Dynamic response analysis of discrete supported electromagnetic railgun

J G Wu¹, Q H Lin², B M Li², Sh B Wen¹ and D Chen¹

¹School of Automotive & Rail Transit, Nanjing Institute of Technology, Nanjing 211167, Jiangsu, China.
²Key Laboratory of Transient Physics, Nanjing University of Science and Technology, Nanjing 210094, Jiangsu, China.

E-mail: wujg8848@163.com

Abstract. In order to analyze the dynamic deformation of rails subjected to transverse moving magnetic pressure, a 3D simulation model consisting of the launcher and integrated launch package was constructed and solved with dynamic finite element method. Critical velocity effects of rail dynamics were obviously observed in the simulation results. The effects not only enlarge the rail deflections but also affect the contact status between the armature and rails. To mitigate this problem, discrete supports with different stiffness were applied in the simulation. By locally enhancing the stiffness of support, especially for the part of rails where the critical velocity happens, the dynamic responses can be effectively controlled.

1. Introduction

Electromagnetic rail launch (EMRL) is an important way to achieve ultra-high speed in millisecond time scale [1]. Previous studies have shown that the high-speed impact damage (i.e. hypervelocity gouging) between armature and rails is related to the movement state of armature in bore [2, 3]. Thus more attention need to be paid to the dynamics of the interaction between the high-speed moving components and rails. The dynamic responses of beams suffering transverse loads under the support of elastic foundation have been explored by many researchers [4, 5]. Tzeng J.T. [6, 7] and Daneshjoo K. [8] solved the dynamic response of rails and the critical velocity based on Euler-Bernoulli beam theory, and analyzed the effect of rail materials on the critical velocity. Johnson A. J. [9] analyzed the interaction pressure between different types of armature and rails with 2D models through ANSYS. Some other researchers [10, 11] tested the responses of rails during the EM launch and found the deflections of rails were enlarged after the armature arrived a critical velocity. In this paper, a 3D simulation model consisting of the launcher and integrated launch package (ILP) was constructed to analyze the dynamic responses at high-speed velocity under electromagnetic pressure. And the use of discrete supports was introduced to suppress the critical velocity effects.
2. Numerical Model

Taking the scalar potential $\phi$ and the magnetic vector potential $A$ as unknowns, the Maxwell equations can be transformed into the following governing equations:

$$\nabla \times \left( \frac{1}{\mu} \nabla \times A \right) - \nabla \left( \frac{1}{\mu} \nabla \cdot A \right) = -\sigma \left( \frac{\partial A}{\partial t} + \nabla \phi \right) + J_s$$

(1)

$$\nabla \cdot \left( -\sigma \nabla \phi - \sigma \frac{\partial A}{\partial t} + J_s \right) = 0$$

Where, $J_s$ is the source current density; $\mu$ is the magnetic permeability; $\sigma$ is the electrical conductivity.

The electromagnetic force on conductor is calculated as:

$$F_{\text{mag}} = \int_{\Omega} J \times B d\Omega$$

(2)

Where, $B$ is the magnetic flux density vector, $B = \nabla \times A$; $J$ is the current density vector, $J = -\sigma \left( \frac{\partial A}{\partial t} + \nabla \phi \right) + J_s$.

The kinetic equation is expressed as:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + F_{bi} = \rho \frac{\partial^2 u_i}{\partial t^2}$$

(3)

Where, $F_{bi}$ is the unit volume force; $\sigma_{ij}$ is Cauchy stress tensor, $\sigma_{ij} = f(\epsilon_{ij}, \dot{\epsilon}_{ij})$; $\epsilon_{ij}$ is strain tensor, $\epsilon_{ij} = \frac{1}{2} \left( u_{i,j} + u_{j,i} \right)$.

As shown in figure 1, a 3D simulation model consisting of the launcher and ILP was constructed based on finite element method (FEM). The caliber of the launcher is 50mm × 40mm. And the projectile of the ILP is simplified as a mass block with two riders. In the model, the insulator-support
structures were simplified as elastic foundation supports with an equivalent elastic modulus of 10 GPa. All of the parts were partitioned with structured grids. With the grids near the contact surface be densified locally, a total number of 40492 elements were used for mesh generation. During the firing process, a distributed moving magnetic pressure is applied on the inner rail surface where the armature has passed. And a pressure proportional to the square of the current value is applied on the armature trailing arms.

For more representative, a typical current profile with a peak value of 1.0 MA shown in figure 2 was applied in the simulation. The current has three stages: a rising stage, a plateau and a decline stage. The rails have a length of 3.0 m and an inductance gradient of 0.45 μH/m. The ILP arrives at the muzzle within 2.5ms and gets a muzzle velocity of 2176m/s, as shown in figure 3.

![Figure 2. A typical current profile.](image1)

![Figure 3. The velocity and displacement of ILP.](image2)

### 3. Results and Discussions

Figure 4 shows the rail deflection in y direction as the ILP accelerates from 0 to 2176m/s. It is worth noting that, when the armature moves at a low velocity, the rails behind the armature behave a quasi-static deforming pattern under the magnetic pressure load. However, as the velocity arrives to a critical value, the deflection of rails are enlarged and “fluctuation” is obviously seen on the rails behind the armature. The critical velocity is about 1330m/s and the moment is 1.45ms. As the velocity gets higher, a more part of rails behind the armature join in the fluctuation. This critical velocity effects is also shown in figure 5 which illustrates the rail deflection at each time. The fluctuation of rails, marked with the color stripes in the figure, is more obvious after the critical velocity moment.

The critical velocity effects will not only enlarge the rail dynamic responses but also affect the contact status between the armature and rails. Figure 6 shows that the points on the contact surface of the ILP, illustrated in figure 1, have a slight displacement changing with time during the firing process. The lateral displacement is not completely proportional to the current wave, but shows a dramatic change around the critical velocity moment. It can be seen that the displacement on the rear part of the armature is larger than that on the head part. The micro vibration on the rear part of the ILP, enlarged around the critical velocity moment, will probably change the interaction status of the sliding surface.
Furthermore, the interaction at hypervelocity may induce impact between the armature and rails, resulting in gouging.

As we know, the critical velocity of the rails is largely depend on the stiffness of the foundation support. Since that the critical velocity effects is appeared on the latter part of the rails, so we do not have to enhance the stiffness of the support for total rails. As shown in figure 7 discrete supports were applied for the launcher. In the simulation model, only a middle part of 1.0 m rail was supported with a stiffer base of 30GPa. Figure 8 shows the deflection of rails under discrete supports at each time. It can be seen that, the deflection of the middle part of rail with stiffer support is successfully suppressed during the firing time. The fluctuation of the rail only appears near the muzzle, a small part that is not strongly supported. Overall, the rail dynamic responses can be effectively controlled by applying discrete supports, especially enhance the stiffness of support for the part of rail where the critical velocity happens. Figure 9 shows the displacement of the interface points under discrete supports at each time. It can be seen that, with the support of rails be locally strengthened, The lateral displacement of the rear part of ILP has been suppressed, especially around the critical velocity moment. This will make it easier for the ILP to pass through the launcher without damaging the rails.

![Figure 4. Rail deflection in y direction as the ILP accelerates from 0 to 2340 m/s.](image-url)
Figure 5. Deflection of the rail under uniform support.

Figure 6. Displacement of the interface points under uniform support.

Figure 7. Illustration of launcher with discrete supports.
4. Conclusion
A 3D simulation model consisting of the launcher and ILP was constructed and solved with FEM to analyze the interaction dynamics as the armature accelerates to a high velocity in the bore. The following conclusions are obtained:
1) Critical velocity effects which is represented by the fluctuation of rail deflection will enlarge the dynamic responses of rails. The part of rails right behind the armature suffers to large deformation as the armature moves to muzzle.
2) As the ILP arrives to the critical velocity, lateral vibration is more obvious on the rear part of ILP and the rails will squeeze the head of the armature. This will probably cause a local impact on the interaction interface.
3) The dynamic responses can be effectively controlled by applying discrete supports, especially enhance the stiffness of support for the part of rails where the critical velocity happens.

Acknowledgements
This work was supported by the Natural Science Foundation of Jiangsu Province of China(No. BK20191009, BK20191014) and the Scientific Research Foundation for Advanced Scholars of Nanjing Institute of Technology(No.YKJ201840, YKJ201842).

References
[1] Fair H D 2014 IEEE Transactions on Magnetics 45 225-30
[2] Wu J G, Tang B, Lin Q H, et al. 2016 Defense Technology 12 90-95
[3] Wu J G, Lin Q H, Wan Gang, et al. 2017 Explosion and Shock Waves 37 307-14
[4] Nechitailo N V and Lewis K B 2006 Int. J. of Impact Engineering 33 485-95
[5] Achenbach J D and Sun C T 1965 International Journal of Solids and Structures 1 353-70
[6] Tzeng J T. 2003 IEEE Transactions on Magnetics 39 472-75
[7] Tzeng J T and Sun W 2007 *IEEE Transactions on Magnetics* **43** 207-13
[8] Daneshjoo K, Rahimzadeh M, Ahmadi R, et al. 2007 *IEEE Transactions on Magnetics* **43** 126-31
[9] Johnson A J and Moon F C. 2007 *IEEE Transactions on Magnetics* **43** 141-44
[10] Johnson A J, Haran T, Moon F C, et al. 2008 Stress Wave Measurements in an Electromagnetic Launcher: 14th Symposium on Electromagnetic Launch Technology.
[11] Lee Y, Kim S, An S, et al. 2017 *IEEE Transactions on Plasma Science* **45** 1639-43