Electromagnetic processes and launch efficiency of railgun systems

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***Abstract*— Detailed analysis of electromagnetic processes in railgun armatures shows that an electromagnetic drag mechanism caused by the generation of eddy currents is an ubiquitous effect in any railgun system. The results of an energy balance analysis allowed us to construct the equivalent electric circuits of railgun armatures. The acceleration in any railgun is equivalent, from an energetic point of view, to charging of a leaking capacitor.**

Simple numerical evaluations of the value of the electromagnetic drag force show that its role in the acceleration process is unavoidable for typical railgun launcher experimental conditions, although a quantitative evaluation of the drag force is difficult to make. Even discounting any known performance loss mechanism of a non-electromagnetic nature, our study gives a consistent qualitative explanation for all irreconcilable phenomena known from experiments; the saturation of attainable velocities, the degradation of plasma armatures, and the problem of high velocity sliding contact for metal armatures. Possible ways of optimizing railgun acceleration and achieving a higher velocity are discussed.

I. Introduction

The modern problem of high velocity macroparticle acceleration is supposed to be solved by future successful development of a railgun as a new type of electromagnetic launcher [1]–[6]. The best results of projectile acceleration have been obtained for plasma armature railguns [7]–[10]. Nevertheless, there have been no substantial improvements in velocity since the early eighties [10]–[13]. In fact, most reproducible velocities are essentially the same as those in the pioneering experiments of Rashleigh and Marshall [7], [14]. The physical phenomena limiting maximum attainable projectile velocities are not completely understood and still remain under discussion [14]–[17].

Jamison and Littrell [10] reported a linear decrease in momentum transfer efficiency of their plasma armature railgun experiments with increasing launch velocity. They also pointed out that it was impossible to match the entire set of experimental results over the 2.5 to 5.6 km/s velocity regime using a single set of loss parameters for ablation, shock, and viscous drag. According to their own words, "an effort to further understand this high velocity plasma armature phenomenon is, however, strongly recommended" [10]. Keefer et al. [18] could not explain the discrepancy between the ponderomotive force calculated by accepted analytical expressions and that calculated by a direct sum of $\boldsymbol{J} \times \boldsymbol{B}$ products for all elementary armature cells of a solid armature which was revealed in careful detailed 3-D simulations.

Numerous results have pointed out a variety of contradictions and have explicitly demonstrated once again the limited knowledge of railgun physics. This paper shows that there is a common physical cause which brings about all of the aforementioned paradoxes.

II. Electromagnetism of real railgun armatures

The relationship between the breech and muzzle voltage in a common railgun has the form of [19], [20]:

$$U_{br} \approx U_{muz} + L'VI + L'x\dot{I} + R'xI \tag{1}$$

where I is the discharge current, R' is the resistance of the rail pair per unit length, L' is the rail inductance gradient, x is the coordinate of the rear armature edge, and V is the armature velocity. The voltage drop on the moving armature increases from $U_f \approx U_{muz}$ at its front edge to $U_r \approx U_{br} - L'x\dot{I} - R'xI$ at the rear edge. The latter expression can be approximately represented as

$$U_r \approx U_{muz} + L'VI. \tag{2}$$

Strictly speaking, this equation is not completely correct for the rear edge of the armature, where the current is very low, but nevertheless can be used to approximate the voltage drop distribution in a moving armature which has been measured reliably in experiments [20], [21].

Even in the case in which all parts of the armature are moving with the same velocity, we should get some "back emf" distribution because of the distribution of rail magnetic fields at the armature location. So, for any closed

Manuscript received April 8, 1996.
This work was done at National Institute of Materials and Chemical Research where O. V. Fat'yanov worked as an AIST Research Fellow from February 1994 to February 1995.

loop which picks up some fraction of rail circuit magnetic flux and is fixed inside the moving armature we inevitably get nonzero vortical emf. The only reason for its appearance is the change of magnetic flux through the chosen loop. If we assume that the magnetic flux through the armature remains constant during an acceleration process, we must get the same value of back emf everywhere in the armature.

To test this assumption, let us consider two different contours as shown in Fig. 1. The first contour is formed by the power source, armature, and rails behind it. The second contour consists of the armature, rails ahead of it, and an "imaginary" emf source of the same value as the voltage drop at the front armature edge. This "imaginary" emf source is necessary to avoid any current appearance in the rails in front of the armature. The analysis of the magnetic flux change for each contour gives different values of back emf for the rear and front armature edges. These values are equal to $L'VI$ and 0 respectively. This shows that our initial assumption of a constant magnetic flux must be wrong.

In a simple railgun, the front edge of the moving armature is crossing the force lines of a magnetic field which is close to zero, while the back edge is crossing the force lines of a magnetic field of nearly maximum strength. This means that the magnitude of a magnetic field entering the armature differs from one going out; that is, we are continuously changing (decreasing) the magnetic flux through the armature during its motion. But this fact means that the railgun armature motion is analogous to the motion of any arbitrary massive conductor through a region of stationary nonuniform magnetic field, in which we inevitably induce Foucault or eddy currents so well known from any textbook of electromagnetism. As a result of the interaction between these eddy currents and the nonuniform magnetic field we get a drag force of the same electromagnetic nature as a propulsive ponderomotive force.

We believe the mechanism of railgun performance degradation identified here is exactly what is responsible for the discrepancy in the railgun force balance obtained by Jamison and Littrell [10] and Keefer et al. [18]. This hidden phenomenon is an effect of the very nature of any railgun, comparable to an electric motor with a high degree of self-excitation.

Unfortunately one cannot determine the exact value of such a drag force without a numerical solution of an essentially 3-D nonstationary problem and detailed calculations of current, magnetic field, and velocity distributions in the armature. In order to make our conclusions and their physical meaning more apparent, we describe the acquisition of kinetic energy in a railgun by means of equivalent circuits.

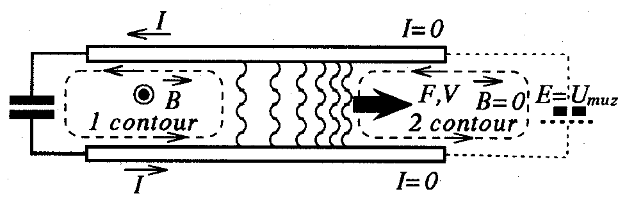

Fig. 1. Schematic of a simple railgun illustrating different back emf values at the rear and front armature edges.

III. Equivalent electrical circuits of a railgun armature

First, we consider the case not of a common railgun but its modification with an independent augmentation [22], [23]. In this case the accelerating force is:

$$F_{pm} = {}^{1}/_{2}L'I^2 + M'I_0 I \tag{3}$$

where L' is the rail inductance gradient, M' is the mutual inductance gradient between the rails and the augmentation coil, I and I_0 are the currents in rails and augmentation coil respectively. Suppose $M'I_0 \gg L'I$, (thus, the ponderomotive force $F_{pm} \approx M'I_0 I$) and let $I_0(t) = const.$ As a result $F_{pm} \propto I$ but not to I^2 as in a common railgun.

Suppose we eliminated friction and any other possible drag forces of mechanical origin. In this case the acceleration of the armature and projectile can be represented as

$$a = \frac{F_{pm}}{m} = \frac{M'I_0 I}{m} \tag{4}$$

where m is the total mass of projectile and armature assembly. For zero initial velocity we get

$$V = \int a \cdot dt = \frac{M'I_0}{m} \int I dt = \frac{M'I_0}{m} \cdot q \propto q \tag{5}$$

where q is the charge that has flowed in the rail circuit from the initial moment of acceleration. The expression for kinetic energy of the accelerated assembly

$$K = \frac{mV^2}{2} = \frac{(M'I_0)^2}{2m} \cdot q^2 \tag{6}$$

coincides, in our special case of $F \propto I$, with the expression for the energy of a charged capacitor $W = \frac{1}{2C} \cdot q^2$, where our effective "capacitance" is

$$C = \frac{m}{(M'I_0)^2} = const. \tag{7}$$

Taking into account the ohmic resistance of the armature which exists in any real conductor, we get the following very rough "lumped-parameter" equivalent electric circuit (Fig. 2).

In the case of any real railgun, we first of all deal with an essentially distributed parameter system. The existence of a negative voltage gradient in the moving railgun armature