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PARALLEL AUGMENTED RAILGUNS

J. Gallant[1,2] and P. Lehmann[2]
[1]*Royal Military Academy, 30 Avenue de la Renaissance, B-1000 Brussels, Belgium*
[2]*French-German Research Institute ISL, 5 rue du Général Cassagnou F-68301, Sai*
Louis, France

Railguns can accelerate projectiles to high velocities. However, high courants are needed which may cause rail erosion. We show that the current intensities on the rail-projectile interface can be reduced by using parallel augmented railguns without loss of kinetic energy. A drawback is that the forces on the rails are higher than with simple railguns. This limits the use of parallel augmented railguns to small calibers, since the structural integrity of the barrel of big caliber railguns is a major problem. Part of the force on the projectile can be provided by an independant energy source, for which no pulsed current must be used. Therefore, the energy supply of parallel augmented railguns will be less voluminous.

INTRODUCTION

Railguns are known for attaining muzzle velocities higher than 2000 m/s with overall efficiencies over 30% [1]. The accelerating force acting on the projectile results from the interaction between the current I_R injected in the rails and the magnetic field B [2]:

$$F = d\, I_R \times B = \frac{1}{2} L' I_R^2 \qquad (1)$$

where d is the distance between the rails and L' the inductance per unit length of the rails.

To accelerate a projectile of several kg up to high velocities (> 2000 m/s) one needs high currents (several MA) and a stored energy of tens of MJ. These high currents may cause rail erosion and the energy density of the energy supplies are still too low to allow the integration of a railgun for operational use. To reduce the current intensities on the rail-projectile interface one can use a parallel augmented railgun or distribute the current injections in time and space (DES-railgun).

In this paper we focus on the parallel augmented railgun.

THE PARALLEL AUGMENTED RAILGUN

A parallel augmented railgun is composed of two electrical circuits (Figure 1). The inner circuit (current I_R) feeds the current to the projectile, the augmented circuit (current I_A) generates an external magnetic field that augments the accelerating force on the projectile :

$$F = \frac{1}{2} L'_R \; I_R^2 + M' \, I_R \; I_A \tag{2}$$

where L'_R is the inductance gradient of the inner circuit and M' the mutual inductance gradient. We can characterize the augmented railgun with a single parameter by introducing the effective inductance gradient L'_{eff} :

$$F = \frac{1}{2} L'_{eff} \; I_R^2 = \frac{1}{2}\left(L'_R + 2 \frac{I_A}{I_R} M' \right) I_R^2 \tag{3}$$

Since the augmenting turn is separately powered, the effective inductance gradient can be changed by changing the augmented rail current, thus producing greater projectile accelerations or for a given acceleration, a lower rail current. This lower rail current results into a reduced rail ablation [3]-[4].

The current in the augmented circuit does not need to be pulsed. Energy sources with a high energy density such as ultra-capacitors could be used to power the augmented circuit, reducing the mass and volume of the energy supply.

THE ISL AUGMENTED RAILGUN

We have chosen the geometry presented in Figure 1 : the copper rails have a 15 mm by 15 mm square cross-section, the caliber of the projectile is 15 mm x 15 mm and the distance between the rails of the inner circuit and the augmented circuit is 6 mm. The length of the gun is 1500 mm. This augmented rail geometry provides a high M', and the forces on the rails are only non zero in the y-direction. The disadvantage of this geometry is an increased rail stress [5].

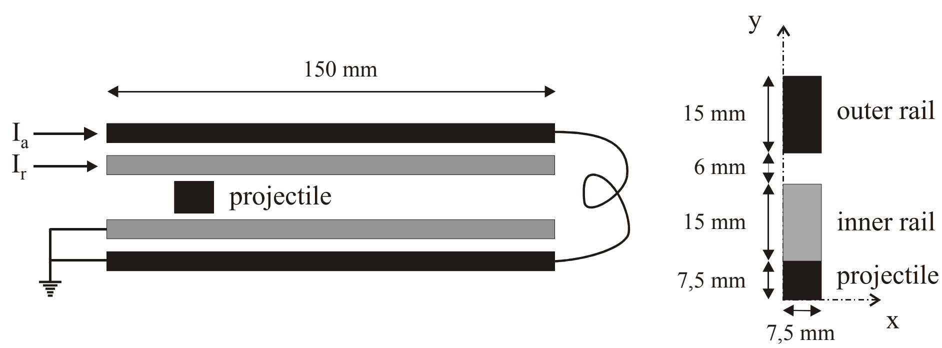

Figure 1. The augmented railgun : electrical circuits (left) and a quarter of the cross-section (right).

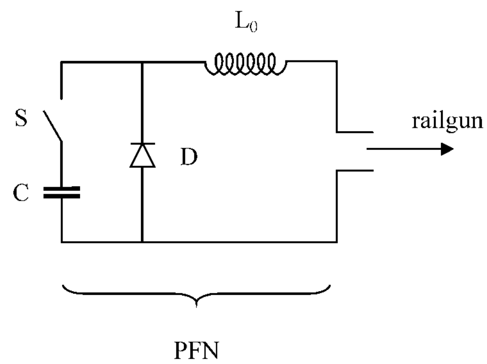

Figure 2. Pulse forming network.

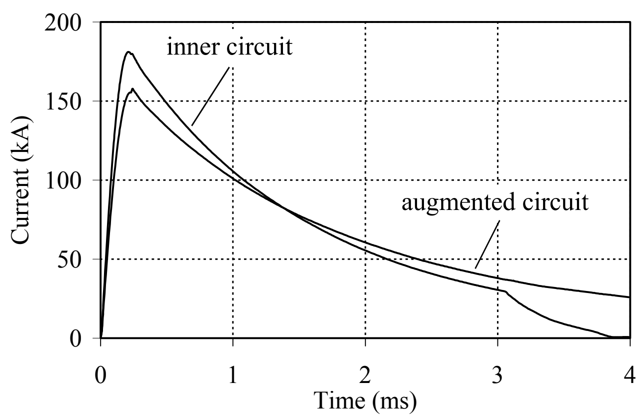

Figure 3. Typical current injections in the inner circuit and the augmented circuit (case 3).

Each circuit is connected by coaxial cables to one or more pulse forming networks (PFN), composed of a capacitive energy source (3.08 mF, 150 kJ if charged at 10 kV), spark gaps as main switch, semiconducting diodes as crowbar switch and a pulse forming inductance (Figure 2). Typical current injections are depicted in Figure 3.

The electrical contact between the rails is assured by a cylindrical brush made of thin CuCd wires. This brush (diameter = 7 mm) is inserted in a projectile made of GRP (Figure 4).

EXPERIMENTAL RESULTS

Four cases are presented : case 1 to 3 discuss experimental results, case 4 is a simulation. The experimental and calculated data are summarized in Table I.

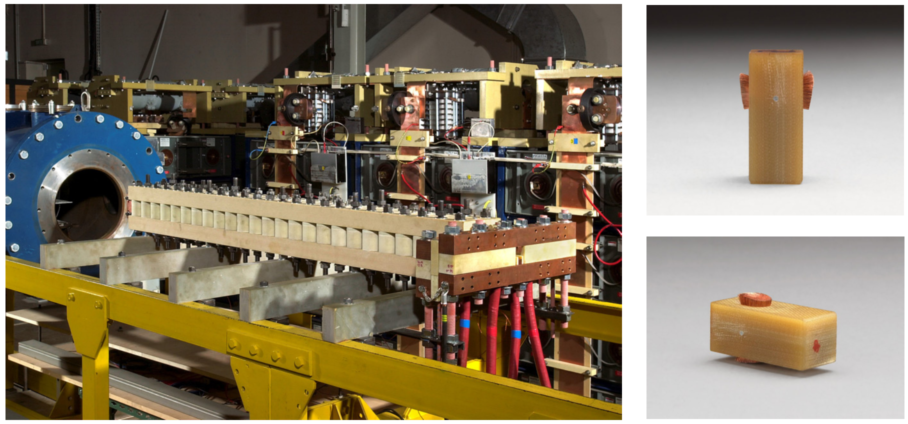

Figure 4. Parallel railgun assembly (left) and the projectile (right)

TABLE I. EXPERIMENTAL AND CALCULATED DATA

	Case 1 experiment	Case 2 experiment	Case 3 experiment	Case 4 simulation
PFN	1 x 10 kV	2 x 7 kV	2 x 10 kV	3 x 10 kV
m_p (g)	17.5	17.3	17.2	17.5
v_m (m/s)	324	314	628	803
t_m (ms)	5.22	5.43	3.06	2.66
L'_{eq} (µH/m)	0.37	0.76	0.80	0.99
µ	0.11	0.15	0.05	0.10
P_R (MPa) max	14.8	20.4	40.9	40.9

Case 1 : Non Augmented Railgun, one 150 kJ PFN

The current in the inner circuit is measured by a Rogowski coil. The position of the projectile as a function of time is provided by four B-dot probes. The initial position of the brush is 60 mm. For our experiments, we have used breakwires to measure the velocity of the projectile at the muzzle v_m. We measured a velocity of 324 m/s.

The force on the projectile during a shot is :

$$F_{proj} = \frac{1}{2} L'_{eff} \, I_R^2 - F_f = \frac{1}{2} (1 - \mu) L'_{eff} \, I_R^2 \qquad (4)$$

where F_f is the friction force and µ the friction coefficient. We introduce L'_{eq} , the "equivalent" inductance gradient :

$$L'_{eq} = (1 - \mu) L'_{eff} \qquad (5)$$

From equations (4) and (5), we have :

$$F_{proj} = \frac{1}{2} L'_{eq} \, I_R^2 \tag{6}$$

and :

$$v_m = \int_0^{t_m} \frac{L'_{eq}(t)\, I^2(t)}{2\, m_p(t)} \, dt \tag{7}$$

where t_m is the launch time (muzzle time) of the projectile and m_p the projectile mass. In our case, mass loss - which could result from the heating of the brush at the rail-projectile interface due to the Joule effect and to friction - can be neglected. If we consider a constant L'_{eq}, we find by solving equation (7) L'_{eq} = 0.37 µH/m.

The force on the projectile can be calculated by equation (6), two integrations provide the velocity and the position curves. These calculated curves and the measured positions of the projectile are plotted on Figure 5. The correspondence between the measured and the calculated position is not exact, due to the choice of a constant L'_{eq} in equations (6) and (7).

In order to obtain a better profile of L'_{eq}, we calculate the accelerating force on the projectile as a function of the measured current with the 3D electromagnetic finite element code MEGA [6]. Application of equation (3) provides L'_{eff} as a function of the time (Figure 6). We see that L'_{eff} varies between 0.46 µH/m (at maximum current) and 0.41 µH/m (at the muzzle). The friction coefficient µ is chosen such that the position curve, calculated with equation (4), fits with the measured positions. For this case we find µ = 0.11.

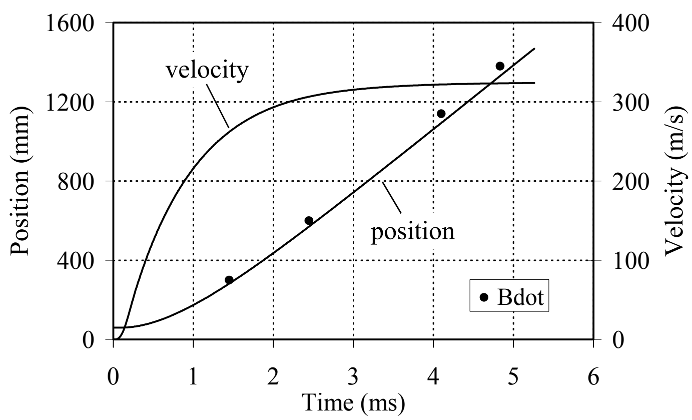

Figure 5. Position (measured and calculated) and velocity curves (case 1).

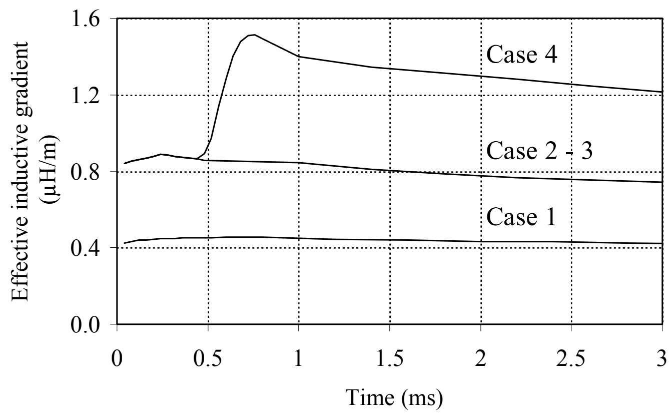

Figure 6. Theoretical effective inductance gradient for the four cases.

Higher velocities with this non augmented railgun cannot be obtained with this projectile without arcing on the rail-projectile interface. Indeed, to obtain a higher velocity, more energy has to be injected in the railgun and thus in the brush. This leads to a higher heat load, which causes the transition of the solid contact to a plasma and which has to be avoided. The heat load is proportional to:

$$\int_0^{t_m} I_R^2 \, dt \qquad (8)$$

The interaction between the current in the rails and the magnetic field causes also repulsive forces on the rails. This rail stress is proportional to I^2 and can be calculated by MEGA. For this case, the maximum stress is 14.8 MPa.

Case 2 : Augmented Railgun, one 75 kJ PFN in each Circuit

For a given acceleration the inner circuit current can by reduced by augmenting the railgun, i.e. by increasing the effective induction gradient. Thus it is possible to reduce the heat load of the projectile brush without changing the muzzle velocity.

We inject at the same instant pulsed current in the inner circuit and in the augmented circuit with PFNs charged at 7 kV (75 kJ). The current profiles for both circuits are similar to the profiles presented in Figure 3, but the amplitude is reduced by a factor $\sqrt{2}$. The maximum rail current is reduced from 180 kA to 127 kA.

A muzzle velocity of 314 m/s is measured. This value is smaller than in case 1, the friction coefficient μ in Equation (4) is higher (0.15). This can be explained by the fact that the contacting brush for this shot was longer than for the other shots - which causes a higher friction – and that energy is lost due to the eddy currents generated in the rails and the interaction between the two circuits. The advantage of this configuration is that the PFN of the augmented circuit can be replaced by an energy supply with a higher energy density since a pulsed current is not necessary for this circuit. The volume and mass of the energy supply for both circuits will then be smaller than in the previous case, while almost the same kinetic energy is obtained.

Case 3 : Augmented Railgun, one 150 kJ PFN in each Circuit

A higher velocity – without increasing the heat load of the brush compared to case 1 – can be reached by injecting more total energy into the augmented railgun. Therefore, we charge both PFNs at 10 kV. Since L'_{eff} depends on the ratio between the rail current and the augmented current, L'_{eff} is the same as in the previous case (Figure 6). The measured muzzle velocity is 628 m/s, almost the double of the value obtained in the previous cases. However, the repulsive stress on the inner rails has more than doubled : 40.9 MPa at the current maximum. The stress on the augmented rails is negative and attains a maximum of –2.2 MPa (Figure 7). The negative value means that the inner and augmented rails are attracted.

This important increase of the rail stress is not a problem for railguns with a small caliber like the one presented in this paper. However, the augmentation of a big caliber railgun could result in too high forces on the rails and large permanent deformations of the railgun structure could appear. Indeed, the stress in a non augmented railgun with a big caliber due to the repulsive forces on the rails is already near the elastic limit of the bore material.

Case 4 : Augmented Railgun, one 150 kJ PFN in the Inner Circuit, two 150 kJ PFN in the Augmented Circuit

In order to attain a higher velocity than in case 3 without increasing the inner circuit current, two current pulses are injected in the augmented circuit. At t = 0 ms, current pulses are injected in both the inner and augmented circuits. At t = 0.5 ms, a second current pulse is injected in the augmented circuit (Figure 8). The inner rail stress does not change with respect to case 3 (40.2 MPa), but the higher I_A/I_R ratio leads to a higher L'_{eff} (up to 1.51 μH/m) and thus to a higher muzzle velocity. Since experimental results are not available for this case, we chose $\mu = 0.10$. The calculated muzzle velocity is then $v_m = 803$ m/s.

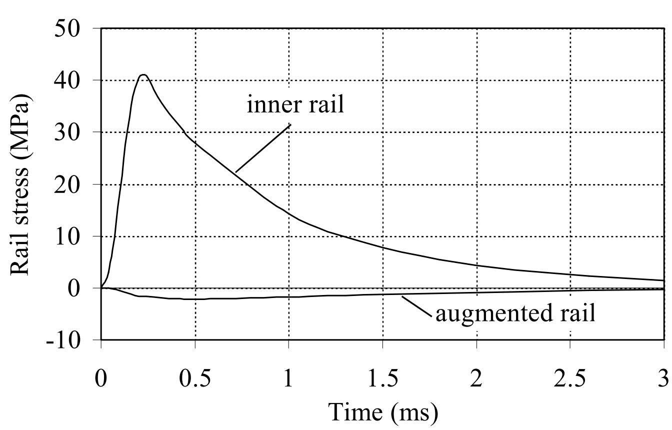

Figure 7. Rail stress on the rails (case 3).

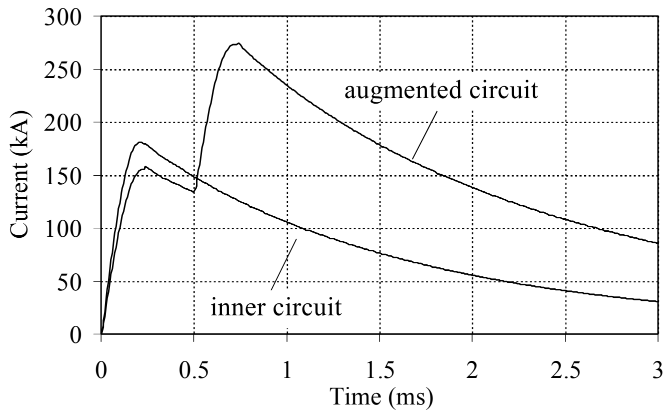

Figure 8. Calculated current profiles (case 4).

CONCLUSION

The muzzle velocity of a projectile launched by a conventional railgun can be increased – without increasing the heat load of the projectile-rail interface – by augmenting the railgun with a second circuit that provides an external magnetic field. Augmentation can also be applied to reduce the heat load for a given acceleration.

The energy supply connected to the augmented circuit does not need to deliver pulsed energy, so an energy supply with a high energy density can be used. Therefore, the energy supply of an augmented railgun can be less voluminous.

The disadvantages of the augmented railgun are a higher structural complexity and a higher rail stress. Due to this high rail stress, augmentation is limited to small caliber railguns.

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