Fast Electromagnetic Launchers

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Abstract—A general discussion of the form of the force equation for fast electromagnetic launchers, and of their energetics, is presented. It suggests that a class of launch devices whose total inductance decrease during the launch cycle has a number of attractive features, especially the potential for high electrical-to-mechanical energy conversion efficiency. Examples of specific launcher concepts in this class are given.

I. INTRODUCTION

Recent publication of the papers presented at the 1980 Conference on Electromagnetic Guns and Launchers [1] provides a sense of the broad interest in electromagnetic propulsion technology. The potential for very high velocity has been an important motivation, with potential applications in the areas of space launch, impact fusion, and weaponry. A prime technical challenge involves the achievement of compact lightweight systems. This puts a premium on overall system efficiency, to reduce the masses associated with the storage of unused energy, and with the disposition of waste heat.

Railguns have demonstrated very high velocities [2]-[4], and they are simple in concept and in practice. A respectable prime technical challenge involves the achievement of compact lightweight systems. This puts a premium on overall system efficiency, to reduce the masses associated with the storage of unused energy, and with the disposition of waste heat.

The purpose of this paper is to discuss a new class of solenoidal launchers being studied in our laboratory. The presentation begins with the form of the force equation, proceeds through a simple general formalism, and ends with examples of specific launcher concepts.

II. FORM OF THE FORCE EQUATION

Electromagnetic launch devices operate by means of the interaction forces between structures carrying electrical currents. The force equation governing such systems has the form

\[ F_q \propto \frac{\partial L}{\partial q} ; \]

(1)

where \( F_q \) is the generalized force along the configuration coordinate \( q \), \( \frac{\partial }{\partial q} \) represents a product of currents flowing in interacting circuit elements, and \( L \) is a generalized inductance term.

The force equation will in general involve sums of terms of the form shown on the right side of (1), but in simple launch devices only a single term is present. For example, the force equation in the direction \( z \) for a simple railgun is

\[ F_z = \frac{1}{2} I^2 \frac{dL}{dz} . \]

(2)

Only a single current \( I \) exists, and the inductance gradient \( dL/dz \) is well-defined. Another example is a pair of coaxial coils carrying currents \( I_1 \) and \( I_2 \), respectively, for which

\[ F_z = I_1 I_2 \frac{d\mathbb{M}}{dz} ; \]

(3)

in which \( d\mathbb{M}/dz \) is the gradient of the mutual inductance between the coils. The presence of multiple turns \( N_1 \) and \( N_2 \) on the two coils increases the force over single-turn coils by the multiplicative factor \( N_1 N_2 \), which in the convention of this paper is implicitly contained in the term \( d\mathbb{M}/dz \) (i.e., \( \mathbb{M} = N_1 N_2 M ; \) \( M \) being the normally defined mutual inductance, in the limit of perfect coupling within each coil).

It is clear from (1) that large forces require large currents and/or large inductance gradients. For simple single-turn railguns (2), \( dL/dz \) is essentially constant in \( z \) but can be no larger than the order of 0.5 \( \mu \text{H/m} \); for coaxial coils, \( dM/dz \) is a strong function of \( z \) whose maximum can be an order of magnitude larger, and \( d\mathbb{M}/dz \) can be further enhanced by a factor of order \( N_1 N_2 \). Thus coaxial machines can achieve comparable accelerations with lower currents, i.e., they can be higher impedance machines.

III. A RELUCTANCE-BASED FORMALISM

Two quantities of considerable value when discussing series electromagnetic machines are magnetic flux \( \phi \) and reluctance \( \mathcal{R} \): \( \phi \) can be considered essentially constant in the fast millisecond time frames associated with many acceleration events, and \( \mathcal{R} \) is a strictly geometrical quantity whose qualitative behavior becomes intuitively clear. While \( \mathcal{R} \) can be defined (with difficulty) in general, its behavior is best conceptualized for simple magnetic circuits as the path integral around a closed flux path,

\[ \mathcal{R} = \oint \frac{dl}{\mu A} ; \]

(4)

where \( \mu \) is magnetic permeability, and \( A \) is an effective area containing the flux. The analogy between the reluctance of a magnetic circuit and the resistance of an electrical circuit should be noted (magnetic permeability and electrical conductivity are analogues in (4)); and the addition of series and parallel reluctances follows exactly that of series and parallel resistances.

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The magnetic energy $U_m$ associated with a series electrical circuit of total inductance $L$ carrying current $I$ can be expressed as

$$U_m = \frac{1}{2} LI^2 = \frac{1}{2} \left(\frac{N^2}{\delta R}\right) I^2 = \frac{1}{2} \phi^2 \delta R;$$

where we have made the substitution $L = N^2/\delta R$ ($N$ being the number of turns, or the current linkage), and the magnetomotive force $NI$ is equal to $\phi R$ (a restatement of Ampere's circuit law).

We take the magnetic flux $\phi$ to be a constant for times short compared to the circuit's inductive decay time, which is equal to $L$ divided by the circuit resistance. The mechanical analogue of $\phi$ is the momentum of a body or system, which is a constant for times short enough to ignore the influence of external frictional forces. The force in the direction $z$ can then be expressed with the assistance of (5) as

$$F_z = -\frac{\partial U_m}{\partial z} = -\frac{1}{2} \phi^2 \frac{\partial \delta R}{\partial z}.$$  

We conclude from (6) that a series electrical circuit will experience forces tending to decrease its reluctance. Note that $\phi$ is taken to be essentially constant, $\delta R$ is a strictly geometrical quantity, and there is no explicit dependence on $N$.

Let us examine the consequences for a railgun launcher in series with a drive inductor of inductance $L_0$, initial current $I_0$, and hence initial magnetic flux $\phi = L_0 I_0$. The reluctance associated with the initial circuit containing only the drive inductor $L_0$ is simply $1/L_0$; and the reluctance associated with the railgun of rail height $h$, distance between rails $d$, and current-carrying length $x$ is approximately $h/\mu zd$. The total reluctance $\delta R$ then becomes

$$\delta R = h(L_0 h + \mu zd)^{-1} = L^{-1} = (L_0 + L_z)^{-1},$$  

where $L_0$ is defined as $\mu d/h$. From (5) and (6),

$$U_m = \frac{1}{2} \phi^2 (L_0 + L_z)^{-1},$$

and

$$F_z = \frac{1}{2} \phi^2 L_0 (L_0 + L_z)^{-2}.\quad (9)$$

It is clear from (9) that to achieve reasonably constant forces over the length of the railgun $z_{max}$, $L_0$ must exceed or be comparable to $L_z_{max}$. If they are equal (implying a four-to-one ratio of peak force to final force), we know from (8) that half the initial magnetic energy remains behind (one-fourth in $L_0$ and one-fourth in the railgun). While this result is well-known, it is discussed here as an example of a feature which is fundamental to single-turn devices: $L$ is then simply $1/\delta R$, and the force tends to increase the system's inductance.

Consider now a solenoid of cross-sectional area $A$, whose length is the varying configuration coordinate of interest; e.g., consider one end of the solenoid to be a "projectile." The reluctance is approximately $z/\mu A$. Such a device will, by (6), experience an acceleration force tending to shorten the solenoid. Note also that for this device, $F = N^2/\delta R$, which varies linearly with $z$ because $N$ is linear in $z$. Such a solenoid device will thus move toward a state of decreasing inductance, and there is no necessity for leaving behind substantial post-launch magnetic energy. Indeed, it is clear from (5) and (6) that there is no intrinsic efficiency penalty for a constant-acceleration solenoidal launcher of the type described. There is, however, an intrinsic ripple in the acceleration profile; and an inherent requirement for commutation at high velocities.

We summarize the attractive general features of solenoid launchers. They are lower current machines for a specified performance by virtue of being higher impedance devices. Higher efficiencies are possible because of decreasing system inductance during the acceleration event. In addition, because the launch energy is initially stored in the launcher itself rather than in a separate storage inductor, the total power train is simpler. In a typical sequence, a solenoid launcher is loaded with current slowly (e.g., hundreds of milliseconds) and discharged in the acceleration time (typically milliseconds). The launcher functions as its own final stage of power compression, and there is no need to transfer energy at the power levels required during the launch event.

IV. SOLENOID LAUNCHER DESIGNS

The type of thinking outlined above led to our interest in a class of solenoid launchers. The common feature in these concepts is some mechanism by which the active (current-carrying) section of a drive solenoid is shortened in the vicinity of a projectile solenoid or coil. The magnetic energy remnant in a just-shorted-out section of the drive solenoid is transferred to the active section by virtue of a solenoid's turn-to-turn coupling. Concept designs for a sequence of four such solenoid devices are briefly discussed here.

The simplest device involves a long solenoidal drive structure in series with a solenoidal projectile (see Fig. 1). Shortening of the drive solenoid is effected directly by the brush structures on board the projectile, which feed current from the drive solenoid to the projectile and then back to the return conductor. One can avoid the leakage inductance associated with the presence of the return conductor using the configuration shown in Fig. 2. A set of Bitter plates is connected to produce two interleaved solenoids, electrically equivalent but mechanically opposite. The device is known as DNA-1 because of its double helical structure. Details of the design, construction, and performance of such a device will be published elsewhere.

One can also dispose of the need for commutation by the projectile, by achieving the shortening of the active part of the drive solenoid externally. The concept design of Fig. 3 shows one way to do this using the recoil of the device. The projectile coil in this design carries a persistent current and has to have an inductive decay time which is short compared to the current-loading time of the system but long compared to the launch time. A number of such devices emerges when specific
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Fig. 1. Solenoid accelerator consisting of drive solenoid in series with short projectile solenoid, with current returned through a conducting bar (RNA-1).

Fig. 2. Double-helical solenoid accelerator (DNA-1) consisting of interconnected Bitter plates which feed a series current to the projectile coil by means of sliding contact brushes.

Fig. 3. Solenoid accelerator of DNA type with projectile carrying a persistent current, and the solenoid driver's active length shortened externally through its recoil motion (DNA-2).

Fig. 4. Compensated double solenoid accelerator concept in which the magnetic field is contained in an annular region, with either projectile-induced or recoil-activated solenoid shortening (ACT-1).

While the class of launchers discussed here is novel, two other concepts are very strongly related. The "helical railgun" launcher proposed and studied by Kolm and colleagues at M.I.T. [6] has much in common with the devices discussed here, but differs in requiring that power be supplied and transferred from an external circuit element. In addition, the discussion of turn-wiping and current multiplication in a paper by Zucker and Long [7] provides insight into the role of coupling in the efficient transfer of energy from a decoupled turn forward.

V. CONCLUSION

A rather simple analysis has allowed general insight into the relative benefits of types of fast electromagnetic launchers and has led to the consideration of a new class of solenoidal devices.

REFERENCES