A Whole Trajectory Simulation for the Electromagnetic Rail Gun

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***Abstract*—With the improvement of electromagnetic launch technology, electromagnetic rail gun will emerged in future battlefield. A whole trajectory simulation is proposed in order to analyze ballistic characteristics. According to analysis of the whole trajectory simulation process of electromagnetic rail gun, the whole trajectory models including inner ballistics model and exterior model are developed to perform simulation task. Several simulation experiments are accomplished under the developed system. Simulation results show that the system can simulate the whole trajectory of electromagnetic rail gun. Meanwhile, the whole trajectory simulation system provides a foundation for the ballistics integration design of electromagnetic rail gun system.**

Keywords-Electromagnetic Rail Gun (EMRG); Simulation System; Whole Trajectory Simulation; Ballistics Model.

I. INTRODUCTION

Electromagnetic launch is a new concept in military technology, which utilizes electromagnetic force to accelerate the projectile and transform the electric energy of power into kinetic energy of launch package to complete many missions [1]. The system consists of energy storage devices, pulsed power, rails, armature, projectile and other related devices. Pulsed power, the core of Electromagnetic Rail Gun (EMRG), is controlled by adjusting the working state to perform charging and acceleration mission. Pulsed power, composed of sets of high-capacity capacitor modules, thyristor switch, pulse-shaping inductor, crowbar diode, can generate very powerful instantaneous current pulse. When the rail is connected power, current flows into armature along one rail and flows back along the other to form close circuit. When strong currents flow along the two parallel rails, a great magnetic field, formed between the two rails, interacts with the current flowing through armature to generate powerful electromagnetic force. This force accelerates armature and projectile along the rails to the bore with high speed, as shown in Figure 1.

EMRG has obvious advantages. Firstly, it has strong survivability and is very safe in application. Secondly, the launch velocity can be controlled by the magnitude of current to increase the shooting accuracy. Thirdly, it has low costs and allows continuous multi-shot. Lastly, the projectile shot from the bore with high initial speed can achieve wide range.

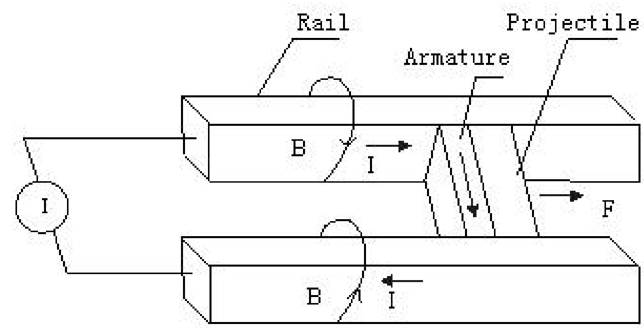

Figure 1. Principle of electromagnetic rail gun

Currently, the development of electromagnetic rail gun mainly focuses on key components, such as pulsed power, rail, armature and projectile [2-4], while researches on ballistics performance, especially on whole-trajectory characteristics, are relatively weak.

The Department of the Navy's science and technology corporate board chartered the Innovative Naval Prototype (INP) construct to foster game-changing and disruptive technologies ahead of the normal requirements process [5].

This paper analyzes the whole trajectory simulation process of EMRG system and, the system requirements of EMRG simulation are determined. The ballistics model including inner ballistics model and exterior ballistics model is established. Then, the EMRG simulation is realized to perform the whole-trajectory simulation and analysis.

II. WHOLE TRAJECTORY SIMULATION PROCESS OF EMRG SYSTEM

There are five stages about the whole trajectory simulation process of electromagnetic rail gun system [6].

--Firstly, discharging and attacking Stage: Pulsed power is charged by energy storage device and launching equipment prepares to launch. Projectile is pushed into the launching rails; Pulsed power discharges to supply appropriate powerful current, which generates a strong magnetic field between rails.

--Secondly, projectile accelerating stage: The projectile is accelerated along the rails by the great Lorentz force. Due to the drag forces, the projectile and rails generate much heat, and the thermal aggregation causes the characteristic alteration of component material.

--Thirdly, projectile flight stage: The off-rail projectile, affected by aerodynamic force and gravity, flies in atmosphere with high speed.

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--Fourthly, attack completion stage: The projectile enters the target area and causes the attacking effect, so that the mission of single shot is accomplished.

--Lastly, launching ending stage: The motion state of the projectile in the barrel is calculated, and analysis of the ballistics performance for rail gun is performed.

III. DEVELOPMENT OF EMRG SIMULATION MODEL

A. Requirement of EMRG Simulation

The functions of the electromagnetic rail gun simulation system include:

Firstly, simulation system should simulate the launch process of the electromagnetic rail gun and the flight process of the projectile.

Secondly, simulation system can manage the various simulation processes including inner ballistics process, exterior ballistics process and whole trajectory to meet many demands.

B. Inner Ballistics Model of EMRG

The ballistics performance of projectile in the barrel is directly governed by effects of various forces on it. The equation expressing the mechanical equilibrium is:

$$(m_p + m_a)\frac{dv}{dt} = F - F_f - F_p \tag{1}$$

where F_f is the friction drag force between rail and armature and F_p is the drag force on the projectile. F is electromagnetic force accelerating armature and projectile, which is determined by

$$F = \frac{1}{2} L' i^2 \tag{2}$$

where L' is per unit inductance of the rails and i is the current in the rails.

The friction drag force on the armature can be expressed by [7]

$$F_f = \mu_f \left(F_{n0} + \frac{kS_b}{2A_b}\left(F + F_p\right)\right) \tag{3}$$

where μ_f is the friction coefficient, F_{n0} is the initial pressure on the rail, S_b and A_b are the perimeter and cross-sectional area of the armature. The drag force on the projectile F_p in (1) is estimated by considering the status of compressed air ahead of projectile [8]

$$F_p = (\frac{\gamma + 1}{2})\rho_0 [A_b v^2 + A_b xa + (1/2) C_f S_b v^2 x] \tag{4}$$

where C_f, γ and ρ_0 are the viscous coefficient, specific heat and density of compressed air, v and a are velocity and acceleration of the projectile, x is distance along the rail.

The rail gun is a launch device to transform the electric energy to kinetic energy. In the application, the rails and armature are considered as the load of pulsed power supply system. The equivalent electrical model for the n segments capacitor banks is shown in Figure 2.

The electrical equilibrium equation of the equivalent circuit is expressed as

$$L_n \frac{di_n}{dt} + R_n i_n + \int \frac{1}{C_n} i_n \mathrm{dt} = -R_{armature} i - R_{rail} i - \frac{d(L_{rail} i)}{dt} \tag{5}$$

where $i = i_1 + i_2 + \ldots i_n$ is the total current flowing through the rails, R_n, L_n and C_n are the equivalent resistance, inductance and capacitance of the n pulsed power segment.

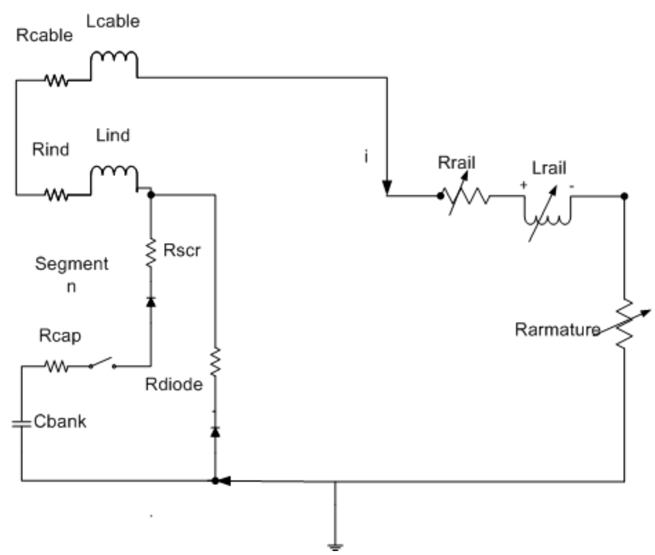

Figure 2. Equivalent electrical model for the n segments capacitor banks

The rail resistance includes heating effect and the current skin effect. The resistance is given by [9]

$$R_{rail} = R_{r0} + \frac{8}{3h}\sqrt{\frac{\pi \mu_r \rho_r}{2t}} x \tag{6}$$

where μ_r is the permeability, h is the rail height, R_{r0} is the initial resistance of the rail, ρ_r is the instantaneous resistivity , which is determined by [10]

$$\rho_r = \rho_0 + \beta \frac{i}{h} \tag{7}$$

where β is the current dependent resistivity.

The rail inductance proportional to the distance along the rail x is expressed by

$$L_{rail} = L' x \tag{8}$$

The armature provides a closed electrical path between the rails. The time varying resistance can be expressed by [11]

$$R_{armature} = \frac{d}{h_a}\sqrt{\frac{\pi \mu_a \rho_a}{2t}} \tag{9}$$

where d is the rail separation, h_a is the height of armature, μ_a and ρ_a are permeability and resistivity of the armature.

C. Exterior Ballistics Model of EMRG

When the projectile flies to the target, the projectile launched by EMRG is assumed to be a pellet with six degrees of freedom in the air. During the flight, the projectile with high speed is affected by the aerodynamics and gravity. In the study, we make assumptions that the effects of the aerodynamic heating and the earth's rotation on the projectile are ignored. The dynamic and kinematic equations of the projectile in the air are expressed by (10)-(13).

Kinematic equations of the moving gravity center

$$\begin{cases} \dfrac{dx}{dt} = v\cos\psi_2 \cos\theta_1 \\ \dfrac{dy}{dt} = v\cos\psi_2 \sin\theta_1 \\ \dfrac{dz}{dt} = v\sin\psi_2 \end{cases} \tag{10}$$

Dynamic equations of the moving gravity center

$$\begin{cases} m\dfrac{dv}{dt} = -\dfrac{1}{2}\rho S C_x v_r (v-\omega_{//}) + \dfrac{1}{2}\rho S C'_y [\omega_{x\perp}^2 + \omega_z^2 - \\ \omega_{x\perp}(v-\omega_{//})\delta_1 + \omega_z (v-\omega_{//})\delta_2] - mg\sin\theta_1 \cos\psi_2 \\ mv\cos\psi_2 \dfrac{d\theta_1}{dt} = F_p \cos\delta_2 \sin\delta_1 - \dfrac{1}{2}\rho S C_x v_r \omega_{x\perp} + \\ \dfrac{1}{2}\rho S C'_y [v_r^2 \delta_1 - (v-\omega_{//})\omega_{x\perp}] - mg\cos\theta_1 \\ mv\dfrac{d\psi_2}{dt} = \dfrac{1}{2}\rho S C_x v_r \omega_z + \dfrac{1}{2}\rho S C'_y [v_r^2 \delta_2 + \\ (v-\omega_{//})\omega_z] + mg\sin\theta_1 \sin\psi_2 \end{cases} \tag{11}$$

Dynamic equations rotating the moving gravity center

$$\begin{cases} C\dfrac{d\omega_\varepsilon}{dt} = \dfrac{1}{2}\rho v_r^2 S l m_{xw} - \dfrac{1}{2}\rho v_r S l d m'_{xd} \omega_\xi \\ A\dfrac{d\omega_\eta}{dt} + C\omega_\xi \omega_\varepsilon - A\omega_\xi^2 \tan\varphi_2 = -\dfrac{1}{2}\rho S l m'_z v_r \\ [(v-\omega_{//})\delta_2 + \omega_z] + \dfrac{1}{2}\rho S l m'_y v_r [(v-\omega_{//})\delta_1 - \omega_{x\perp}] \\ A\dfrac{d\omega_\xi}{dt} - C\omega_\varepsilon \omega_\eta + A\omega_\eta \omega_\xi \tan\varphi_2 = \dfrac{1}{2}\rho S l m'_z v_r \\ [(v-\omega_{//})\delta_1 - \omega_{x\perp}] + \dfrac{1}{2}\rho S l m'_y v_r [(v-\omega_{//})\delta_2 + \omega_z] \end{cases} \tag{12}$$

Kinematic equations rotating the moving gravity center

$$\begin{cases} d\varphi_a / dt = \omega_\xi / \cos\varphi_2 \\ d\varphi_2 / dt = -\omega_\eta \\ d\gamma / dt = \omega_\xi - \omega_\xi \tan\varphi_2 \end{cases} \tag{13}$$

Geometric relation equations is given by (14)

$$\begin{cases} \sin\delta_{r2} = \sin\varphi_2 \cos\psi_r - \sin\psi_r \cos\varphi_2 \cos(\varphi_a - \theta_r) \\ \sin\delta_{r1} = \sin(\varphi_a - \theta_r)\cos\varphi_2 / \cos\delta_{r2} \\ \cos\delta_r = \cos(\cos\delta_{r1} \cos\delta_{r2}) \\ \sin\alpha_{ar} = \sin(\varphi_a - \theta_r)\sin\psi_r / \cos\delta_{r2} \end{cases} \tag{14}$$

IV. EMRG SIMULATION AND RESULTS

Simulation experiments are performed by utilizing the described model including inner ballistics model and exterior ballistics model to analyze the ballistics performance. In these experiments, length of rail is 3 meter, mass of projectile is 50 gram, and six capacitor modules are triggered to supply pulsed current. Some simulation results of position and velocity of projectile are shown in Figure 3 and Figure 4. It indicates that the velocity of the projectile is about 2095 m/s and the launch time is 3.3 ms. Slope of the velocity curve is decreased to zero at the final stage in launch process and the shot out velocity achieved the peak value for this experiment.

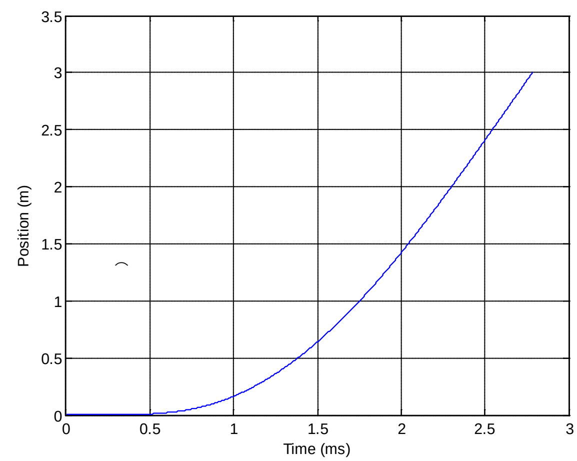

Figure 3. The simulation results of projectile position in the bore

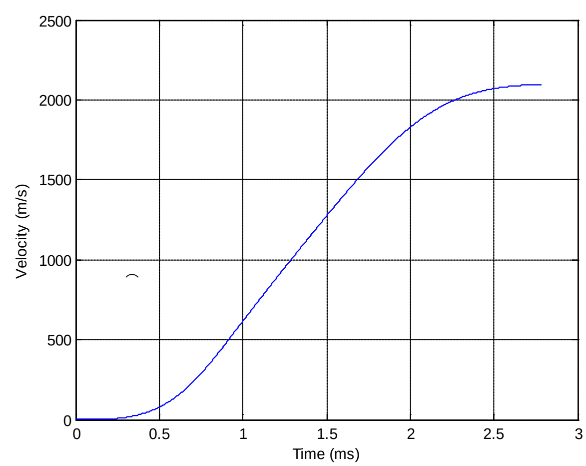

Figure 4. The simulation results of projectile velocity in the bore

The curve of discharging at 6 kv is shown in Figure 5. The performance of pulsed power is 1.1 ms flat-top pulse duration, 0.59 MA peak current and 0.22 MA residual current. The six capacitor modules are switched by thyristor in a certain time sequence to supply flat top current pulse, which makes the rising time of current reduced and the peak current increased greatly.

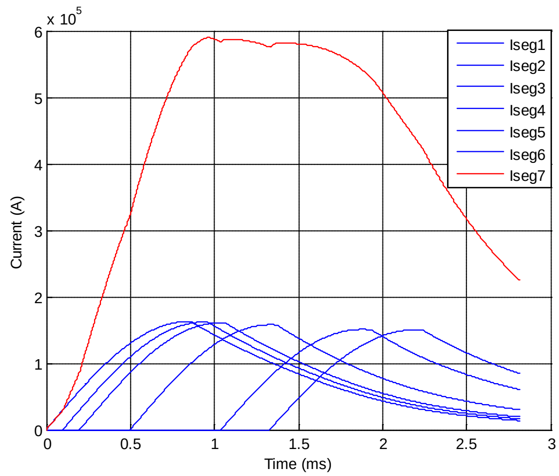

Figure 5. Discharge current of each module and the total current of six modules

The acceleration of the projectile in the bore is shown in Figure 6. It is found that the acceleration curve has the similar shape with that of the total current. The launch process is easily controlled by adjusting the magnitude and shape of the current in the rail.

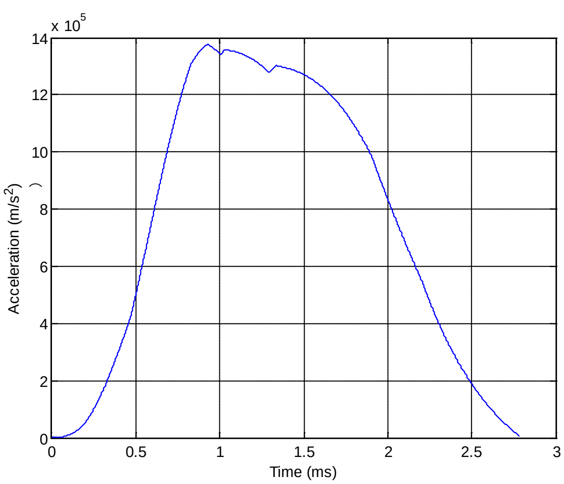

Figure 6. The simulation results of projectile acceleration in the bore

The simulation results of Lorentz force, friction force and air drag force are shown in Figure 7. Comparing these forces, it is obvious that the Lorentz force proportional to the current plays a major effect and friction force is very small and stable during launch. The air drag force is relatively small at the initial stage of acceleration process, but it will increase dramatically with the velocity of the projectile.

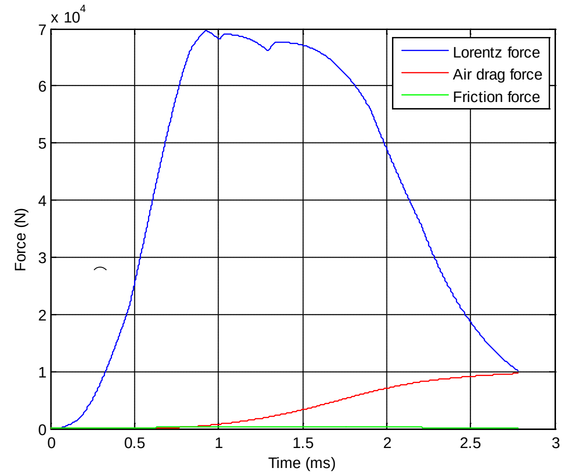

Figure 7. Lorentz force, air drag force and friction force

After the capacitor modules finish discharging, the projectile is shot out the bore with 45° departure angle. The flight velocity of the projectile in the air is shown in Figure 8. The flight velocity decreased greatly in the early stage of flying process because of the effect of the gravity and aerodynamic drag on projectile, but it will slowly decline in the latter stage.

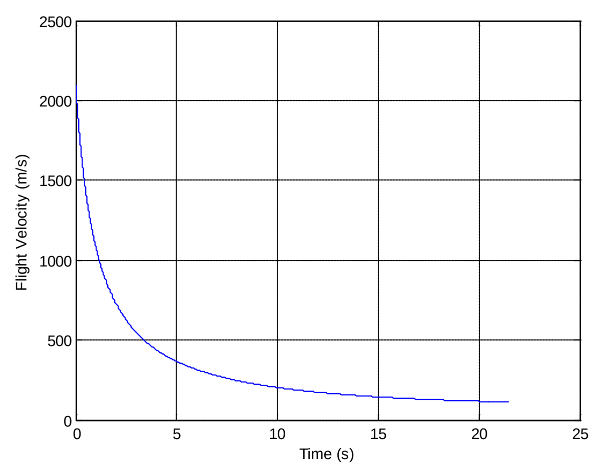

Figure 8. Flight velocity of the projectile in air

The simulation results of projectile range and height in the air are shown in Figure 9 and Figure 10.

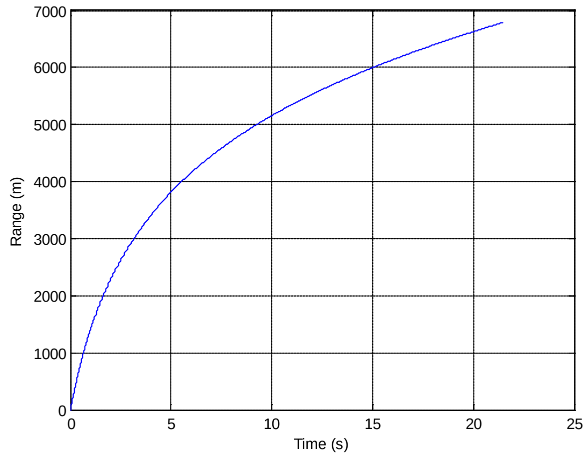

Figure 9. The simulation results of projectile range in air

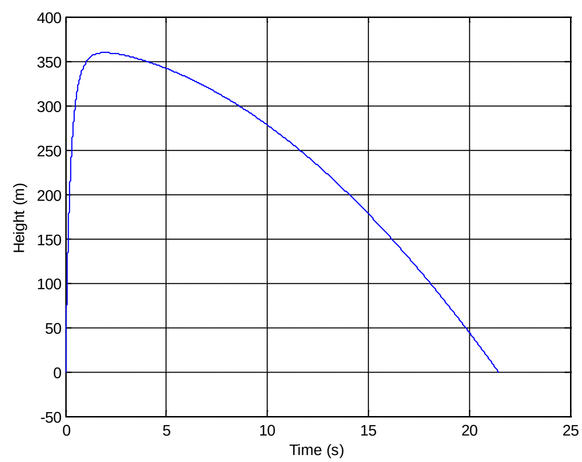

Figure 10. The simulation results of projectile height in air

The range of projectile is 6785 m and the flight height is 365 m during about 23 ms flight time. In the most time of flight the projectile is descend in the air. To improve the exterior ballistics characteristics of the electromagnetic rail gun, decreasing departure angle is an effective way.

V. CONCLUSION AND FUTURE WORK

Some whole trajectory simulations for electromagnetic rail gun are proposed based on the development of whole trajectory simulation models of EMRG. The system can simulate the launching process and the flight process of projectile. The simulation result comparison to the real data will be done in the future work once the data of the prototype or existing system can be obtained.

The application of the simulation system contributes to improve the efficiency of EMRG system designing and lays foundation for the ballistics integration design of EMRG in early design stage.

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