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Amperian recoil and the efficiency of railguns

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In this paper the mechanical efficiency of the railgun is defined as the force accelerating the armature-projectile combination divided by the total electrodynamic force generated in the gun. The energy expended in a shot may then be equated to the ohmic loss plus the kinetic energy that would have been developed in the absence of mechanical losses. In this way it can be shown that the overall energy efficiency can never be greater than the square of the mechanical efficiency. Comparing calculations with experimental data makes it clear the reported disappointing performance of railguns is due to some ill-understood mechanical deficiency. A simple experiment is described which reveals buckling and distortion of the rails by recoil action. This explains the mechanical inefficiency. In relativistic electromagnetism, the recoil force should act "on the magnetic field" and absorb field-energy momentum. The Ampère–Neumann electrodynamics, on the other hand, requires the recoil forces to reside in the railheads and push the rails back toward the gun breech. Experiment confirmed the latter mechanism.

I. EFFICIENCY OF RAILGUNS

The overall energy efficiency of the railgun will be shown to be dominated by friction and similar mechanical losses rather than the Joule heat dissipated in the pulse-discharge circuit. Some fraction of the electrodynamic force F_e, applied to the armature-projectile combination, has to be given up to overcoming friction and other mechanical hinderances in the path of the armature. Only the remainder, denoted by F_a, is available for accelerating matter contained in the armature and the projectile. Let the mechanical efficiency of the railgun be defined by

$$\eta_m = F_a/F_e. \tag{1}$$

The instantaneous electrodynamic force on the railgun armature may be expressed as

$$F_e = (\mu_0/4\pi)ki^2 \text{ (N)}, \tag{2}$$

where i is the instantaneous current and k is a numerical performance index of the accelerator, which depends on geometrical factors like the rail cross section and spacing and the shape of the armature. The constant $(\mu_0/4\pi)k$ has the dimension of H/m and is the self-inductance gradient of the railgun loop in the direction of armature motion. For published railgun designs the performance index varies between $k = 3$ and approximately $k = 15$, the highest figures applying to augmented (multiturn) railguns.

If m is the mass being accelerated to the muzzle velocity v_m, the final change of momentum of this mass is given by

$$mv_m = \int F_a\, dt = \eta_m \int F_e\, dt = \eta_m 10^{-7} k \int i^2\, dt \text{ (kg m/s)}. \tag{3}$$

Over more than 95% of the length of practical railguns, the self-inductance gradient is very nearly constant. The small error due to changes in this gradient, when the armature is located close to the breech, may be ignored. The integrals of Eq. (3) have to be taken over the acceleration period. In electrical science the integral

$$A = \int i^2\, dt \text{ (A}^2\text{ s)} \tag{4}$$

is known as the action integral of a current pulse. For constant k, pulses of any shape, duration, and magnitude will produce the same momentum change provided their action integrals are the same. This makes it possible to compare the performance of railguns subjected to very different current pulses.

Restricting the analysis to metallic armatures, let an effective resistance R_e of the pulse circuit be defined such that the total Joule heat H generated in the circuit is

$$H = R_e \int i^2\, dt = R_e A \text{ (J)}. \tag{5}$$

In the absence of all mechanical losses we have $\eta_m = 1$, and the launcher would then produce the ideal projectile velocity v_i. The kinetic energies associated with v_m and v_i are

$$E_m = \tfrac{1}{2} mv_m^2, \quad E_i = \tfrac{1}{2} mv_i^2. \tag{6}$$

Hence the overall energy efficiency of the railgun is

$$\eta = E_m/(E_i + H). \tag{7}$$

On substituting Eq. (6) into (7), it can be shown that

$$\eta = \eta_m^2/\{1 + [2R_e\eta_m/(10^{-7} kv_m)]\}. \tag{8}$$

In this last formula the railgun efficiency is seen to be independent of the action integral and, therefore, the current pulse. It is also unaffected by the armature-projectile mass.

Figure 1 is a plot of the railgun efficiency versus performance index k for an accelerator of the relatively high effective resistance $R_e = 5$ mΩ and $v_m = 10$ km/s. It demonstrates the overriding influence of the mechanical efficiency. However good the electrical performance of the railgun may be, its overall energy efficiency cannot exceed η_m^2. In other

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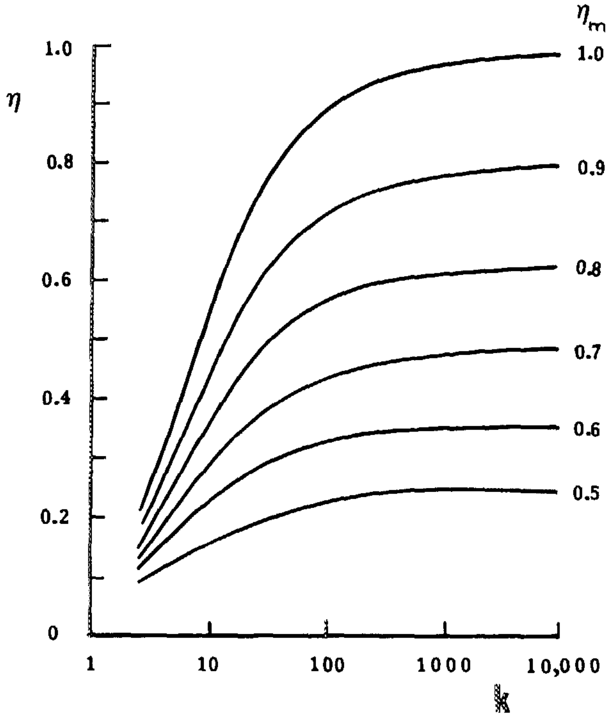

FIG. 1. Railgun efficiency graph.

words, when the mechanical efficiency is 0.5, the limiting energy efficiency is 0.25, and at least 75% of the large and costly energy storage facility are condemned to produce waste heat and wear and tear of the railgun.

Equation (2) applies to all pulsed electromagnetic accelerators with constant k, and so does Fig. 1. Railguns have the lowest performance index up to $k = 15$. Massdrivers,[1] induction accelerators,[2] and water-plasma guns[3] have the potential of raising the performance index to an upper limit of perhaps 10 000. For this reason Fig. 1 has been extrapolated to very high k values. A high index of (electrical) performance cannot eliminate the detrimental effect of friction and other mechanical losses, but it reduces the efficiency penalty due to the effective circuit resistance R_e.

Let us apply the efficiency formula (8) to data from an experimental shot with a metallic armature. Deis, Scherbarth, and Ferrentino[4] accelerated a 0.317-kg mass to a velocity of 4.2 km/s with a railgun in which $k = 5.85$ and $R_e = 0.5$ mΩ. The energy was supplied by a homopolar generator with a stored kinetic energy of 16.3 MJ. Had the gun been free of mechanical losses ($\eta_m = 1$), the overall efficiency given by Eq. (8) should have been 0.711, as compared with the measured efficiency of 0.172. It is possible that the quoted resistance was the cold resistance of the circuit instead of the effective value R_e which lies somewhere between the cold and the hot resistance. Assuming the higher resistance of $R_e = 0.75$ mΩ, the overall efficiency with no mechanical losses would drop to 0.621, which is still far higher than the observed result. From this we have to conclude that mechanical energy losses played an important role in the railgun shot reported by Deis, Scherbarth, and Ferrentino.

Equation (8) may be used to calculate the mechanical efficiency of the Deis, Scherbarth, and Ferrentino shot. For $R_e = 0.5$ mΩ and $\eta = 0.172$ it comes to $\eta_m = 0.45$. This immediately limits the overall efficiency to 0.202. From these figures the actually observed efficiency of 0.172 appears to be reasonable, indicating a satisfactory electrical performance.

In the same experiment the maximum current was $i = 2.1$ MA. Inserting this into Eq. (2) we find, for $k = 5.85$, a maximum electrodynamic force of 2.58 MN which represents 263 ton weight. Nearly half of this force may have been required to overcome mechanical resistance, including friction and eleastic and plastic deformation forces. Surely a much smaller mechanical resistance would be found if the armature were pushed through the gun barrel with a long rod. What is it then that could account for so much transient mechanical impedance during the railgun shot?

II. RELATIVISTIC RECOIL

In the numerous papers written about railguns in recent years, remarkably little has been said about the recoil mechanism. The reason for this, undoubtedly, is a sense of uncertainty with regard to currently taught relativistic electromagnetism. In an effort not to violate Newton's third law, this theory is forced to claim that vacuum can sustain large reaction forces. Clarification of this issue requires some knowledge of the historical evolution of electromagnetic theory. From 1820 until almost the year 1900, while generators, motors, transformers, and transmission lines were invented, theory was based on the old electrodynamics proposed by Ampère in France and Neumann in Germany. Like Newtonian mechanics and Coulomb's original electrostatics, this was an instantaneous action-at-a-distance theory. It was derived empirically and holds good for metallic circuits, but not for electron beams and charges convecting in vacuum and dielectric fluids. We will refer to it as the Ampère–Neumann electrodynamics of metals.[5] Field theory, as we know it today, was created by Faraday, Maxwell, Lorentz, and Einstein. After the introduction of the special theory of relativity in 1905, relativistic electromagnetic field theory completely displaced the old electrodynamics in spite of the latter's experimental infallibility.

The most important principle of modern electromagnetism is *contact action*, also known as Einstein's local action. When applied to railguns it means the force F_e experienced by the armature is literally exerted by local magnetic field pressure. It is said to arise from changes in field-energy momentum as prescribed by the Poynting vector. The reaction force to F_e, therefore, should be a force *on the field* inside the armature which decelerates and stops magnetic energy flying toward the armature at the velocity of light.

Pappas[6] was first to show by experiment that the recoil mechanism, based on field-energy momentum conservation, is fictitious. His experimental discovery was confirmed by this author.[5] All railgun experiments prove the same point. Phipps[7] recently wrote about the recoil force mechanism: "...the Lorentzian account of the location of reaction forces is so preposterous as barely to merit attempts at observational refutation."

Consider the shot reported by Deis, Scherbarth, and Ferrentino. Momentum conservation calls for

$$m v_m = m_e c, \tag{9}$$

where m_e is the equivalent electromagnetic mass striking the armature at the velocity of light c. For this shot Eq. (9) requires $m_e = 4.44$ mg. The kinetic energy carried by this mass is, according to special relativity, equal to $m_e c^2$ or 3.99×10^{11} J. This should have been supplied by the homopolar generator which, we know, stored only 16.3 MJ. It proves the relativistic concept of generating magnetic pressure is not true.[8] Sensible explanations of the recoil force, therefore, have to be based on nonlocal actions.

III. AMPERE RECOIL MECHANISM

What the Ampère–Neumann electrodynamics has to say about railgun recoil was first discussed in 1982.[9] It was then found that equal recoil forces should have their seats in the railheads, just behind the armature, and push the rails back to cause buckling. Some experimental support for the Ampere mechanism was also reported. Since then direct experimental confirmation of longitudinal rail recoil has been obtained in the Center for Electromagnetics Research of Northeastern University.[8]

Recoil rail buckling was demonstrated with the simple experiment of Fig. 2. The rails were supported on the outside by wooden beams (D) so that transverse forces on the rails could not deflect them outward. The main portions of the rails (A) consisted of 0.5-in-high, 0.05-in-thick copper strips secured to the wooden beams up to 30 cm behind the stationary copper armature (a). The last 40 cm of the rails (B) consisted of much thinner strips of the same height as the thick rails. Both aluminum and stainless steel were used for the thin rail extensions. The latter were pinned at (p) to the thick copper rails and the beams. A 0.5-in.-diam copper rod formed the armature (a) and was in light contact with the thin rails.

An 8-μF capacitor bank, charged to various voltages up to 80 kV, was discharged through the railgun setup in which the rails were spaced $d = 25$ cm apart. Current pulse amplitudes varied up to 100 kA. With sufficient current to heat the thin rail portions to within a few hundred degrees of their melting points, the strips (B) were found to deform plastically in two buckling modes. They retained their distorted shapes during cooldown for subsequent inspection and photography. The simple inward deflection of Fig. 3(a) was obtained with aluminum rails. Steel rails buckled in concertina fashion, as can be seen in Fig. 3(c). When the thin rail extensions were not perfectly aligned with the copper rails, the former would be pushed up or down by the recoil, pivoting about the pinned joints.

It is easy to perform many simple experiments of this nature to prove that the rails experience the full recoil action predicted by Ampère's force law. The enormous recoil forces of working railguns will buckle and deflect the rails in both the eleastic and plastic mode. This is likely to cause interference between projectile and rails which gives the impression of severe friction. It explains the low mechanical efficiency. After each shot the rails will spring back to almost their

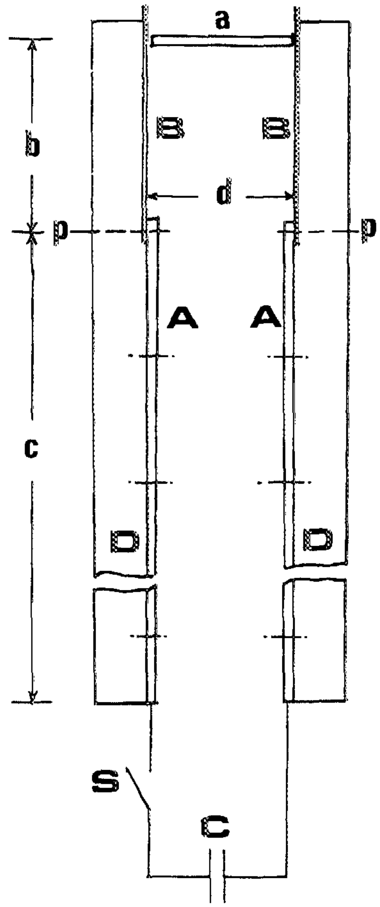

FIG. 2. Railgun recoil experiment. A, thick rails; B, thin rails; D, wooden side boards; p, anchor pins at rail joints; a, stationary armature; S, switch; C, 8 μF, 100-kV capacitor bank; $b = 30$ cm; $c = 200$ cm; $d = 25$ cm.

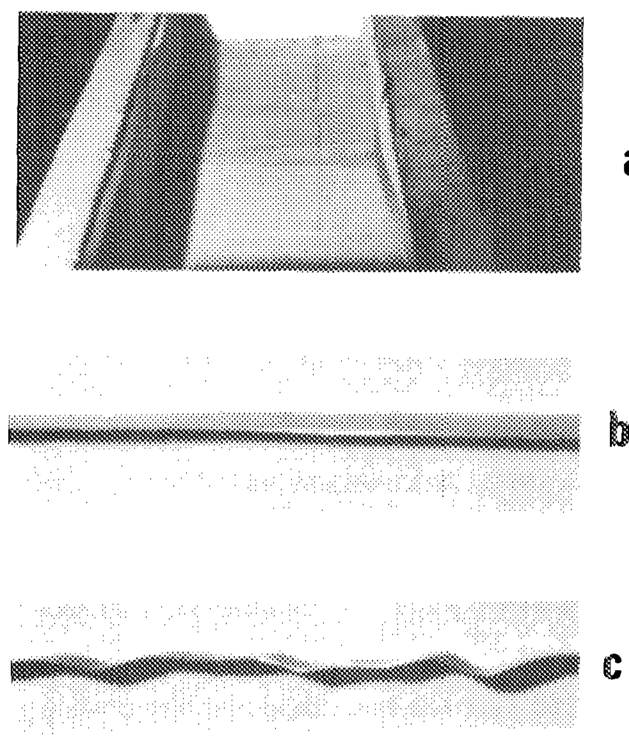

FIG. 3. Buckling of thin rails: (a) inward deflection of aluminum rail; (b) steel rail before recoil experiment; (c) steel rail after recoil experiment.

original position, leaving little evidence of the recoil problem. The permanent bowing of the copper-cadmium rails described by Bedford[10] was probably the result of recoil action. Projectile-bore interference reported by Peterson *et al.*[11] could also have been caused by Ampère recoil action.

IV. CONCLUSION

Experiments have proved that the recoil action of the railgun is not exerted on the field, but consists of a set of two equal forces located in the rails, close to the projectile, pushing the rails back. Because of the large magnitude of the recoil forces, the rails almost certainly have to deflect laterally, giving rise to mechanical interference between the rails and the projectile. This interference, which is indistinguishable from friction, is the most likely explanation of the disappointingly low efficiencies of powerful railguns.

The rail recoil action was predicted with Ampère's force law. Finite current element analysis is suitable for calculating the recoil force distribution.

ACKNOWLEDGMENT

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