Modeling and numerical simulation on launch dynamics of integrated launch package in electromagnetic railgun

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Abstract. This paper presents a numerical approach to modeling launch dynamics of integrated launch package in railguns. This approach was based on the three-dimensional transient finite element solutions of the multi-physical field equations. Numerical simulations were conducted for a railgun system composed of the capacitor-based pulse forming network, advanced containment launcher, and integrated launch package. Some issues about induced eddy currents, stress distributions, and projectile lateral motions were discussed. The results show that the in-bore motion of the projectile is sensitive to the launch package configuration and launcher stiffness. Moreover, the armature under a heavy current is prone to serious deformation and then leads to launch failure. The launch dynamics model provides a method to predict the in-bore processes and evaluate the in-bore survivability of the integrated launch package in a railgun.

Nomenclature

| Symbol | Description |
|--------|-------------|
| \(u_{ck}\) | capacitor voltage |
| \(i_k\) | branch current |
| \(i\) | exciting current |
| \(R\) | resistance |
| \(L\) | inductance |
| \(C\) | capacitance |
| \(t\) | time |
| \(A\) | magnetic vector potential |
| \(\phi\) | electric scalar potential |
| \(\mu\) | permeability |
| \(\sigma_e\) | electrical conductivity |
| \(B\) | magnetic flux density |
| \(H\) | magnetic field intensity |
| \(E\) | electric field intensity |
| \(J\) | current density |
| \(q\) | ohmic heating power |
| \(T\) | temperature |
| \(\rho\) | mass density |
| \(c\) | specific heat |
| \(\kappa\) | thermal conductivity |
| \(\sigma\) | stress tensor |
| \(V\) | velocity vector |
| \(f\) | Lorentz force density |
| \(u, v, w\) | nodal displacement |
| \(\varepsilon\) | strain |
| \(x_i\) | coordinate |
| \(n_i\) | normal vector |
| \(G. E.\) | governing equation |
| \(B. C.\) | boundary condition |
| \(L_W, L_F\) | inductance gradient |

1. Introduction

The launch dynamics of projectile is a science to study the in-bore motion of projectile and its related problems during the launch phase. It has significant influences on the projectile survivability during...
the launch phase and the accuracy at the impact. The complexity of the projectile launch dynamics in a conventional gun is caused by the interaction between the gun and the projectile. The launch dynamics of the conventional gun has been studied extensively, and its model is generally based on the multi-body system dynamics method [1-2]. The launching principle and launcher structure of the electromagnetic railgun are quite different from those of the conventional gun, therefore, there are inevitably some new contents arising from the projectile launch dynamics in the railgun.

What the weaponized railgun launches is the integrated launch package (ILP), which contains some key components such as the armature, sabot, and projectile. The interactions between ILP and launcher, as well as the interactions between the ILP components, should be considered in the launch dynamics model. However, in previous studies, only the interaction between armature and rail has received wide attentions. Some models were developed to investigate the dynamic response of the rail due to the armature movement [3-5]. To examine the disturbances acting upon a projectile during railgun launch, Zielinski A E [6] conducted a series of experiments and found that the projectile accuracy was related to its in-bore dynamics. Chu S H [7] proposed a simple launch dynamics model to study the balloting motion of ILP. He assumed the launch system to be rigid everywhere except at the contact regions between the barrel and the launch package.

The need for precise launch dynamics model became apparent in recent years. Satapathy S [8] conducted in-bore dynamics analysis for their ILP designs using the explicit finite element code DYNA3D. Li G [9] used the nonlinear finite element software ABAQUSS/explicit to calculate the dynamic response of the ILP under the given acceleration. The structure models of their simulations were greatly simplified, and the 3D distributed electromagnetic force loads were also replaced by the pressure or acceleration curves.

The actual railgun launcher has a heterogeneous and non-axisymmetric structure, and the propulsion force acting on the armature is the volume force rather than the pressure as in the conventional gun. In the interior ballistic cycle of several milliseconds, the instantaneous release of electric energy generates strong distributed electromagnetic force, and then excites the dynamic response of the launcher and ILP, which forms a complex dynamic process under the coupled multi-physical field. Numerical simulation about the transient multi-physical field is helpful to understand the projectile launch dynamics with more details. The numerical examples of some 3D computational programs for railguns, such as EMAP3D, EFEM3D, and RGUN3D [10-12], were mainly focused on the armature and rail, whereas the modeling of projectile launch dynamics needs to be aimed at the complete structures including the launcher and ILP. Moreover, some non-linear factors such as the material elastoplasticity, large structural deformation and contact collision need to be considered, which increases the complexity of the modeling.

We have been devoted to the research on the railgun launching theory and technology for more than ten years, and developed a transient multi-physical field solver for the electromagnetic, thermal and structural fields [13-14]. We attempted to apply this solver to study the projectile launch dynamics in the railgun. Numerical simulations were conducted to the system composed of the advanced launcher with filament winding containment structure, and the launch package with the mid-riding or base-push configurations. This paper is organized as follows. In Section 2, the models are described. Section 3 contains the numerical results and the analysis about the launch processes. Finally, in Section 4, the conclusions are presented.

2. Computation model

2.1. Mathematical and physical model
The framework of the computational model is shown in figure 1. The model consists of four parts: the external circuit, electromagnetic field, thermal field, and structure field.
The external circuit refers to a pulse forming network (PFN) based on capacitor banks. The armature and rails are regarded as the PFN's loads. The exciting current at any moments can be obtained by solving a set of ordinary differential equations with the Runge-Kutta method.

The conductors, insulators and free space are included in the computational domain of electromagnetic field. The conductors are described by the magnetic diffusion equations and discretized by the finite element method. The exciting currents are applied to the breech ends of the rails. The insulators and free space are described by Laplace equation and discretized by the boundary element method. The finite elements and boundary elements are coupled on the conductor surface [15]. Therefore, only the conductor and insulator regions need to be meshed, and the mesh is shared by the electromagnetic field, thermal field and structural field. After solving the electromagnetic field equations, the field quantities including the magnetic flux density $B$, magnetic field intensity $H$, electric field intensity $E$, current density $J$, ohmic heating power density $q$, and Lorentz force density $f$ are calculated. The ohmic heat and Lorentz force are transfer as the source terms to the thermal field and structural field respectively. Moreover, the resistance and inductance calculated according to the electromagnetic field quantities are input to the external circuit model to implement the field-circuit coupling simulation.

The Lorentz force leads to the structural motion and deformation in the launcher and launch package. The structural field is described by the continuum mechanics equations and discretized by...
the explicit finite element method, which has the abilities to track the deformation, motion, contact, collision, and stress wave propagation in complex structures. The updated mesh configuration of the structure field is fed back to the electromagnetic and thermal fields in time, and is used to calculate the magnetic and thermal diffusion processes.

The ohmic heat causes rapid local heating in the conductors. The boundary of the computational domain is assumed to be adiabatic because the launcher and ILP have little heat dissipation during the several milliseconds of the launch cycle. With the ohmic heating power as the source term, the thermal field is described by the temperature diffusion equation and discretized by the finite element method. The influence of the thermal field on the electromagnetic field and structural field is mainly reflected in the constitutive law of materials because both the electric conductivity and the structural strength decrease with the temperature rising. The influence of temperature can be neglected in some cases, and only the coupling of electromagnetic field and structural field are considered.

All of the three fields are defined in Lagrange coordinates, so the time differential in their governing equations shown in figure 1 is described by material derivatives. Given the geometric structures and material properties of the Launcher and ILP, as well as the external circuit parameters, the distribution and evolution of the electro-magnetic-thermal-mechanical quantities in the launching process can be calculated.

2.2. Calculation conditions

Although the models shown in figure 2 have been highly simplified, the typical structural features of the advanced containment launcher and ILP are retained. The round-bore launcher has a caliber of 40 mm and a length of 2.4 m. It consists of five components, that is two rails, two insulators, and a filament wound housing. The material of the rails is elastic, which the density is $8.9 \times 10^3$ kg·m$^{-3}$, the Young’s modulus is 124GPa, and the Poisson’s ratio is 0.34. The insulators are also set as elastic with the density, Young’s modulus, and Poisson’s ratio are $8.9 \times 10^3$ kg·m$^{-3}$, 340GPa, and 0.22 respectively. The material properties of the filament wound housing are expressed by the orthotropic elastic model, with the material constants of each simple layer of multilayer composite structure integrated into the apparent engineering constants [16]. In the structural field model, all of the degrees of freedom of the nodes at the breech end of the launcher is constrained to make the whole launcher form a cantilever beam structure.

The two ILPs have almost the same mass which is about 0.5 kg. The projectile has a diameter of 14.5 mm and a flare-stabilized aerodynamic shape. To reduce the mesh complexity, the wind shield of the projectile is neglected. There are several annular grooves near the mass center of the projectile, which are jointed with the armatures of the mid-riding ILP or the sabots of the base-push ILP.

![Figure 2](image_url)  
**Figure 2.** Cross section of the launcher and schematic diagrams of mid-riding and base-push ILP.

The total energy storage of the pulsed power supply system that drives the railgun launcher is 7MJ, which is composed of 140 capacitor-based energy storage modules with equal parameters in parallel. The module shown in figure 3 consists of 4 high-power devices, that are the capacitor, inductor, thyristor, and silicon stack, respectively. The stray resistance is also accounted in the circuit model. The circuit parameters are: $C_L=1$ mF, $L_L=20$ μH, $R_c=2$ mΩ. All of the modules are divided into 20 groups. The thyristors of each group are turned on according to the pre-set delay time to achieve sequential discharge and obtain the desired current waveform on the launcher.
3. Results and discussion

3.1. Results with elastic material model
Firstly, the mechanical properties of all components except the filament wound housing were set to linear elasticity. The calculation began from the turn-on time of the first energy storage module and ended when the ILP exit the muzzle. Some dynamic characteristics of the whole launch process are analysed as follows.

3.1.1. Induced current of projectile. Imperfect electrical contacts in the systems conducting heavy currents usually lead to some adverse effects. Therefore, except the contact between the armature and rail, other electrical sliding contacts should be avoided as far as possible in a railgun. The insulation treatment on the projectile surface can prevent it from conducting currents, but it is still inevitable to induce eddy currents in a pulsed high magnetic field because the projectile is usually made of metal.

The numerical results show that the eddy currents are induced on the projectile of the mid-riding ILP in the initial stage of launching. As shown in figure 4, at 0.200 ms, the current density magnitude of the projectile on the left side of the armature is similar to that of the armature and rails, whereas the eddy current on the projectile vanishes at 0.620 ms.

![Figure 3. Circuit diagram of capacitor-based energy storage module.](image)

![Figure 4. Current density contours of mid-riding ILP.](image)

![Figure 5. Current density contours of base-push ILP.](image)

Figure 5 shows the current density contour of the base-push ILP at 0.200 ms. The projectile of the bash-push ILP are all in front of the armature, where the magnetic field is relatively weak. Even at the beginning of discharge when the magnetic field changes rapidly, there is no apparent eddy current on the projectile.

In order to examine what effects the projectile eddy currents will have on the launching process, numerical simulations were conducted on the models with or without the eddy current effects of the projectile considered. The results show that the contribution of projectile eddy current to the ILP acceleration is less than one in ten thousand for both the mid-riding and base-push. Therefore, the eddy current of the projectile can be neglected, which can reduce the amount of calculation for the electromagnetic field.
3.1.2. **Lorentz force acting on ILP.** The current diffusion shown in figure 4 and 5 also results in the non-uniform distribution of Lorentz force. The Lorentz force vectors of the mid-riding and base-push ILP cases are compared in figure 6. The distributions of the Lorentz force acting on the rails are approximately the same. There are high magnitude vectors at the rail segments behind the ILP, and these vectors are mainly located at the edges of the rails, which associates with the current density concentration caused by the velocity skin effect. The force vectors on the rails point to the outside of rails during most of the launch cycle, however, when the ILPs approach the muzzle at 2.564 ms in figure 6(a) and 2.567 ms in figure 6(b), some inward vectors appear at the rails near the breech ends. This does not mean that the Lorentz force makes the rails attractive to each other, because these vectors only exist at the edges of the rails, and the reverse of the local Lorentz force vectors is just a response of the current and magnetic field distribution to the current magnitude drop.

![Vectors of Lorentz force](image)

**(a) Mid-riding ILP case. (b) Base-push ILP case.**

**Figure 6.** Vectors of Lorentz force.

The Lorentz force vectors acting on the ILPs show different distributions due to the quite different ILP configurations, and lead to different in-bore velocity traces as shown in figure 7. Although the current curves almost coincide and the ILP masses are nearly the same, the muzzle velocities are obviously different.

![Current and velocity traces](image)

**Figure 7.** Current and velocity traces.

![Inductance gradient curves](image)

**Figure 8.** Inductance gradient curves.

The accelerating efficiency can be evaluated by the inductance gradient. The inductance gradient curves shown in figure 8 were calculated by two methods, which the curve $L_w$ was directly calculated from the energy storage of the magnetic field, and the curve $L_F$ was calculated according to the classical formula $F=0.5L\dot{I}^2$.

The amplitudes and variation trends of the two $L_w$ curves in figure 8 are roughly the same, which is determined by the same rail configuration. The two $L_F$ curves vary with the time, and the curve of the mid-riding ILP has a lower amplitude than that of the base-push ILP after 2.0 ms, which implies that the accelerating efficiency is affected by the armature configuration.
3.1.3. 

Stress distribution in ILP. Figure 9 shows the stress in the launcher and ILP at about 2.0 ms. Generally, the stress on the ILP is higher than that on the launcher. In figure 9(a), high stress appears at the front bore-rider of the armature and the connecting section between the projectile and the armature. In figure 9(b), the high stress zone is mainly located on the projectile, and it increases gradually from the projectile tip to the tail, which presents a typical distribution of the inertial stress.

![Stress contours at about 2.0 ms.](image)

Figure 9. Stress contours at about 2.0 ms.

Figure 10 plots the stress contour sequences of the mid-riding ILP and launcher, in which the stress is displayed with a level one order of magnitude lower than figure 9. It can be seen that there are still some shadows in front of the ILP, or that there are stress variations at the position where the ILP does not reach, which indicates the propagation of the stress wave in the launcher.

![Stress contour sequences of the mid-riding ILP and launcher.](image)

Figure 10. Stress contour sequences of the mid-riding ILP and launcher.

The generation and propagation of stress wave will lead to dynamic deformation of the launcher [17], and act on the projectile through the coupling of launch package and launcher, resulting in a dynamic response of the projectile.

3.1.4. 

In-bore lateral motion of projectile. Although the projectile is constrained by the armature or sabot, the in-bore lateral motion of projectile cannot be ignored because it is related to muzzle jump, intermediate and terminal ballistics and, consequently, weapon system accuracy. The transverse motion and rotation around the mass centre of the projectile were calculated according to the finite element results of the structural field. Figure 11 shows the curves of the transverse displacements of the projectile mass centre, $d_y$, $d_z$, and the rotation angles $R_{xy}$ and $R_{xz}$ around the mass centre on the $xoy$ and $xoz$ planes.
Oscillation is a common feature of all curves in figure 11. In the mid-riding ILP, the armature plays key roles in both generating the propulsion force to and stabilizing the in-bore motion of the projectile. The disturbances of the lateral forces derived from the Lorentz force act on the projectile directly, so the in-bore lateral motion of the mid-ride ILP seems more complex than that of the base-push ILP.

Although the curves of the base-push ILP are smoother than that of the mid-riding ILP, the amplitude of the base-push ILP is much larger. This is because that the propulsion force of the armature acts on the projectile base, and it is prone to produce rotational torque to the projectile; whereas the projectile of the mid-riding ILP is connected with the projectile near the mass center.

3.2. Effects of launcher stiffness on in-bore lateral motion

The components of the launcher and integrated launch package constitute a multi-body dynamic system. Besides the ILP configurations mentioned above, the in-bore lateral motion of projectile may also be affected by the launcher. It has been recognized that launchers need sufficient stiffness to prevent the arc transition due to the rail expansion [18-19]. We studied whether the launch dynamics process is sensitive to the launcher stiffness. Because the launcher stiffness is dependent on the thickness and material modulus of the filament wound housing, we carried out numerical simulations with the same conditions except for the elastic modulus of the orthotropic-elastic material along the circumferential direction of the barrel reduced from 143.0 GPa to 95.0 GPa. The results show that the lateral motion of the mid-riding ILP has changed completely, which can be found by comparing figure 12 with figure 11 (a). The curves of the base-push ILP are not listed here because they have barely changed.
3.3. Effects of material properties on launch stability
The above examples, which are based on the elastic material model, and neglect the effect of temperature on the material properties, are mainly used to describe the generation mechanisms of the launch dynamic responses in a railgun. However, in an actual launch process, as the main load-bearing component of Lorentz force and ohmic heat, the armature is easy to enter the plastic state and produce irreversible large deformation, which not only lead to a different launch dynamic process, but also has a serious threat to the in-bore survivability of the ILP.

Numerical simulations were conducted by the armature modeled as an elastic-plastic material with a yield stress of 322 MPa. Figure 13 shows the stress contours before and after large deformation. In figure 13(a), large deformation appears at 0.712 ms on the position that the armature connects with the projectile, which seriously affects the armature's propulsion on the projectile. In figure 13(b), the bending of the armature arms at 0.691 ms will lead to the failure of the electrical contacts between armature and rail, and cause the launch performance degraded.

![Figure 13. Large deformation of the armature during launch.](image)

(a) Mid-riding ILP. (b) Base-push ILP.

4. Conclusions
The launch of ILP in a railgun is a complex dynamic process under multi-physical field coupling and multi-body interaction. We used the multi-physical field solver to simulate the launch dynamic process of the ILP. The in-bore dynamic behaviors of the ILP were analyzed, the factors affecting the in-bore motion of projectile and the survivability of ILP were discussed, and some major conclusions were summarized as follows:

1. The induced eddy current on the projectile of the mid-riding ILP is apparent in the initial stage of launching, but it has little influence on the propulsion process.
2. The axial propulsion characteristics of the armature are related to the armature geometry.
3. High stress usually appears on the ILP, and there are stress waves propagating in the barrel.
4. Compared with the base-push ILP, the in-bore lateral motion of the mid-riding ILP is more sensitive to the launcher stiffness.
5. The material properties of armature have an important influence on the in-bore stability of ILP.

The multi-physical field solver can capture some details of the launch dynamics in railguns. It provides a method for evaluating the in-bore survivability of ILP and predicting the muzzle exit conditions.

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