Research on a novel integral projectile combining of warhead and armature for the railgun

B Tang¹, Y T Xu¹, G Wan¹, Y Jin¹, H Y Li¹ and B M Li¹,²

¹ National Key Laboratory of Transient Physics, Nanjing University of Science and Technology, Nanjing 210094, Jiangsu, China
² China Academy of Ordnance, 69 Zizhuyuan Street, Haidian District, Beijing, China

E-mail: tangbo90@126.com

Abstract. Railgun can accelerate the projectile to high speed. The common launching method is using an armature to propel the projectile. When the projectile flies out of the muzzle, armature and sabots are separated from the projectile which become the harmful fragments. Therefore, an integrated projectile which combines the flying warhead and armature is proposed in this paper. This integrated projectile has two advantages, one is that the combination of warhead and armature does not throw dangerous fragments at the muzzle, the projectile has low aerodynamic resistance and flies stability by rotation stability. Another advantage is that in exterior ballistics, the combination of armature increases the total mass of the flying body and may improve the range and damage power. According to the requirements of railgun launching and flight stability of exterior ballistics, structure of the integrated projectile is proposed. Computational fluid dynamics method is used to calculate the aerodynamic characteristics of the new integrated projectile, which is compared with NATO projectile. The calculation shows that the projectile has good aerodynamic characteristics. The rotational stability of the new projectile is calculated and the electromagnetic launch test is carried out. Research of this novel integral projectile will provide reference value for the application of railgun.

1. Introduction

It has an important significance to launch rotating projectile for railgun. In the history of the cannon gun, firing the high accuracy rotating projectile is the key point that the rifle gun replaced the smooth bore gun in large quantities. In the future, the spinning-stabilized projectile launched by the rifle gun may also be launched by the electromagnetic gun. There are few researches on the field of launching spinning-stabilized projectile by railgun. Since the railgun mostly launches high-speed fin-stabilized projectiles [1]. Railgun may be more useful for launching spinning-stabilized projectile, which is suitable for the large caliber long range grenades or small caliber electromagnetic launching. However, due to the inner bore of the railgun mostly uses the composite structure of the copper rails and the insulators, it is difficult to realize the rotation of the projectile by the rifles. Challita [2] studied the deflection of the projectile in railgun launching, and found that the electromagnetic force caused the armature to rotate in the bore. If the rotating electromagnetic force can be controlled, the railgun will steadily launch the spinning-stabilized projectile. Liu Hanjun [3] studied the method of the coil gun to launch rotating projectiles. Through experiments verified that the multipole field electromagnetic can
realize the forward or reverse rotation of the armature. This research shows that it is feasible to launch high speed rotating projectiles by electromagnetic force. The railgun using the electromagnetic force to launch the rotating projectile will greatly extend the application of railgun. Besides, through the electromagnetic force the rotational speed can be adjusted according to the muzzle initial speed, which is significance to the ballistic control of the intelligent weapon [4]. In our recent research, using electromagnetic force the round bore railgun can drive the rotation of the projectile [5]. In this paper, aerodynamic characteristics of a novel spinning-stabilized projectile is analysed, which has fine electrical contact performance and also has fine aerodynamic characteristics.

2. Design method of a novel projectile

The railgun always launches hypervelocity fin-stabilized projectiles. The hypervelocity fin-stabilized projectiles always have cone shape, which are different from the conventional cannon gun projectiles in structure. However, if the railgun may launch the conventional cannon projectiles, the railgun will have better compatibility and scalability. This paper will study a novel projectile which is similar to the conventional cannon gun projectiles. Small caliber gun may be seen as the direct fire weapon, its projectile can be designed by the linear flight spinning stability theory. According to literature [6], the spinning stability coefficient $\sigma$ is expressed as:

$$\sigma = \sqrt{1 - \frac{\beta}{a^2}}$$  \hspace{1cm} (1)

It is necessary to make $\sigma > 0$ for the spinning stability of the projectile. The $\beta$ means moment parameter. The $a$ means precession angular velocity.

$$a = \frac{J_z - \omega \kappa \xi}{2J_y}$$  \hspace{1cm} (2)

$$\beta = \frac{M_z - \kappa \xi}{J_y} = k_y v^2$$  \hspace{1cm} (3)

$$M_z = \frac{h d^2}{g} \times 1000 \frac{\rho_0}{\rho_m} H(y) v^2 k_m (M) \delta$$  \hspace{1cm} (4)

$$\sigma_0 = \sqrt{1 - \frac{4000}{\pi^2} \frac{\eta^2}{\mu_i C_m g \frac{d}{d J_y} k_m (M)}}$$  \hspace{1cm} (5)

In the equations, $\sigma_0$ means the spinning stability coefficient at the muzzle. $J_z$ means the axis moment of inertia. The $\mu_i$ means mass distribution coefficient of projectile. $W$ means rotation rate. $C_m$ means relative mass of projectile. $J_y$ means the transverse axis moment of inertia. The $\omega$ means projectile angular velocity. $M_z$ means air overturning moment. The $\delta$ means nutation angle of projectile. The $h$ means distance from the center of projectile’s mass to the center of drag resistance force. The $\rho_0/\rho_m$ means air density ratio of the shooting condition to the standard. $H(y)$ means function depending on ballistic height. $K_m(M)$ means flight Mach number function of the turning moment.

According to the above method, the structural parameters of the projectile can be calculated. In this paper, the overall structure and dimensions of the novel projectile are basically on the NATO 5.56mm [7]. This projectile combines the conventional warhead and armature as the integrated structure. The common projectile used in railgun always separating the warhead and armature, which is suitable for launching the fin-stabilized projectiles. When the projectile is pushed out of the barrel by the armature, the armature and sabots become invalid loads and will separate, which are harmful to the surroundings. The novel integrated projectile makes the warhead and armature becoming one part, the armature will increase projectile mass as to increases the range and damage ability. and the muzzle surroundings are more safe.
The novel integrated projectile for electromagnetic launch is shown in figure 1. The solid part in the front of the projectile is the warhead, the tail arm in the rear is the armature. Compared with the conventional cannon gun projectile [8], the novel integrated projectile has no band and its rear part is not solid [9]. The tail arm may be slightly expanded to make the electrical contact tighter. So the tail arm makes the integrated projectile have some characteristics of fin-stabilized projectiles, as the center of mass is in the front of the projectile and the rear tail arm is a bit like the tail fins. This structure may improve the flight stability of the projectile. However, unlike the tail fins, the rear tail arm cannot produce large stability moment [10], so the integrated projectile needs to rotate to ensure the flight stability [11].

3. Projectile aerodynamic characteristics
In order to make a comparative analysis, the overall dimension of the novel integrated projectile in this paper is the same as the NATO projectile. The main difference is adding a tail arm at the rear of the projectile, similarly adding a C-type armature. We called this structure as an integrated electromagnetic projectile(EMP). In the process of exterior ballistics flight, the tail arm of the projectile will have a certain impact on the aerodynamic characteristics. Using computational fluid dynamics to calculate the aerodynamic characteristics of the projectile. In the calculation, it is assumed that the projectile is stationary and the air flow has velocity. The calculation results are as follows.

When flying in the air, shock wave will be generated at the warhead, and expansion wave will be generated at the tail arm [12]. This characteristic is the same as conventional projectiles. The main difference is that the tail arm causes the air flowing through the slot of the tail arm, some air flow disturbance will be generated at the tail of the projectile, seen as figure 2.
Figure 3. Comparison of the drag coefficient.

The drag coefficient of EMP in this paper is slightly higher than the NATO projectile, as shown in figure 3. The drag coefficient of EMP is 8% larger than NATO projectile at 4° attack angle. With the increase of attack angle, the difference of drag coefficient decreases gradually. The drag coefficient of EMP is slightly higher, which is mainly due to the disordered air flow of the slot at the tail arm.

Figure 4. Influence of tail arm size of projectile on the drag coefficient.

The influence of different tail arm size on the drag coefficient of the EMP is analysed, as shown in figure 4. Under the condition of 0° angle of attack, the drag coefficient is smaller and closer to the NATO projectile. Since the smaller the tail arm length, the smaller the aerodynamic characteristic influence of the projectile is. At Ma 2, the drag coefficient may reduce 6.3%. However, the smaller tail arm is harmful to electrical contact, the size of tail arm should refer to the C-type armature.
The lift coefficients of the two kinds of projectiles are basically the same, as shown in figure 5. At lower Mach number, the lift coefficient of the EMP slightly higher. However, at the effective firing range, the Mach number is always high, so it can be considered that the lift coefficient of the EMP is consistent with the NATO projectile.

Under different attack angles of projectile, the pitch moment coefficients of the EMP and NATO are different, as shown in figure 6. The pitching moment coefficient of the EMP is obviously smaller than that of the NATO projectile. As the rear tail arm of the EMP causes the mass center of the projectile nearer to the head, which reduces the pitch moment. For this type of projectile, the pitch moment is the overturning moment. The smaller the overturning moment the better the flight stability [13]. Therefore, the overturning stability of the EMP is better than that of the NATO projectile. At the angle of attack of 4° and Ma 1, the pitch moment coefficient is about 33.7% smaller.
The Magnus force is due to the different air velocity at the two sides of the projectile resulting by rotation [14]. It is found that the Magnus force of the EMP is much smaller than that of the NATO projectile, as shown in figure 7. This is due to the existence of the tail arm, the air can flow through the slot of the tail arm, reducing the velocity difference on both sides of the rotating projectile. Therefore, the Magnus force of EMP is smaller than the NATO projectile. The Magnus force coefficient is about 62.0% smaller at 4° angle of attack and Ma 1, shows that the EMP has better flight stability.

When the projectile rotates at high speed, the roll damping moment coefficient of the EMP is larger than that of the NATO projectile, as shown in figure 8. It is mainly due to the existence of tail arm increases the rotation resistance, that the roll damping moment coefficient increases about 9% at 40000 rad/s. However, the difference between the two kinds of projectiles is not significant, and the influence of the tail arm on the projectile rotation is relatively small. The roll damping moment coefficient may be seen as the same.

4. Conclusion
A novel integrated electromagnetic projectile for railgun is designed. This projectile combined with the characteristics of electrical contact for electromagnetic launch, and the characteristics of fine aerodynamic characteristics. Comparing with the aerodynamic characteristics of the NATO projectile, the exterior ballistic performance of the integrated EMP is similar to this conventional projectile. The drag coefficient of the EMP is slightly larger, which is about 8% larger at 4° angle of attack. And the
lift coefficient is basically the same. Compared with the NATO projectile, the pitch moment coefficient and Magnus force coefficient of the EMP are 33.7% and 62.0% smaller at 4° angle of attack and Ma 1. Which means the EMP has higher flight stability. Through the research of this paper, the novel spinning-stabilized integrated projectile can be used for the railgun. It has not only good electrical contact performance, but also good flight aerodynamic characteristics, which may well expand the application of railgun.

Acknowledgments
This work was supported by the Fundamental Research Funds for the Central Universities, 309190112A3.

References
[1] O'Rourke R 2016 Navy lasers, railgun, and hypervelocity projectile: background and issues for congress Congressional Research Service Reports. Library of Congress. Congressional Research Service
[2] Challita A, Bauer D P, Hanlin G A, et al. 1995 Analysis of rotational forces in round bore railguns IEEE Transactions on Magnetics 31 pp 123-7
[3] Liu Hanjun 2015 Based on sextupole’s multipole electromagnetic propulsion system’s launching performan improvement Chengdu: Southwest Jiaotong University
[4] Fuller S R, Woodley C R 2001 Smart gun” for artillery muzzle velocity control: simulations and experimental proof of principle IEEE Transactions on Magnetics 37 pp 157-60
[5] Wei Huizhi 1985 Theory of projectile design (Beijing: National Defense Industry Press) p 91
[6] Tang B, Xu Y T, Wan G, et al. 2018 Method of ballistic control and projectile rotation in a novel railgun Defence Technology 14 628-34
[7] McCoy R L 1985 Aerodynamic and flight dynamic characteristics of the new family of 5.56mm NATO ammunition Memorandum Report pp 9-18
[8] Pu Fa, Wang Zhongyuan 1989 The analysis of drag reduction in supersonic speed for projectiles with base cavity Journal of Ballistics 1 pp 63-7
[9] Wang Fang, Lang Tian, Wei Zhifang 2014 Effect of base cavity to projectile drag coefficient Ordnance Industry Automation 11 1-3
[10] Yang Guanghui, Cao Hongsong, Zhang Xiaoyan, et al. 2014 Journal of Projectiles, Rockets, Missiles and Guidance 34 98-100
[11] Lu Haibo, Zhuang Sun Shizhou, Sun Fengwen, et al. 2016 Journal of Projectiles, Rockets, Missiles and Guidance 36 112-4
[12] Huang Zhicheng Aerodynamics of hypersonic vehicle (Beijing: National Defense Industry Press)
[13] Shen Zhongshu and Liu Yafei 1984 Projectile aerodynamics (Beijing: National Defense Industry Press) p204
[14] Lei Juanmian, Li Tiantian, Huang Can 2013 Acta Armamentarii 34 718-25