Comparative study on longitudinal momentum characteristics of L-type and I-type breech in railgun

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Abstract. The position and magnitude of the longitudinal force during launch are very important to the design of electromagnetic railgun. This problem has become a hot topic of research for a long time. Previous experiments showed that most of the recoil force of the electromagnetic railgun locates at the breech. In order to study the stress distribution and momentum characteristics of the breech during launch. Based on Maxwell’s stress tensor, the momentum conservation equations for electromagnetic railgun were derived. Depending on whether the direction of the source current is perpendicular to the current direction in the rails, the breech is simplified and summarized into I-type and L-type structures. Then, the 3-d models of the two breeches were established and the launch process was simulated by finite element method. Some results such as the current density, magnetic field intensity and electromagnetic stress of the current injector plates and coaxial power connector under both models were obtained. The simulation results show that the longitudinal force on the breech is concentrated on the current injector plates. The longitudinal force on the power connector of L-type breech is much bigger than that of the I-type breech, up to nine times. Besides, different structures of the breech will not affect the launch performance of the railgun.

1. Introduction

Due to the higher projectile velocities of railgun compared with the traditional powder guns, many research on scientific foundations and system engineering of electromagnetic launch have been made by scholars and institutions in recent decades [1–6]. The dynamic characteristics of railgun when launching are of great importance to the railgun system. Among them, the longitudinal force has been received continuous attention. When the railgun is launched, the armature is subjected to a forward electromagnetic force. According to the momentum conservation law, there must be a corresponding reverse axial force. However, the magnitude and position of the reverse force have been controversial.

On the one hand, Peter Graneau et al. [7–11] used the Ampere’s law to calculate and simulate the closing current in a metal circuit. The results showed that the opposing force exists on the guide rail near the armature [12–15]. On the other hand, many researchers believed that Lorentz force law is the right way to calculate the reversed force [16]. G. Cavalleri et al. believed that Ampere force and Lorentz force are equivalent in calculating the stress of the guide rail, and the recoil force acts on the breech of railgun [17,18]. To solve this argument, Robson, A E designed an experiment that can directly measure the longitudinal force on the rail, and the experimental results show that there are no longitudinal force in the conductor [19]. Further, Putnam and Schroeder set up a railgun system with
segmented rail, and measured the longitudinal force on the rail. The experimental results show that the magnitude of the force on the armature is at least 70 times the reaction force on the track. So they think that recoil does not exist on the rails [20,21]. Schneider, Markus simulated the electromechanical properties of the railgun component with the three-dimensional finite element software COMSOL. The results showed that the forces acting on the projectiles during the launch are offset by the recoil forces appearing in the current injection device of the breech [22]. At this point, we can believe that the reverse force acts on the current pool at the breech of railgun. Generally, the breech is mainly composed of a coaxial cable connector, a current injection plate and insulating support. However, the influence of different types of breech current injection structure on the reversed momentum has not been studied.

In this paper, based on the Maxwell equations, the momentum conservation equation of the electromagnetic railgun was derived. And, two types of breeches finite element models were established. Then, the electromagnetic field distribution of the breech during the launch process was simulated with The finite element method. Some results, such as, the electromagnetic field distribution and the momentum density distribution of different breeches were obtained. According to the simulation results, the momentum characteristics of different components in different breeches were compared and analyzed.

2. Equations

2.1. Momentum conservation equations

The force density of the charge is:

\[ f = \rho E + J \times B \] (1)

Where, \( f \) is electromagnetic force density on the charge, \( \rho \) is the charge density, \( E \) is the electric field intensity, \( J \) is the current density, \( B \) is the magnetic flux density. In Maxwell’s equations:

\[ \nabla \cdot B = 0 \] (2)

\[ \nabla \times E = -\frac{\partial B}{\partial t} \] (3)

\[ J = \frac{1}{\mu_0} \nabla \times B - \varepsilon_0 \frac{\partial E}{\partial t} \] (4)

According to the equations (2 - 4), the equation (1) can be rewritten as:

\[ f = \varepsilon_0 (\nabla \cdot E) E + \varepsilon_0 [\nabla \times E + \frac{\partial B}{\partial t}] \times E + \frac{1}{\mu_0} (\nabla \cdot B) B + \frac{1}{\mu_0} E \times B - \varepsilon_0 \frac{\partial E}{\partial t} \times B \] (5)

Here define:

\[ g = \varepsilon_0 (E \times B) \] (6)

\[ \bar{T} = -\varepsilon_0 E E - \frac{1}{\mu_0} B B + \frac{1}{2} \bar{T} (\varepsilon_0 E^2 + \frac{1}{\mu_0} B^2) \] (7)

Where, \( g \) is the field momentum, \( T \) is the Maxwell tensor. For a space \( V \), integrate both sides of the equation (5), according to equation (6, 7), equation (5) could be rewritten as:

\[ \int_S \bar{T} \cdot dS = \int_V f dV + \frac{\partial}{\partial t} \int_V g dV \] (8)

Where, equation (8) is the momentum conservation equation of the whole system including electromagnetic field [23]. For a brief expression, we define:

\[ F_S = \int_S \bar{T} \cdot dS \] (9)

\[ F_m = \frac{\partial G_m}{\partial t} = \int_V f dV \] (10)
Hence, equation (8) could be derived as:

\[ F_s = F + F_e = \frac{\partial}{\partial t} (G_m + G_e) \]

Where, \( G_m + G_e \) is the total momentum of railgun system, which includes mechanical momentum and electromagnetic field momentum. \( F_s \) is the surface force subjected to external electromagnetic fields, which could characterize the transfer of momentum. For the longitudinal momentum, it only needs to take the axial component of \( F_s \).

### 2.2. Governing equations

The momentum conservation equations are based on the Maxwell’s equations. Electromagnetic field distribution of the railgun breech could be simulated with the transient eddy current field solver. And the magnetic field generated by the displacement current could be ignored. Besides, the scalar potential and the vector magnetic potential were taken as variables. Also, the Coulomb criterion was introduced. The transient eddy current field control equations [24] could be given in equation (13, 14).

\[
\nabla \times (\frac{1}{\mu} \nabla \times A) - \nabla (\frac{1}{\mu} \nabla \cdot A) = -\sigma (\frac{\partial A}{\partial t} + \nabla \phi) + J_s \tag{13}
\]

\[
\nabla \cdot (-\sigma \nabla \phi - \sigma \frac{\partial A}{\partial t} + J_s) = 0 \tag{14}
\]

Where, \( \phi \) is scalar potential, \( A \) is magnetic vector potential, \( \nabla \) is vector differential operator, \( J_s \) is source current density, \( \mu \) is magnetic permeability, \( \sigma \) is conductivity. Current density \( J \), magnetic \( B \) and magnetic force \( F \) could be derived as equations (15-17).

\[
J = -\sigma (\frac{\partial A}{\partial t} + \nabla \phi) + J_s \tag{15}
\]

\[
B = \nabla \times A \tag{16}
\]

\[
F = \int_\Omega (J \times B + \rho E) dV \tag{17}
\]

\[
\frac{\partial A(x,t+\Delta t)}{\partial t} = A(x,t+\Delta t) - A(x_0,t) \tag{18}
\]

Where, \( A(x, t+\Delta t) \) is the current magnetic vector at position \( x \), \( A(x_0, t) \) is the last time magnetic vector at position \( x_0 \). The conductors are surrounded by air domains and the magnetic vector potentials at the far field position are set to zero. An electric scalar potential boundary condition is imposed on one end face of the coaxial cable power connector.

### 3. Models and simulation parameters

According to the electromagnetic momentum conservation equation, the characteristics of the electromagnetic momentum in the breech are related to the direction of the source current. Based on whether the direction of the source current is the same as the current direction in the rails, the breech can be divided into two types, L-type and I-type structures. The source current direction of the L-type breech is perpendicular to the current direction of the rails. The typical L-type breech railgun is the 32MJ railgun prototype from BAE company. And the direction of the source current of the I-type breech is parallel to the current direction of the rails. The typical L-type breech railgun is the 32MJ railgun prototype from General Atomic company.
The structure of the L-type breech is shown in figure 1. Conductor parts of the L-type breech mainly include a current injection positive plate(plate-P) on the upper side, a current injection negative plate(plate-N) on the lower side, and eight coaxial power connectors. The eight coaxial power connectors are distributed in two rows on the plate, and their numbers are shown in figure 2. Each coaxial connector consists of inner conductors(connector-P) and outer conductors(connector-N) respectively. The breech surface is located on the end surface of the rails. In addition to the conductor, each component is tightly supported by insulating material outside. In the calculation of electromagnetic fields, the structure of the insulator is replaced by air. The characteristic of the L-type breech is that the direction of the source current in the coaxial power connector is perpendicular to the direction of the current in the rails.

The structure of the I-type breech is shown in figure 3. Similar to the L-type breech, the I-type breech is also mainly composed of a positive plate, a negative plate and eight coaxial power connectors. However, the direction of the source current in the coaxial power connector is parallel to the direction of the current in the rails. The eight coaxial power connectors are distributed in a circle on the board, and their numbers are shown in figure 4.

| Component     | L-type breech x*y*z(mm) | I-type breech x*y*z(mm) |
|---------------|--------------------------|--------------------------|
| Rail1         | 150*20*10                | 150*20*10                |
| Armature      | 10*10*10                 | 10*10*10                 |
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The structure parameters of the breeches are listed in table 1. The starting position of the armature is four times the caliber from the breech surface. According to reference [23], the material of the armature is aluminum alloy 6065, and material of the other conductors is beryllium copper alloy C17500, outer space is full of vacuum. The finite-element method was used in this paper to solve the problem. Three-dimensional models of the two types breech were first established with ANSYS software. Under Mesh order, automatic mesh generation was performed in the model using tetrahedral elements. The finite-element meshes of the L-type breech and I-type breech are shown in figure 5 and figure 6.

|          |          |          |
|----------|----------|----------|
| Rail2    | 150*20*10| 150*20*10|
| Plate-P  | 50*140*10| 10*90+90 |
| Plate-N  | 50*140*10| 10*90+90 |
| Connector-P| φ6*100   | φ6*100   |
| Connector-N | (φ10−φ8)*70 | (φ10−φ8)*70 |

Figure 5. Finite-element meshes of the L-type breech.

Figure 6. Finite-element meshes of the I-type breech.

Initial conditions include initial source current and boundary conditions. The source current is a sine wave with a peak of 100kA and a period of 20ms. It was applied to the end surfaces of the power connectors and the boundary condition was set to Dirichlet boundary. The Maxwell transient electromagnetic field solver was employed. And the electromagnetic results are substituted into equation (12) for further calculation to obtain the momentum distribution of the breeches.

4. Results and discussions

4.1. Field results

The current distribution and magnetic field distribution of the L-type breech railgun at the peak current are shown in figure 7 and figure 8. It could be seen that the maximum value of the current density and magnetic field strength were concentrated on the breech surface. And the current density and magnetic field intensity in the eight power connectors are Uneven, and the closer the breech surface is, the larger the current density is.

Figure 9 and figure 10 are the current distribution and magnetic field distribution of the I-type breech railgun at the peak current. Obviously, the current density and magnetic field intensity distribution of the I-type breech are much more uniform than that of the L-type breech.
4.2. Magnetic force results

Based on the simulation results of the electromagnetic field, the force on different components of the railguns could be obtained with equation (17).

Table 2 listed the results of the longitudinal magnetic forces on components of the two railgun with L-type breech and I-type breech. In the results, the resultant longitudinal force of the L-type breech railgun is -9N, which accounts for 0.3% of the total force, and that of the I-type breech railgun is 7N, which accounts for 0.25% of the total value. These values are within the calculation accuracy. So the longitudinal force is conserved.

In the simulation of the two railguns, the structural parameters of the armature and the rails, the source current loaded keeps the same, only the structure of the breech is inconsistent. The forces on the armatures are 2333N and 2331N, respectively. It indicates that the different structure of the breech will not affect the launch performance on the armature. This phenomenon can be explained by the four-caliber rule. 99.6% propellant force on the armature is generated by the rails at four times the caliber behind the armature.
Table 2. Results of longitudinal magnetic force on the railgun.

| Component       | $F_{mx}$ (L-type) (N) | $F_{mx}$ (I-type) (N) |
|-----------------|-----------------------|-----------------------|
| Rail1           | 236                   | 208                   |
| Armature        | 2333                  | 2331                  |
| Rail2           | 236                   | 195                   |
| Plate-P         | -1006                 | -1269                 |
| Plate-N         | -900                  | -1356                 |
| Connector       | -908                  | -102                  |
| Total           | -9                    | 7                     |

Figure 9. Current density distribution of I-type breech at peak current.

Figure 10. Magnetic field distribution of L-type breech at peak current.

Figure 11. Comparison of longitudinal force distribution on two types of breeches.

Figure 11 showed the magnitude and proportion of the longitudinal forces on different parts of the two types breeches. Among them, the reverse force on the L-type breech is most distributed on the two current injector plates and the power connectors. And that on the I-type breech is mainly concentrated on two current injector plates. The longitudinal force on the electrical connector is very small, which accounted for only 3.76%. The force on current injection plates of the I-type breech is a little greater than that of the L-type. However comparing magnetic field and current distribution in different breeches shown in figure 7-10, it could be obtained that the force on L-type breech plate is mainly
concentrated on the breech surface, and the force on I-type breech plate is more uniform. In summary, I-type breech is better in structural strength as the aspect of longitudinal force distribution.

4.3. Surface force results
According to equation (12), the surface force could present the momentum distribution of the whole railgun including the field momentum and the mechanical momentum. In order to study the features of longitudinal momentum, take the $x$ direction component of the surface force named $F_{sx}$.

$F_{sx}$ is the integral over the six outer surface. It consists of six components. According to reference [23], when calculating the longitudinal force, compared with the $x$ direction component $F_{sx}(X)$, the components on the other directions can be ignored. Calculation diagrams of the surface force $F_{sx}(X)$ on different surfaces in $x$ direction are shown in figure 12 and figure 13. The parameter of L-type breech in the $x$ direction is 50mm, and that of I-type breech is 100mm. The corresponding conductors are different at different $x$-position surfaces.

![Figure 12](image1.png) **Figure 12.** Calculation diagram of the surface force in L-type model.

![Figure 13](image2.png) **Figure 13.** Calculation diagram of the surface force in I-type model.

Figure 14 is the curves of the surface force $F_{sx}(X)$ of the L-type breech at different $x$ position. The blue curve represents the surface force $F_{sx}(X)$, and the red curve represents the gradient of $F_{sx}(X)$ in the $x$ direction. According to different corresponding conductors at $x$, the breech could be divided into 5 regions in the $x$ direction. According to equation (8), the gradient of $F_{sx}(X)$ represents the electromagnetic force experienced by the conductor, which also shows the momentum distribution on the breech.

In region 1, the electromagnetic momentum decreases extremely fast. And correspondingly, current injector plates suffer strong force. The electromagnetic force on the end face of the gun in region 1 is close to 500N at the maximum, however, the electromagnetic forces on region 3 and 5, located at the current injector plates are almost zero. Regions 2 and 4 are where the power connectors connect to the plates. In these two regions, the surface force $F_{sx}(X)$ is alternating, which indicated that the electrical connectors are under internal stress. It showed that the net electromagnetic force experienced by the electrical connector is less than the peak electromagnetic force that on the inside of the connector. For further study, the surface force density distribution at different $x$ positions is shown in figure 15.
Figure 14. Curves of the surface force in L-type breech.

Figure 15. Distribution of the momentum in L-type breech.

The distribution of the surface force density at \(x=5,15,32\) mm are shown in figure 15, which correspond to the regions 1, 2, and 3 in figure 14 respectively. It can be seen from the figure that the electromagnetic momentum is mainly transmitted through the electromagnetic field between the plate-P and plate-N. When \(x=5\) mm, the force is mainly concentrated in the middle of the two plates. When \(x=15\) mm, the force is mainly concentrated on the inner conductor of the first row of connectors. And the forces on connectors 2 and 3 are greater than that on connectors 1 and 4. When \(x=32\) mm, The force is very small.
Figure 16. Curves of the surface force in I-type breech.

The curves of the surface force $F_{sx}(X)$ of the I-type breech at different $x$ position is shown in figure 16. Similarly, the breech could be divided into 4 different regions in the $x$ direction. Overall, compared with the L-type, the surface force distribution on the I-type breech is much smoother. The surface force changes are mainly concentrated in region 1 and region 3, which indicates that the two current injector plates have received the most electromagnetic force. On the other hand, it represents that the force on the connector is very small.

Figure 17. Distribution of the momentum in I-type breech.

The surface force density distribution of I-type breech at different $x$ positions is shown in figure 17. On the whole, the surface force is mainly concentrated on the center of the plate near the rail2. Compared with the L-type breech, the force distribution on the connectors is more uniform, but it is small. Besides, there is still a large surface force when $x=32$mm.

5. Conclusions
In this paper, railguns are divided into two types based on the direction of the source current in the breech. According to the momentum conservation equations, two types breeches were modeled and
simulated with the finite element method. By analyzing and discussing the simulation results, the conclusions are as follows.

1) The momentum of the railgun system is conserved, and the reversed force is transmitted to the breech by the electromagnetic field in the forms of the surface force. Besides, different structures of the breech will not affect the launch performance of the railgun.

2) The reverse force is mainly concentrated on the current injector plates and the power connectors. Moreover, the force on the I-type breech is more uniform than that of L-type breech.

3) The longitudinal force on the power connectors of L-type breech is much bigger than that of the I-type breech, up to nine times.

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