Optimization Calculation and Analysis of Moving Load of the Railgun by Newton Method

Wen Liu (Corresponding author) & Leilei Wang
School of Sciences, Yanshan University, Qinhuangdao 066004, China

Xiangzhong Bai
School of Civil Engineering & Mechanics, Yanshan University, Qinhuangdao 066004, China
E-mail: liuwen1961@hotmail.com

Haijun Zhang
School of Sciences, Yanshan University, Qinhuangdao 066004, China

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Abstract

To explore influences from drive current on the projectile launched speed, and the spacing and width of rails on the maximum value of current in the electromagnetic gun. The motion equation of plasma armature is analyzed by the Newton method. In this paper, considering armature motion subjected to plasma viscous drag and inertial drag, the optimization model between armature speed and drive current was built. The results showed that the projectile launched speed would get the maximum value when the drive current was the specific value. Moreover, the influences from spacing and width of rails on the maximum value of current and the projectile launched speed were proved. Therefore, the optimization model that was built by the Newton method research the electromagnetic railgun is of great significance.

Keywords: Railgun, Plasma armature, Newton method, Driving current, Maximum of speed, Optimal calculation

1. Introduction

The electromagnetic launcher makes use of ampere force to accelerate driving projectile, so far it has a century. With electromagnetic forces push projectile, the projectile can reach very high acceleration. Such as Dr. Richard Ashleigh and Dr. John Barber in the Australian national university used the generator and plasma armature to accelerate a carbonic acid projectile weighed 3g to 5.9km/s in 1978. The Su Rense.Livermore Nation Laboratory and the Lowes.Alamos Nation Laboratory, once have cooperated to accelerated a projectile weighed 2.2g to a supervelocity of 10km/s. Fluid Physics institute of the Chinese Engineering Academy had built the first electromagnetic rail launcher, which can accelerate the projectile weighted 0.34g to 16.8km/s. While the velocity of the conventional cannon is only 2km/s, which is so closed to the limitation of physics that the range is not possible to be farther. On the contrary, the thrust of the electromagnetic railgun is ten times bigger than that of the traditional launcher. The projectile can be accelerated to several kilometers or even to dozens of kilometers in one second, for it possesses huge kinetic energy which greatly enhances the range and power of the weapon (Liu Wen and Li Min, 2010).

At present the studies about electromagnetic gun still continue, involving different areas of studying. About the model problem of the velocity of a projectile, Parker thinks speed of electromagnetic railgun relates to chamber wall ablation and increased plasma mass; Ray introduced the resisting force relates to speed from angle of motion resisting force. In this paper, combining with method of Parker and Ray, they put forward the forces and speed model of an armature movement, and by Newton method to optimize calculation.

2. Constructing Model

The armature pushes the projectile high-speed movement under the effect of electromagnetic force. So the choice of the armature is an important link in the system of electromagnetic gun. Currently, there are three kinds of forms of armatures used in electromagnetic railguns, including solid armature, plasma armature and composite armature, as shows in fig.1.

Solid armature is simple in design, has a very small ablation viscous force, low resistance. The heat consumption is mainly concentrated in the armature inside, the defect is that an armature quality is larger, the projectile velocity is low. The quality of plasma armature is lesser, and has good capability with the contact of rail under higher speed. So it can obtain higher speed. The defect is higher electrical resistance, can also appear second impedance under the effect of plasma instability and impedance wave power. This erodes orbit seriously and limits the capability of the projectile, but also easily under viscous force etc many kinds of factors influences. The compound armature uses the combination of above two kinds of the armature. The plasma armature exists in between solid armature and rail, it improved the contact capability of solid armature and rail. The defect is that the institution is more complex, speed is limited. In this paper, we mainly discuss the movement of plasma armature in orbit.

When large current through, the armature was rapidly melted and vaporized in a very short time, and forming the plasma. The plasma armature in orbit under electromagnetic force influence, along with the armature current is increasing and time is continuing, the temperature of plasma is also increasing. This caused local melting and evaporation of rail inside and the materials of a projectile. Moreover, mixed with plasma area and formed so-called viscosity resistance F_v. Some materials migrated to the armature, the quality of plasma armature is increased, formed inert resistance F_d (Yang Yudong and Wang Jianxin, 2008).

1) According to the electromagnetic theory, electromagnetic force can be expressed as follows:

$$F_L = \frac{\mathrm{d}E}{\mathrm{d}x} = \frac{\mathrm{d}\left(\frac{LI^2}{2}\right)}{\mathrm{d}x} = \frac{I^2\,\mathrm{d}L}{2\,\mathrm{d}x} = \frac{L'I^2}{2} \tag{1}$$

Where F_L is the driving force, E is the conservative energy of system, mainly distributes the magnetic energy of inductance for the orbit (Jiang Zhongqiu and Tang Chenglin, 2010). L' is inductance incremental, reflects inductance of unit length rail. L is the displacement of the armature movement.

2) The viscous resistance F_v can be expressed as follows:

$$F_v = \frac{\mu v^2 m_a (d+w)}{\mathrm{d}w} \tag{2}$$

Where μ is viscous factor, relate to armature, processing precision and smoothness of orbit. In conditions of higher precision and smoothness, $\mu = 0.0125$; v is armature speed; m_a is armature quality; d is spacing of rail; w is width of rail.

3) The inert resistance F_d can be expressed as follows:

$$F_d = \frac{v\,\mathrm{d}m_a}{\mathrm{d}t} \tag{3}$$

Armature quality m_a can be obtained by the solution of (4):

$$\frac{\mathrm{d}m_a}{\mathrm{d}t} = \alpha I U_a \tag{4}$$

$$m_a = m_0 + \alpha U_a \int_0^{\tau} I\,\mathrm{d}t \tag{5}$$

Where α is ablation coefficient, relates to speed, armature and material of orbit. Take it as a constant. For copper material, $\alpha \approx 4.7\times10^{-8} kg/J$, $m_0 = 0.01kg$ is armature initial quality, U_a is arcing voltage. If the plasma is in a smoothly situation, arcing voltage was approximately calculated by measuring voltage of the orbit outlet.

Arcing voltage and armature resistance can meet ohm's law:

$$U_a = IR_a \tag{6}$$

Where R_a is resistance of armature.

For a particular structure of rail gun in experiment, the workers of the Canberra laboratory found that the muzzle voltage is basically independent of the armature current. In their experiments (L EHMANN P RECK B, 2007), armature current changes from 300KA to dozens of KA. The muzzle voltage is generally 200V. Therefore, let the muzzle voltage is constant in numerical calculation.

The resultanting force of plasma armature can be expressed as follows:

$$F = (m_a + m_p)a = F_L - F_v - F_d \tag{7}$$

Where m_a is quality of armature; m_p is quality of projectile; a is acceleration of armature.

From Newton's law and kinematics formula, the armature instantaneous speed and displacement respectively can be derived.

That is

$$\begin{cases} v = v_0 + \int_0^t a\,\mathrm{d}\,t \\ L = L_0 + \dfrac{1}{2}\int_0^t v\,\mathrm{d}\,t \end{cases} \tag{8}$$

From (1), (2), (7), (8) , we obtain a velocity equation of plasma armature:

$$\begin{cases} a = \dfrac{\mathrm{d}^2 L}{\mathrm{d}t^2} = \dfrac{\mathrm{d}v}{\mathrm{d}t} = \dfrac{1}{(m_a + m_p)}[\dfrac{L'I^2}{2} - \dfrac{\mu v^2 m_a (d+w)}{dw} - \dfrac{v\,\mathrm{d}\,m_a}{\mathrm{d}t}] \\ m_a = m_0 + \alpha U_a \int_0^t I\,\mathrm{d}\,t \end{cases} \tag{9}$$

3. Optimization Design

3.1 Model design

The motion equation of plasma armature gives spacing and width of the track, and the relationship between drive current and velocities of the armature. The optimization design of electromagnetic railgun makes use of Newton method, the object is that take different width and spacing of orbit as design variables. When the velocity of a projectile is maximum, we calculate the driving current and the speed of a projectile.

Based on motion equation (8) and (9), optimization design model of a railgun is as follows:

$$\begin{cases} \text{Objective function} : \min f(\mathrm{X}) = -v \\ \text{Constraint conditions} : \mathrm{X} = \mathrm{X}(I) \end{cases} \tag{10}$$

Where X is independent variable; v is the velocity of a projectile; I is driving current.

Restriction condition and the calculated parameters are as follows:

$$\begin{cases} 0.05m \le d \le 0.1m \\ 0.05m \le w \le 0.1m \end{cases} \tag{11}$$

inductance gradient	$L' = 0.3\mu H/m$	velocity of the projectile	$v_0 = 0m/s$	(12)
the quality of the armature	$m_a = 0.002kg$	the resistance of the armature	$R_a = 5\times10^{-4}\Omega$	
the quality of the projectile	$m_p = 0.003kg$	voltage of muzzle	$U_a = 200V$	
the length of the rail	$L = 5m$			

3.2 Algorithm design

① Given initial point $x^{(0)}$, precision $\varepsilon > 0$, let $k = 0$;

② If $\left|f'\left(x^{(k)}\right)\right| \le \varepsilon$, stop, minimum points $x^{(k)}$;

③Let $x^{(k+1)} = x^{(k)} - f'\left(x^{(k)}\right) \big/ f''\left(x^{(k)}\right)$;

④Let $k = k+1$, turn (②).

4. The optimization result and analysis

Tab.1 analyzes the influence spacing and width of a rails on drive current and launched speed of the projectile, drive current on launched speed of the projectile when $0.05m \le d \le 0.1m$ and $0.05m \le w \le 0.1m$. It shows that the maximum launched speed of projectile $v = 1716.7m/s$ when the spacing of rail $d = 0.1m$, width of rail is $w = 0.1m$, drive current $I = 1.6384\times10^5$ A .

In this paper, the calculated parameters we chose are basically the same as Marshall experimental parameters. Moreover, spacing and width of orbit were increased (Asghar keshtkar and Toraj Maleki, 2009). Tab.1 shows spacing and width of track have important effect on launched speed of the projectile. Along with the spacing and width of orbit increasing, the launched speed of the projectile is a increasing trend. So we obtain a conclusion: increasing spacing and width of the track is a way to improve the speech of a projectile. When spacing and widths of the orbit are both increased, materials used to construct actual railguns are also increased. According to the practical application of guns, the date of spacing and width of the orbit is $0.1m$. Another problem showed is that along with the spacing and width of track increasing, the current is an increasing trend. Fig.2 shows spacing and width of orbit have effect on the current. The result optimized with Newton method shows that first along with launched speed of the projectile increasing, the drive current is increasing(J.Mankowski,2007; Asghar Keshtkar,2009; Wang Zijian,2009 and Thomas G.Engel,2006), and then is decreasing. Finally, launched speed would achieve a constant when driving current increases to a certain value. When driving current is maximum, launched speed of the projectile is also maximum. (Yang Yudong, 2010)So it is an affective method for improving the speed of a projectile to access to current reasonably.

5. Conclusions

(1) Based on the plasma armature resistance by the viscous resistance and inertia resistance, built the mathematical model includes some important variables such as armature speed, drive current, width and spacing of the orbit etc;

(2) The optimization calculation brings from Newton method. When driving current $I = 1.6384 \times 10^5$ A , orbit width $w = 0.1m$, spacing $d = 0.1m$, the launched speed of a projectile is the maximum, the maximum value $v = 1716.7m/s$ .In order to improve the velocity of the projectile; we should be properly select width, spacing and length of the orbit.

(3) The optimization results compared with the other simulation and experimental results, we verified rationality and effectiveness of the model. It provides theoretical basis for the design and manufacture of guns.

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Table 1. Results of optimization

d(m)	w=0.06m		w=0.08m		w=0.1m	
	$I(10^5 A)$	$v(10^3 m/s)$	$I(10^5 A)$	$v(10^3 m/s)$	$I(10^5 A)$	$v(10^3 m/s)$
0.051	1.0873	1.5488	1.1733	1.5797	1.2366	1.6011
0.056	1.1209	1.5612	1.2165	1.5944	1.2878	1.6177
0.063	1.1634	1.5762	1.2720	1.6127	1.3546	1.6384
0.068	1.1908	1.5857	1.3086	1.6243	1.3992	1.6518
0.075	1.2259	1.5976	1.3560	1.6389	1.4579	1.6687
0.079	1.2444	1.6037	1.3814	1.6465	1.4897	1.6775
0.082	1.2576	1.6080	1.3997	1.6519	1.5127	1.6838
0.085	1.2703	1.6121	1.4173	1.6570	1.5351	1.6899
0.094	1.3054	1.6232	1.4669	1.6712	1.5986	1.7066
0.097	1.3162	1.6266	1.4824	1.6755	1.6187	1.7117
0.100	1.3266	1.6299	1.4974	1.6797	1.6384	1.7167

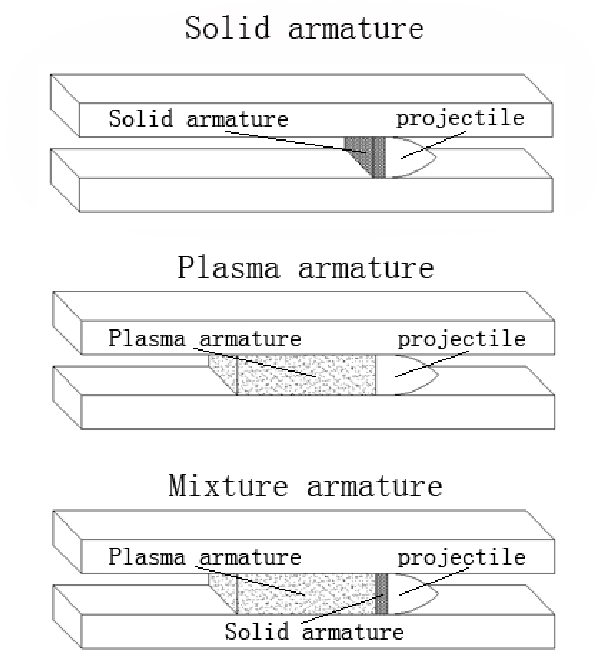

Figure 1. The conventional types of armature

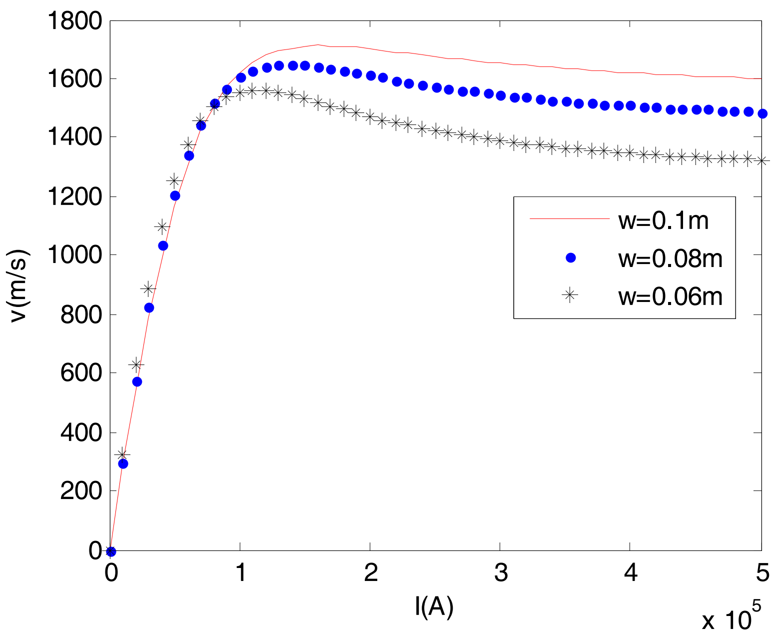

Figure 2. The variation picture of the maximum value of current and the launched speed of the projectile in conditions of different the spacing and the width of rails