Analysis and optimization of the two-dimensional model of the armature rotation on the electromagnetic railgun

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INTRODUCTION

It is well-known that the electromagnetic railgun is a hot topic in the research of the electromagnetic launch technology in recent decades. At present, there have been many researches on the mechanism of armature motion. A dynamic interior ballistic process considering the friction loss, nonlinear electrical contacts and aerodynamic drag is established to study the armature movement. A normal pressure model caused by electromagnetic force is considered into the friction of the armature. Besides, a ballistic model containing the movement and rotation of the armature is established to realize the ballistic control. These methods have important influence on the research of the armature motion mechanism.

In this paper, first a movement equation of the armature is deduced for the augmentation railgun with four rails. Then in order to generate the electromagnetic torque on the armature, an asymmetrical rail layout is adopted. According to the Biot-Savart Law, a two-dimensional armature model is established to analyze this structure. At last, based on the movement model and the rotation model, the optimization for the size parameters of the armature are carried.

ROTATION MODEL OF THE ARMATURE

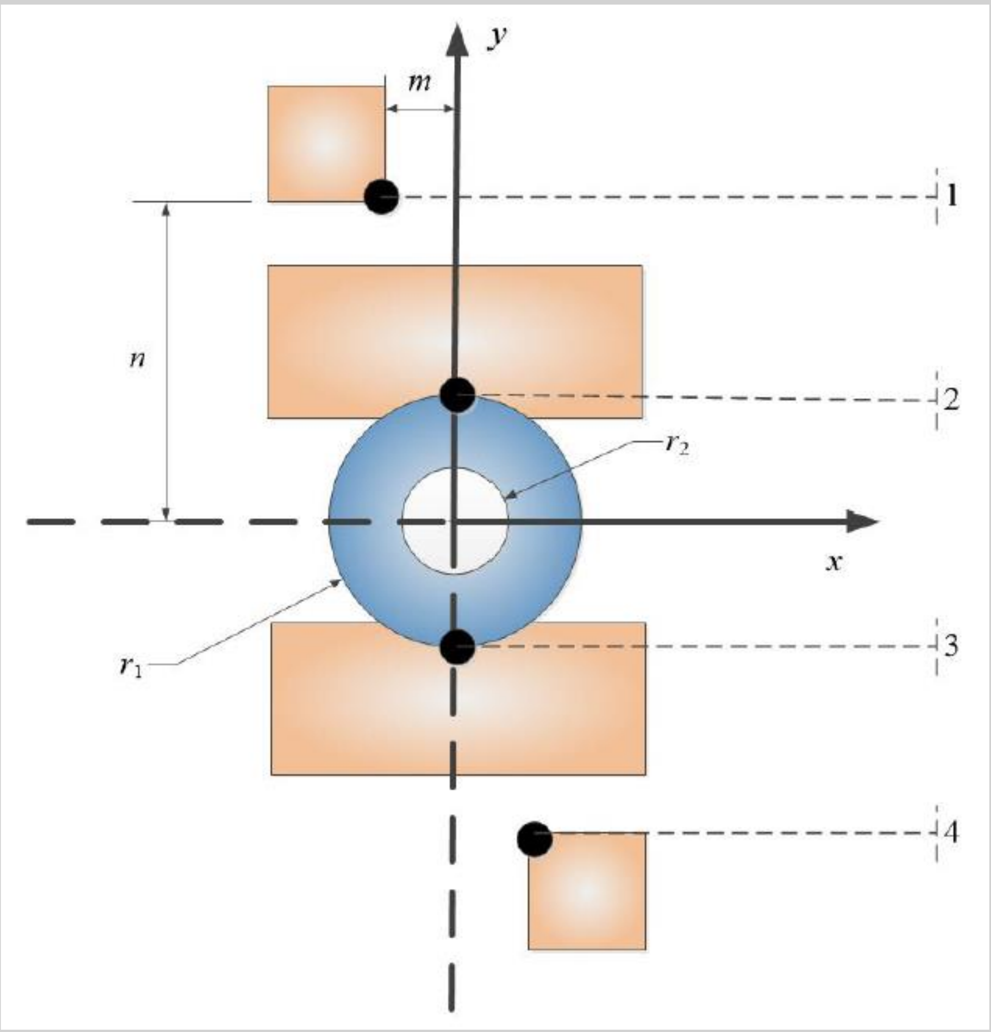

Fig. 1 The cross-section of the rail.

CONTROL EQUATIONS

The circuit model of the electromagnetic launch system consists of two parts: the pulse power supply (PPS) circuit and the railgun circuit model. For the augmentation railgun, the circuit equations can be described as follows.

$$
\begin{cases}
\begin{cases}
\dfrac{\mathrm{d}u_c}{\mathrm{d}t} = -\dfrac{I}{2C} \\
\dfrac{\mathrm{d}I}{\mathrm{d}t} = \dfrac{u_c - I\left(R_m' x + R_{arma} + R_a' \cdot l_{rail} + R_s + R_{in}/2 + (L_m' + 2M')v\right)}{(L_m' + 2M')x + L_a' \cdot l_{rail} + L_s + L_{ind}/2}
\end{cases} & u_c > 0 \\
\dfrac{\mathrm{d}I}{\mathrm{d}t} = \dfrac{-I\left(R_m' x + R_{arma} + R_a' \cdot l_{rail} + R_s + R_{in}/2 + (L_m' + 2M')v\right)}{(L_m' + 2M')x + L_a' \cdot l_{rail} + L_s + L_{ind}/2} & u_c \le 0
\end{cases}
$$

The movement equation of the armature is as follows.

$$
m_a \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{1}{2}(L_m' + 2M')I^2
$$

The torque of the armature is as follows.

$$
M_z = \mu_0 \left(\frac{I}{4\pi}\right)^2 l_a \int_0^{2\pi} \mathrm{d}\theta \int_{r_2}^{r_1} \Phi \rho \mathrm{d}\rho
$$

$$
\Phi(x,y,z) = (x\cdot g + y \cdot h)\left(\frac{\partial h}{\partial x} - \frac{\partial g}{\partial y}\right)
$$

$$
\vec{B} = \vec{B_1} + \vec{B_2} + \vec{B_3} + \vec{B_4} = \frac{\mu_0 I}{4\pi}\left[g(x,y)\vec{i} + h(x,y)\vec{j}\right]
$$

$$
\vec{B_1} = \frac{\mu_0 I}{4\pi} \cdot \frac{(y-n)\vec{i} - (x+m)\vec{j}}{(x+m)^2 + (y-n)^2} \cdot \frac{16 r_1}{\sqrt{(x+m)^2 + (y-n)^2 + 64 r_1^2}}
$$

$$
\vec{B_2} \approx \frac{\mu_0 I}{4\pi} \cdot \left[(y-r_1)\vec{i} - x\vec{j}\right] \cdot \left(\frac{3y^2}{r_1^4} - \frac{x^2}{r_1^4} + \frac{2y}{r_1^3} + \frac{1}{r_1^2}\right) \cdot \frac{8 r_1}{\sqrt{x^2 + (y-r_1)^2 + 64 r_1^2}}
$$

$$
\vec{B_3} \approx \frac{\mu_0 I}{4\pi} \cdot \left[-(y+r_1)\vec{i} + x\vec{j}\right] \cdot \left(\frac{3y^2}{r_1^4} - \frac{x^2}{r_1^4} - \frac{2y}{r_1^3} + \frac{1}{r_1^2}\right) \cdot \frac{8 r_1}{\sqrt{x^2 + (y+r_1)^2 + 64 r_1^2}}
$$

$$
\vec{B_4} = \frac{\mu_0 I}{4\pi} \cdot \frac{-(y+n)\vec{i} + (x-m)\vec{j}}{(x-m)^2 + (y+n)^2} \cdot \frac{16 r_1}{\sqrt{(x-m)^2 + (y+n)^2 + 64 r_1^2}}
$$

Table 1. The parameters of the PPS and the barrel.

parameter	value	parameter	value
L_{ind} (μH)	16	R_s (mΩ)	2
C (mF)	7.8	l_{rail} (m)	1.4
R_{in} (mΩ)	5	m_a (g)	7.5
L_m' (μH/m)	0.4	$J_{inertia}$ (g•mm^2)	169.86
M' (μH/m)	0.1	m (mm)	6
L_a' (μH/m)	0.2	n (mm)	15
R_m' (mΩ/m)	0.357	r_1 (mm)	6
R_a' (mΩ/m)	2.8	r_2 (mm)	3
R_{arma} (pΩ)	2.06	$u_{initial}$ (kV)	5
L_s (μH)	5	l_a (mm)	10

NUMERICAL ANALYSIS

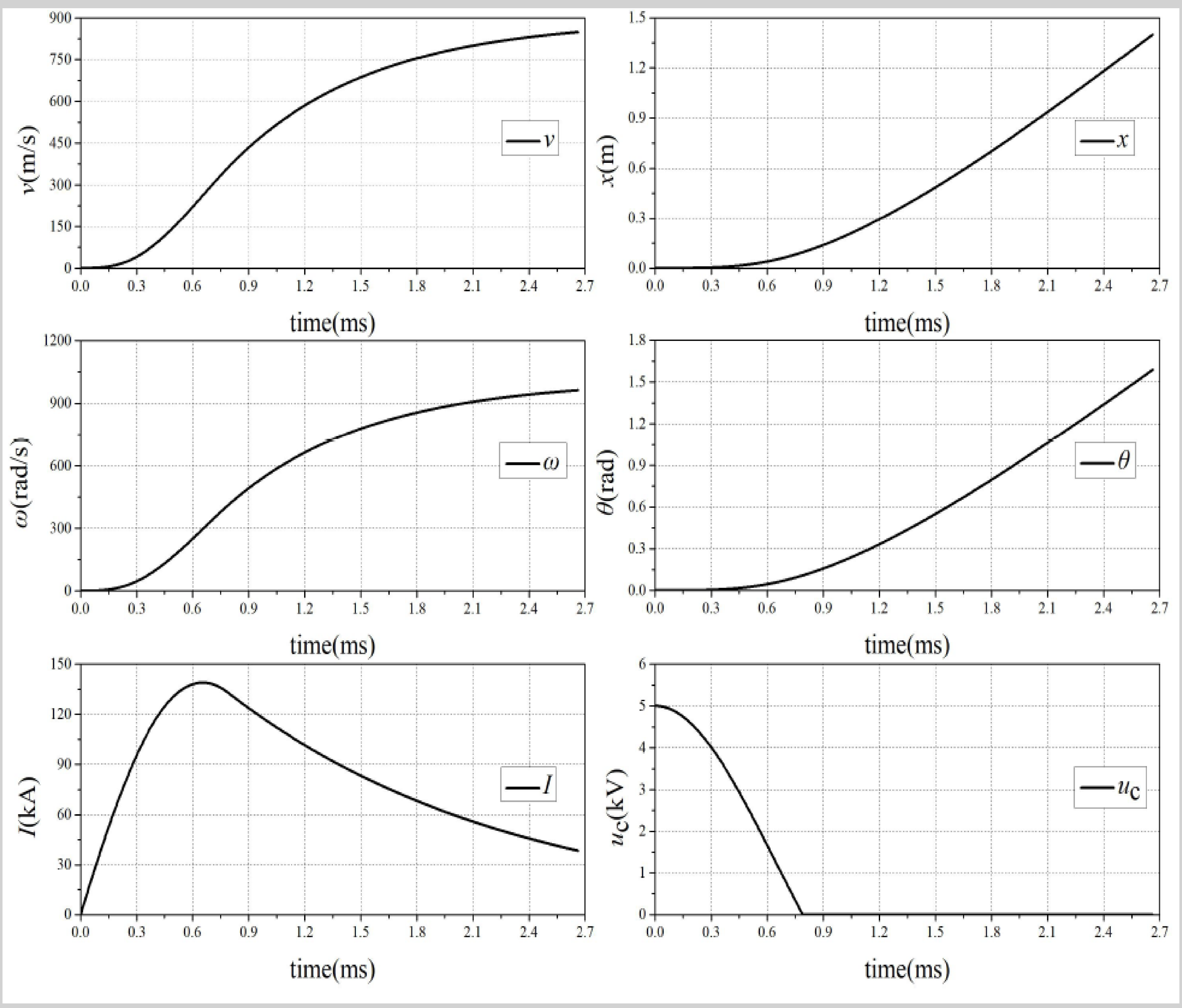

Fig. 2. The simulation results under the above parameters.

As shown in Fig. 2, the total current peak is 138.9kA, and the total current has dropped to 38.4kA when the armature comes out of the muzzle. The capacitor ends discharging at 0.79ms. The armature comes out of the muzzle at about 2.7ms. What's more, the muzzle velocity reaches 848.8m/s. Meanwhile, the angular velocity ω reaches 962.4rad/s. In other words, the rotation rate of the projectile is about 153r/s. During this period, the armature has rotated about 1.59rad in the bore.

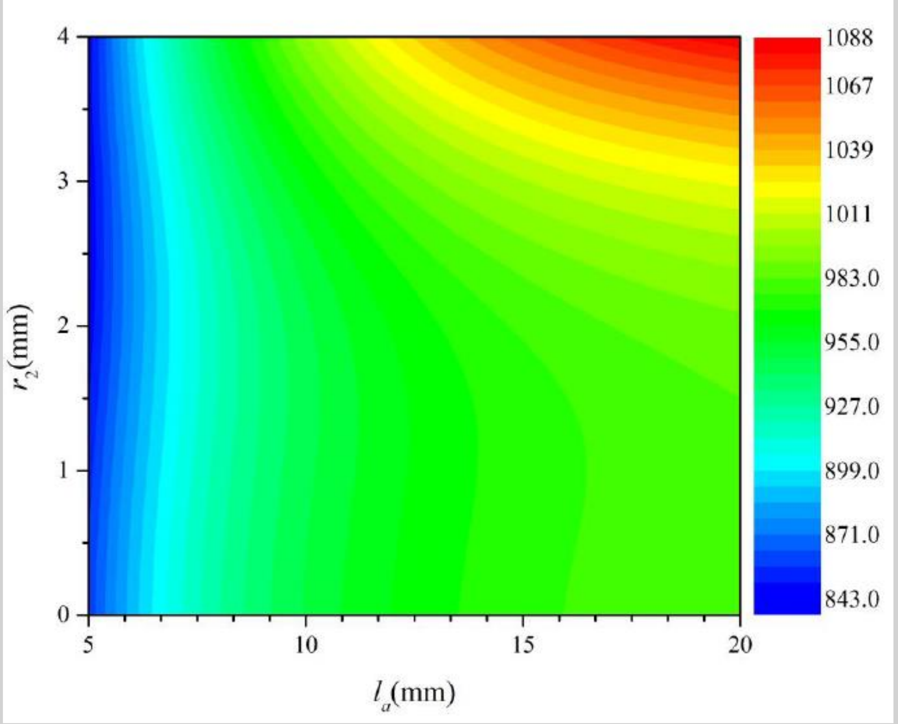

Fig. 3. The cloud chart of the muzzle angular velocity.

As shown in Fig. 3, when l_a is less than 6mm, no matter how r_2 changes, the muzzle angular velocity is mostly less than 900rad/s. Furthermore, excluding the top right-hand corner, there is a little change for the muzzle angular velocity. Most of them are less than 1000rad/s. When l_a is 20mm and r_2 is 4mm, the muzzle angular velocity reaches the maximum. The maximum value is 1087.3rad/s. However, in this case, although the muzzle angular velocity is the largest, the muzzle velocity is much smaller. The corresponding velocity value is 596.3m/s. It is equivalent to sacrificing the muzzle velocity in order to pursuit the larger angular velocity. Therefore, in practice, it is necessary to improve the muzzle angular velocity under the premise of meeting all requirements. The method in this paper has certain guiding significance.

CONCLUSION

In this paper, a translational equation of the armature is first established for the augmentation railgun with 4 rails. Then an asymmetrical rail layout is adopted to generate the electromagnetic torque. According to the Biot-Savart Law, a two-dimensional armature model is established to describe the rotation of the armature. Based on these above models, the optimization for the size parameters of the armature are carried. In the process of optimization, the device parameters of the PPS and the barrel are fixed. Taking the effective length of the armature and its radius of the internal contour as independent variables, these variables range are respectively 5~20mm and 0~4mm. The optimized results show that when the above two variables are 20mm and 4mm respectively, the armature can achieve the best angular velocity. The maximum angular velocity can reach 1087.3rad/s. It is meaningful to guide the research on the armature rotation of the electromagnetic railgun.

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