RECOIL IN ELECTROMAGNETIC RAILGUNS

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Abstract - Gun designers have long accepted and understood the fact that guns experience recoil when fired, and many ingenious mechanisms have been devised to cope with the problem. But hope springs eternal, and when confronted with a revolutionary new technique for accelerating projectiles, where the accelerating mechanism may be somewhat mysterious, the gun designer hopefully asks, "Does it recoil?"; knowing in his heart that it does. The more difficult question with regard to the electromagnetic (EM) railgun is "Where and how do these recoil forces appear and can their location and distribution be controlled?" That is the topic of this paper.

BACKGROUND

When a thermodynamic gun is fired, the recoil is caused primarily by the pressure of the combustion products against the breech closure (Fig. 1). Whereas the lateral forces due to gas pressure are reacted against each other by the "hoop strength" of the gun barrel, the gas pressure acting against the breech block is uncompensated (except by friction between the projectile and bore) and pushes the gun barrel backward as the projectile is accelerated forward. An additional source of recoil is the rocket-like action of the combustion products leaving the muzzle after the projectile exits. Overall, of course, the prevailing requirement is the conservation of momentum. Because the system started initially (prior to firing) with zero net momentum (both gun and projectile at rest) the net momentum of the system must remain zero. This means of course that

$$M_{GUN}\bar{v}_{GUN} + M_{PROJ.}\bar{v}_{PROJ.} + M_{GAS}\bar{v}_{GAS} = 0,$$

so that as the projectile acquires forward momentum through the action of gas pressure on its base, the gun acquires momentum in the opposite direction through the action of gas pressure on the breech plug. We shall see that an analogous situation occurs with the railgun.

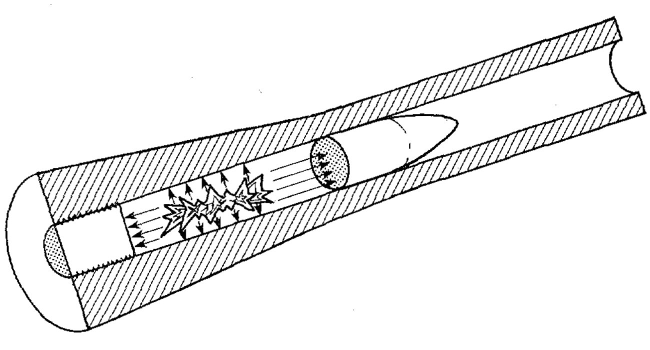

Fig. 1. Recoil in a conventional gun.

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Perhaps the simplest illustration of the forces at work in a railgun is the response of a flexible cable carrying a large current (Fig. 2). When the current is passed through the cable, the cable expands to include the largest area possible, typically a circle if not otherwise constrained. It can be envisioned that since the current flowing in the cable produces a uniform amount of flux per unit length of cable, the flux density is somewhat higher inside the circle than outside due simply to the curvature of the cable. Furthermore, application of the familiar "right hand rule" will show that the flux contributions for various sections are additive (in the same direction) inside the circle and subtractive outside the circle. Both of these factors result in a higher magnetic flux density inside the circle than outside, and a net "magnetic pressure" causing the cable to expand into a circle.

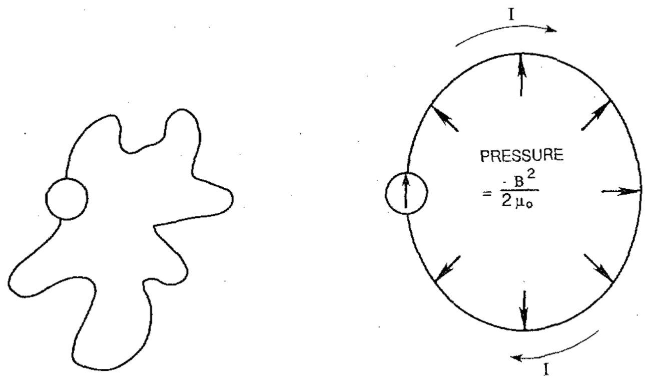

Fig. 2. Response of a flexible cable to a large current.

More rigorously, the force is equal to the derivative of the magnetic coenergy with respect to generalized coordinate x

$$F = \frac{\partial W^*}{\partial x}\Bigg|_{I = ct} = \frac{\partial(\frac{1}{2}LI^2)}{\partial x}\Bigg|_{I = ct},$$

$$F = \frac{1}{2}I^2 \frac{\partial L}{\partial x}.$$

The force, acting locally on each element of the flexible cable, is in a direction to increase, by local contributions, the inductance of the loop, thereby, expanding it into a circle.

The local forces will be higher at the points and along the directions where the inductance gradient is higher:

$$\bar{F} = \frac{1}{2}I^2 \text{ grad } L = \frac{1}{2}I^2\nabla L.$$

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The integral of a gradient over any closed curve is zero. This shows that Newton's third law is respected in a global sense.

SIMPLE RAILGUNS

These same relationships can be more specifically applied to the railgun as shown in Fig. 3. Of course the force on any part of the railgun circuit is simply the vector product of the current in that part and the magnetic flux density at that point; commonly called the Lorentz force. To the extent that the railgun is symmetrical along the center line (Fig. 3), the forces tending to separate the rails are symmetrical also and may be conveniently reacted against each other in the containment structure. This leaves the Lorentz force on the armature to be reacted upon the portion of the circuit which "closes the breech," in this case the power supply! In the simple railgun shown in Fig. 3 the recoil situation is analogous to that for the conventional gun in Fig. 1, the recoil force is applied to the circuit conductor at the breech closure. Of course few railguns are laid out as simply as that in Fig. 3, the power supply often comprising several components instead of the simplified ideal current source shown.

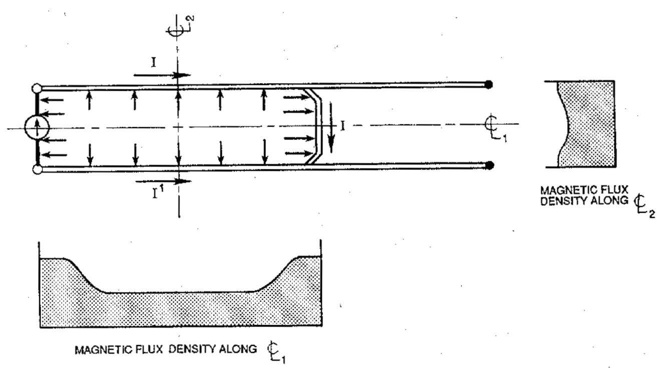

Fig. 3. Simplified railgun, schematic.

MORE COMPLEX CONFIGURATIONS

The admonition that "the recoil forces appear upon the power supply," if taken too literally, may lead one astray. Applied for example to the somewhat more realistic railgun circuit in Fig. 4a, the gun designer might joyously conclude that the recoil force would be directed downward! Alas, we must apply the lesson of Fig. 3 in more detail to determine the true nature of the recoil forces for the railgun in Fig. 4. In a simplified sense the parallel sections of the gun itself (1 and 2) can be reacted against each other as before, as can the parallel sections of the power supply bus (3 and 4). Using this same logic the power supply (5) can be reacted structurally against section (6) of the buswork. This means that the accelerating force on the armature (7) must react against section 8 of the buswork which "closes the breech," at least in the electromagnetic sense.

Unfortunately this situation has led more than one novice railgunner to consider the configuration shown in Fig. 5 in an effort to redirect the recoil force. By making the breech transition from the edge of the rails rather than the ends, the breech closure is avoided. While this is certainly an advantage for attaching an autoloader, what happens to the recoil force in this case? Perhaps it is eliminated?

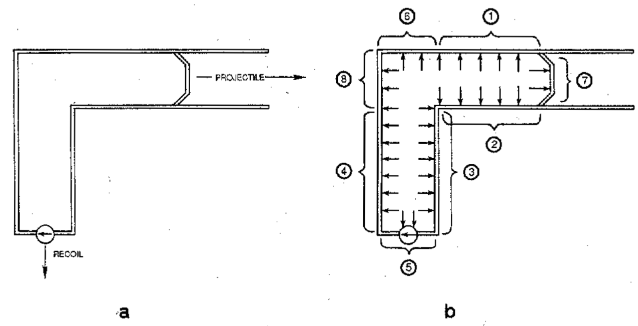

Fig. 4. Recoil forces in a more complex railgun.

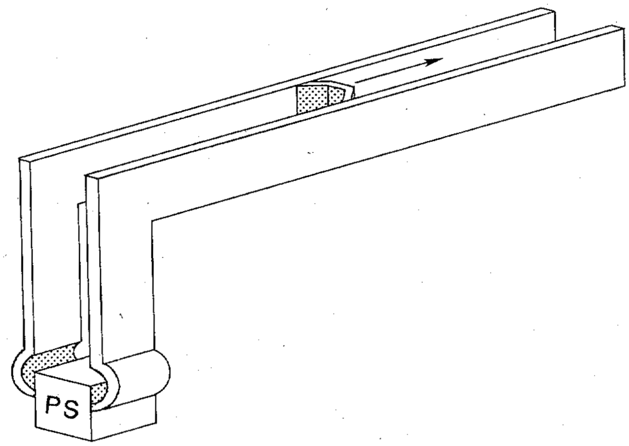

Fig. 5. Another approach to the recoil problem.

In this instance of what we shall call the side-fed rails it is a bit more difficult to trace the recoil force. It is doubly important to do in this case, however, because of the consequences. If the magnetic field around the breech of the railgun in Fig. 5 is plotted (as in Fig. 6) then the recoil force can be characterized. More importantly the side load on the projectile resulting from this geometry becomes apparent. Figure 7 shows the direction of the Lorentz force on the armature and the resultant recoil force on the railgun for three positions of the armature. In Fig. 7a, the bus from the power supply acts as a railgun and no forward force is applied to the armature at all. It is simply forced against the insulating sidewall of the railgun. Even with the armature forward of the power supply bus (Fig. 7b) a significant fraction of the Lorentz force is applied against the sidewall. As the armature travels down the railgun (Fig. 7c) the Lorentz force vector rotates to become more nearly aligned with the railgun. Obviously this case must be avoided since the possibility of locking the projectile in the breech section of the barrel exists. At the very least, substantial damage to the sidewall insulator will result. The problem of the side-fed railgun can be solved by feeding it symmetrically from both sides (Fig. 8) in this case the transverse components of the Lorentz force will cancel leaving only the longitudinal component to act on the projectile. Great care must be taken however to insure equal current distribution in both legs of the power supply bus.

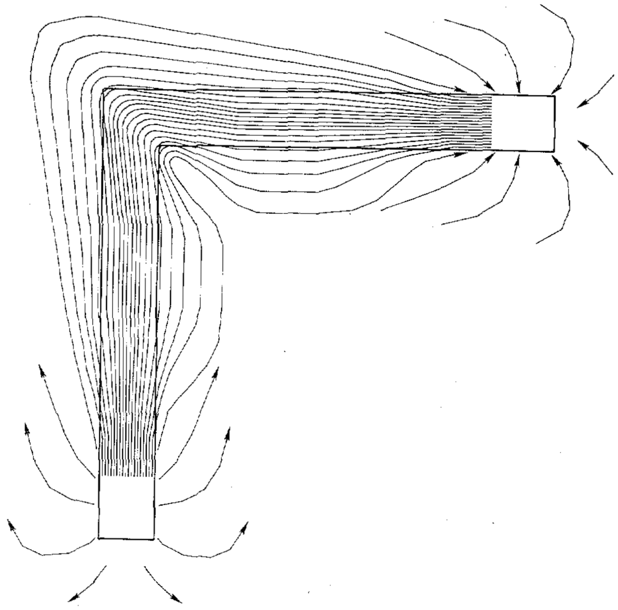

Fig. 6. Magnetic flux distribution for sid-fed railgun.

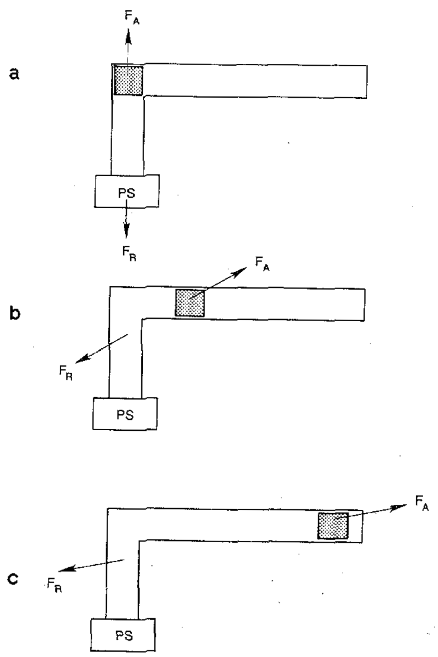

Fig. 7. Armature and recoil forces in a side-fed railgun.

OTHER CONSIDERATIONS

We have now come to see that regardless of geometry, the railgun recoil force appears wherever the breech of the railgun is "closed" in the electromagnetic sense. As we examine the problem in more detail a few other interesting aspects present themselves. For example, if we examine the current path from the railgun rail into the armature (Fig. 9) or power bus we find that there is some transverse component of current in the rail itself and therefore a longitudinal component of force applied to the rail conductor at this point. Since this phenomenon occurs at both

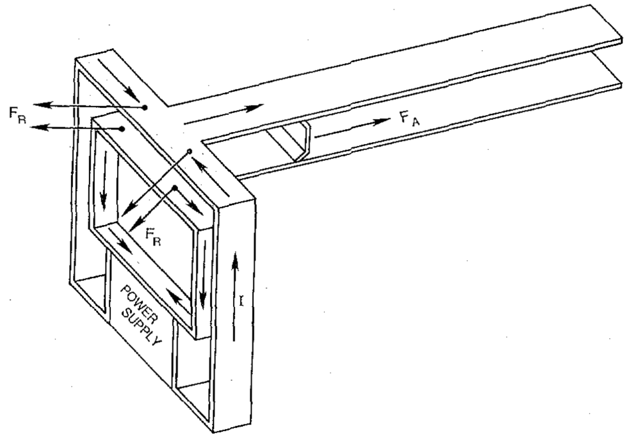

Fig. 8. Symmetrically side-fed railgun.

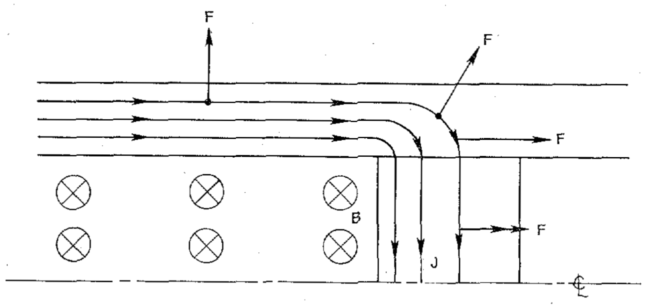

Fig. 9. Current path in rail-to-armature transition.

ends of the rail, a tensile load is applied to the rail and it is important for the gun designer to recognize this.

Having established that electromagnetic railguns do indeed experience recoil forces in much the same way as conventional guns; we will offer one interesting possibility of what might be done in the way of recoil management that is not practical with conventional guns. Railguns powered by pulsed rotating machinery (homopolar generators (HPGs) or compulsators) must deal with the substantial discharge torque of the rotating machine as well as the recoil of the gun. Of course the net discharge torque can be reduced to zero by the use of counter rotating generator rotors, but for the compulsators [1] at least an interesting possibility exists for the single rotor machine. Unlike the HPG which must charge an intermediate inductive store, the discharge torque profile of the compulsator can be made to exactly match the recoil force profile of the railgun during the launch time. This suggests the interesting configuration shown in Fig. 10. If the railgun is solidly mounted to the compulsator stator; the railgun recoil can be reacted against the compulsator discharge torque. Unfortunately this does not result in a cancellation of the forces, but does result in the recoil of the railgun appearing as a lateral force at the <u>base</u> of the compulsator. Dissipative losses in the system may prevent the compensation from being perfect, but the technique does offer the promise of substantially reducing the overturning moment of a high performance compulsator-driven railgun mounted on a vehicle.

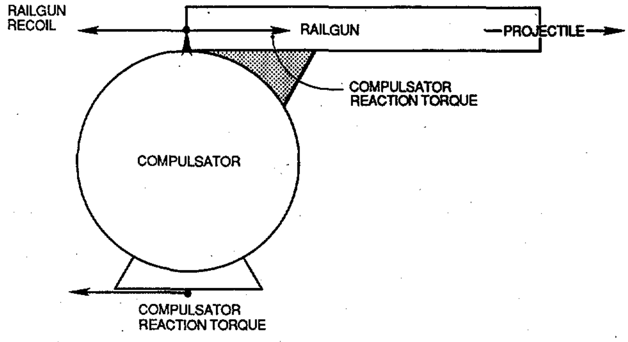

Fig. 10. Compulsator driven railgun recoil considerations.

CONCLUSION

Recoil forces in EM railguns appear wherever the breech of the railgun is closed electromagnetically. This means recoil forces may appear on power supply leads, switches, or power supply components themselves. Careful attention is required on the part of the railgun designer to control the location of the recoil loading and provide means for sustaining the loads. Careless design can result in undesirable forces being applied to the projectile armature as well. On the other hand a thorough understanding of where and how recoil forces are generated can be used to good advantage in some EM gun systems. In closing we offer aspiring railgun designers one bit of advice originally offered to HPG machine designers by Mr. B. G. Lamme in 1906, "You can't fool the flux."

REFERENCES

[1] M. L. Spann, et al., "Rapid Fire, Compulsator-Driven Railgun System," presented at The 3rd Symposium on Electromagnetic Launch Technology, April 20-24, 1986, Austin, TX.