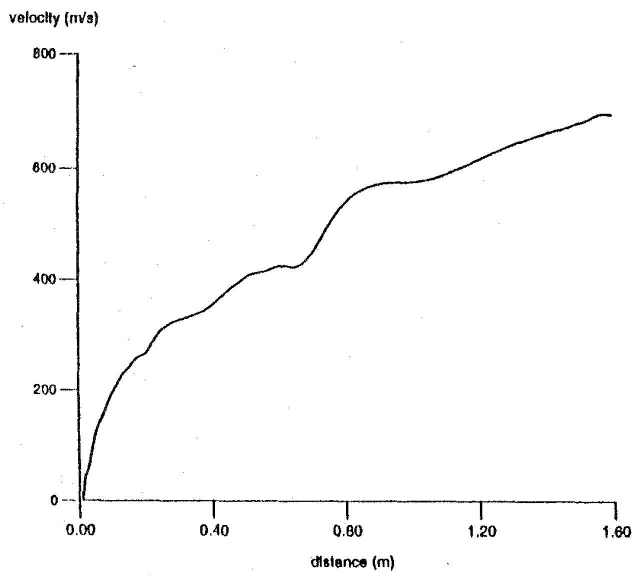

Fig. 4: Velocity vs. distance ($l_s = \tau = 0.1$ m)

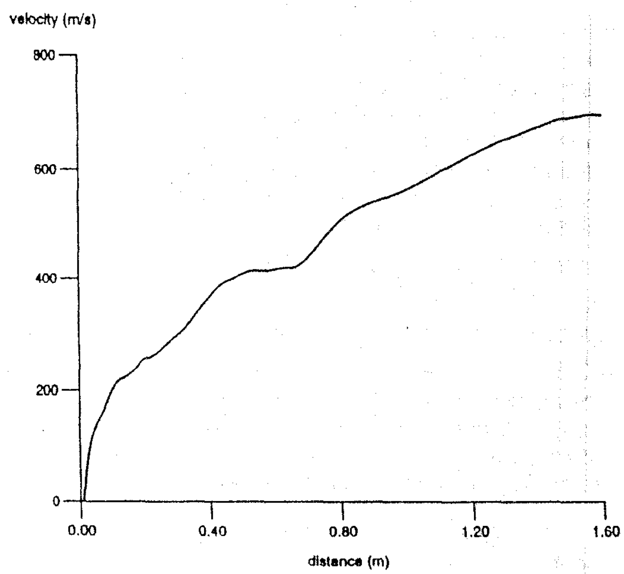

Fig. 6: Velocity vs. distance ($l_s = 2\tau = 0.2$ m)

IV. CONCLUSIONS

It appears that the pole pitch length should be made at least twice the caliber in order to obtain good coupling between the barrel coils and the sleeve. Also, it is advantageous to increase the surface of interaction between the barrel coils and the sleeve by increasing its length. However, if the increase in sleeve length comes at the expense of decreasing its thickness, in order to maintain its weight constant, a limit is reached when the sleeve length is made equal to twice the pole pitch. If the payload is made of conducting material, it may be possible to eliminate the sleeve altogether.

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Appendix A: Preliminary Design of Flywheel Motor/Generator Set

The set consists of a flywheel that also serves as the field structure of a synchronous machine. The flywheel is surrounded by the armature winding of the synchronous machine which is brought up to full speed while operating as a motor fed by an adjustable-frequency inverter. The kinetic energy thus stored is later discharged into the barrel coils with the synchronous machine operating as a generator. Key design parameters of such a power supply unit for the third section (of the last design of the launcher) are given as an example.

Specifications

Assuming 12 shots per burst, the energy/burst needed to accelerate the 0.34 kg projectiles from 428 m/sec to 700 m/sec with an efficiency η_e = 69% is 9.07 $\times 10^5$ J. Assuming that the efficiency of the generator is η_g = 90% and that only one fourth of the stored energy is utilized, the flywheel must store an energy $E_{stored} = 4.03 \times 10^6$ J.

We consider a cylindrical flywheel made of carbon fiber composite with a set of permanent magnets attached to it. The moment of inertia is

$$J = \xi \frac{\pi r^4}{2} h ,$$

where r is the radius of the flywheel, h is its height, and ξ its average density. The frequency $f = p \cdot rps$, where p is the number of pole pairs, is the same as that of the launcher current, i.e., $f = v_s/2\tau$, where v_s is the synchronous speed, and τ is the pole pitch. The stored kinetic energy is then:

$$E_{stored} = \frac{1}{2} J\omega^2 = \frac{1}{4}\xi\pi r^4 h(2\pi \cdot rps)^2 .$$

Assuming $h = kr$, the radius of the flywheel becomes

$$r = \left[\frac{E_{stored} p^2}{\pi^3 k f^2 \xi}\right]^{1/5}$$

Letting $p = 2$, $k = 1.5$, $f = 3{,}560$ Hz, and $\xi = 6{,}000$ kg/m^3, the radius of the flywheel becomes $r = 0.0855$ m and its height $h = 0.128$ m. The peripheral speed is then 956 m/s. This speed compares favorably with the 1370 m/sec speed of the Oak Ridge flywheel [A1], which holds the speed record, and with the 1600 m/sec envisaged by American Flywheel Systems, Inc. for their electromechanical batteries [A2]. The mass of the flywheel is 17.6 kg. Doubling the mass to include the stator, the total mass of the motor/generator set is then about 35 kg. The peak power output is

$$P = \frac{\langle F \rangle v_3}{\eta_e\, \eta_g} = \frac{5.21 \times 10^4 \times 700}{.69 \times .90} = 5.87 \times 10^7 \text{ W} .$$

This is the major challenge in the design of the motor/generator set, because a power density of 1.67 $\times 10^6$ W/kg is difficult to achieve, but the duration of the pulse is only a few milliseconds. Due to the very short period of operation, minimization of friction, which usually implies the need for operation in vacuum and magnetic bearings, is not a critical factor here. However, as the amount of stored energy increases, the weight and cost of the permanent magnets becomes prohibitive and other types of synchronous machines such as the homopolar inductor one [A3] must be used.

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Appendix B: Efficiency Calculation [6]

The efficiency is given by $\eta = \dfrac{E_{kin}}{E_{kin} + (P_b + P_s)T}$

where $P_b = \dfrac{K_b^2\, 2\pi\, r_b\, l_b}{2\, \gamma_{cu} a_b}$; *and* $P_s = \dfrac{K_s^2\, 2\pi\, r_s\, l_s}{2\, \gamma_{al} a_s}$

are the losses (W) in the barrel and sleeve, and T = transit time = l_b / (average velocity).

K_b(A/m) is the amplitude of the current in the barrel per unit of length, along the barrel, determined from Eqn. (8), $\langle f_s \rangle$, and Eqn. (11) of [6].

K_s (A/m) is the amplitude of the current in the sleeve per unit of length, along the sleeve, determined from K_b and Eqn. (6) of [6].

a_b ; a_s are the thicknesses of the barrel; sleeve.
r_b ; r_s are the average radii of the barrel; sleeve.
l_b ; l_s are the lengths of the barrel; sleeve.