Research on the Dynamic Properties of Electromagnetic Railgun Launch System

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Abstract. Electromagnetic railgun launch system is the part designed for launching projectile. The dynamic properties of the launch system contribute to the firing accuracy. This paper models the finite element model of a square-shaped railgun. The Ansys ACP module is used to design the layer of carbon fibre barrel of the railgun. Modal analysis of the launch system is performed using Ansys. On this basis, the modal superposition method is used to calculate the dynamic response of the launch system caused by the electromagnetic expansion force during launching. This paper analyses the steel encapsulation barrel as a comparison and verifies the rationality of using the composite material. The results provide support for the engineering design of electromagnetic railgun.

1. Introduction
The electromagnetic railgun uses electromagnetic thrust instead of traditional gunpowder to provide launching power for the projectile. It is a new concept weapon with superior performance such as high initial velocity and long range [1]. The launch system acts upon the projectile directly and its dynamics properties have a direct impact on the firing accuracy. Scholars have made a series of studies on the dynamic and static characteristics of railguns [2-4]: Tian Zhenguo simplified the composite rail to an elastic foundation beam, and obtained the local stress near the interface between armature and rail and the dynamic response of the rail [5, 6]; the characteristics of recoil motion during launching of electromagnetic railgun were analysed by Shi Jiangbo et al. [7]; Kamran Daneshjoo, J.T. Tzeng studied the relationship between critical velocity and barrel response [8, 9]. The launching process of railgun is a complex process of interaction among barrel, cradle and recoil device. Kinetic analysis of a single barrel or other component does not examine the dynamic properties of the system in general. From the overall point of view, the modal analysis and transient dynamic analysis of the launching system of a railgun are carried out, which provides a reference for the design of the railgun launching system.

2. Modal analysis of railgun launch system
According to the traditional artillery design experience, in the design process of the relevant components, it is necessary to consider the influence of the firing frequency to avoid the resonance caused by overlap of firing frequency and the natural frequency of the component. Therefore, it is necessary to perform modal analysis on the electromagnetic railgun launch system centred on the overall launch index. Modal analysis is the basis of other dynamic analysis. The finite element modal analysis uses finite element method to determine the modal parameters of the system.
The multi-degree-of-freedom system free vibration differential equation is

\[ M\ddot{X}(t) + C\dot{X}(t) + KX(t) = 0 \]  \hspace{1cm} (1)

where \( M \), \( C \) and \( K \) are respectively the mass matrix, damping matrix and stiffness matrix of the system; \( \dot{X}, \ddot{X} \text{ and } X \) are respectively structural acceleration array, structural velocity array and structural displacement array.

This equation has a solution to make

\[ x_i = A_i e^{\omega_i t}, (i = 1, 2, ..., n) \]  \hspace{1cm} (2)

The characteristic equation of the MDOF system is obtained after bringing the solution into differential equation. The \( n \)-order natural frequencies and modes of the system can be obtained by solving the characteristic equation \([10, 11]\).

2.1. Finite element modeling of the launch system

The electromagnetic railgun launch system includes a barrel, a neck tube, a gun tail feeding module, a cradle and a recoil device. The barrel is mainly composed of rails, support bodies and an encapsulation layer. When the current is transmitted through the rail behind the armature and acts on the magnetic field, a strong electromagnetic expansion force is generated on the two rails. This requires a structure on the outside of the rail to resist the expansion of the rail to ensure that the rail spacing deformation meets the requirement. The fibre winding packaging technology is used to form a composite material barrel with the characteristics of light weight, good rigidity and good encapsulation by winding the composite material on the outside of the rail and the insulating support body, which is an ideal solution for realizing the engineering application of the electromagnetic railgun \([12]\).

This paper established the launch system model using Creo three-dimensional modelling tool, simplified some of the components and reserved a modelling space for the composite barrel winding layer. The recoil device was processed into a spring with damping. The model barrel is 3 m in length and 40 x 40 mm in diameter. In order to ensure the barrel deformation in a reasonable level and to control the barrel recoil trajectory, a half-long neck barrel was used to restrain the barrel. The Ansys ACP (Ansys Composite Prepost) module was used to lay out the layered carbon fibre wound layer which was made of fibre-reinforced resin-based composite material T700/Epoxy with excellent mechanical properties. Elastic characteristic parameters (\( E_1, E_2, G_{12} \) and \( v_{12} \)) were obtained by unidirectional plate performance test. Based on the basic theory of composite mechanics, nine parameters of orthotropic material were calculated and input into the material properties.

| Material | \( E_x \) (GPa) | \( E_y \) (GPa) | \( E_z \) (GPa) | \( V_{xy} \) | \( V_{yz} \) | \( V_{xz} \) | \( G_{xy} \) (GPa) | \( G_{yz} \) (GPa) | \( G_{xz} \) (GPa) |
|----------|----------------|----------------|----------------|------------|------------|------------|----------------|----------------|----------------|
| T700     | 154.2          | 11.4           | 11.4           | 0.33       | 0.49       | 0.49       | 7.1            | 3.8            | 7.1            |

10 layers of 0.1mm-thick fabric makes a sub-laminate. Three laminates with thickness of 7mm and 6mm are created by sub-laminates. Three laminates are assembled into carbon fibre winding layer from outside to inside with the thickness of 7mm, 6mm and 7mm in order. The winding angles of the three laminates are 0, 45 and 90 degrees in order. The carbon fibre wound layer has a total thickness of 20 mm.

The composite barrel winding layer was imported into the reserved space of the assembly, and the contact was set up to complete the launch system modelling.

Figure 1. 0 degrees carbon fibre layer.
2.2. Material Properties and Boundary Conditions

The material performance parameters of each component are shown in the table.

794,759 nodes and 167,063 units engendered after the model was meshed. The cradle is coupled to the gun carriage through the trunnion, so a fixed support is imposed on the hole of the trunnion.

| Main part            | material       | density(g/cm³) | elastic modulus (MPa) |
|----------------------|----------------|----------------|-----------------------|
| Rail                 | copper         | 8.25           | 1.3e+5                |
| Support body         | glass fibre    | 1.8            | 1.5e+4                |
| Compressed steel plate| structure steel| 7.86           | 2.0e+5                |
| Sleeve               | carbon fibre   | 1.85           | 1.54e+5               |
| Cradle               | aluminum alloy | 2.7            | 7.0e+4                |
2.3. Modal analysis results

After applying constraints to the finite element model of the railgun launch system, the modal solution is solved by Ansys, and the first six natural frequencies and modes of the system are obtained. The frequencies of the system in the form of steel package is also calculated as a comparison.

Table 3. The first six natural frequencies.

| Mode | frequency/Hz (composite material) | frequency/Hz (steel) |
|------|----------------------------------|----------------------|
| 1    | 8.8905                           | 7.139                |
| 2    | 9.2987                           | 7.6131               |
| 3    | 64.94                            | 47.974               |
| 4    | 71.566                           | 57.553               |
| 5    | 80.975                           | 71.547               |
| 6    | 141.72                           | 130.72               |

Figure 7. First order mode.

Figure 8. Second order mode.

Figure 9. Third order mode.
This result shows that the first six modes of the railgun launch system are mainly bending deformation. The firing frequency is lower than the natural frequency of the launch system. It could be found from the comparison that the application of composite barrel could generally improve the natural frequency of the launch system, and the weight is significantly reduced.

3. Dynamic response of launch system subjected to electromagnetic force
During the launching process of the electromagnetic railgun, the rail behind the armature bears a huge electromagnetic expansion force under the action of strong pulse current. This force can be regarded as a moving load along the rail direction.
3.1. Calculation of electromagnetic force
The image is the launching principle of the railgun. According to the principle of electromagnetic action, the electromagnetic repulsion force per unit rail length is equal to that on armature per unit span.

\[
\frac{F_y}{z} = \frac{1}{2} \frac{\partial}{\partial y} L'I^2 = \frac{L'I^2}{2s}
\]  \hspace{1cm} (3)

The pressure on the rail is

\[
p = \frac{1}{2} \frac{\partial}{\partial y} L'I^2 h^{-1}
\]  \hspace{1cm} (4)

where \( s \) is the distance between two rails; \( h \) is the height of the rail.

\( s \) is set to 40mm; \( I \) is set to 420KA; the inductance gradient calculated by finite element method is \( 0.42 \mu H / m \). The pressure is \( p = 24.8 MPa \).

The initial speed is 2000m/s. Assuming that current value is constant, the motion of armature is uniformly acceleration. Acceleration speed is

\[
a = v^2 / 2s = \frac{2}{3} \times 10^6 m / s^2
\]  \hspace{1cm} (5)

Time that armature moves on the rail is

\[
t = v / a = 3 ms
\]  \hspace{1cm} (6)

3.2. Electromagnetic force loading simulation
The Slice cutting process was performed on the rail to simulate the loading process of electromagnetic force. The rail was equally divided into 30 regions in the axial direction, and the loads were respectively applied in accordance with the time sequence of the current passing.

![Figure 14. Electromagnetic force on the rail.](image)

3.3. Result
The modal superposition method is used to solve the response results. The results are as follows.

![Figure 15. Muzzle transverse displacement response.](image)
Figure 16. Muzzle longitudinal displacement response.

Figure 17. Muzzle transverse acceleration response.

Figure 18. Muzzle longitudinal acceleration response.

The results show that the muzzle displacement response of the launch system with composite barrel is less than that with the metal package barrel. The response convergence of the composite barrel is better than that of the metal package, which indicates that the composite material has a strong damping effect that is beneficial to reducing the vibration. Therefore, it is more reasonable to use carbon fibre composite barrel in engineering design.

4. Conclusion
In this paper, based on the dynamic properties of electromagnetic gun launch system, a three-dimensional model of square-calibre electromagnetic railgun launch system is established. Modal analysis of the mainstream launch system consisting of carbon fibre reinforced composite barrels is carried out, and the first six natural frequencies and modes are obtained. The results show that the natural frequencies of the launch system are much higher than the firing frequencies and the resonance
is reasonably avoided. The results of dynamic response of muzzle subjected to electromagnetic force is obtained using modal superposition method, which verifies the rationality of using composite barrel. The conclusion can be taken as a reference for engineering design of railgun.

There is room for further improvement and optimization in this study: adjusting the performance and laying parameters of composite materials may obtain better indicators; refining Slice tool may make the simulation results more accurate; the simulation does not fully conform to the actual working conditions since the electromagnetic force is not only distributed on the inner surface of the rail, but also unevenly distributed in the interior of the rail; this simulation does not consider the electromagnetic expansion force of armature arm and the varying inductance gradient near armature, which should be considered in the follow-up work.

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