Dynamic Research on 2-Stage Reluctance Electromagnetic Launcher

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Abstract. During the process of electromagnetic launching, the electromagnetic force applied to the projectile correlate with the structure, trigger position and initial velocity. So, it's very important to choose appropriate trigger position with different initial velocity in multi-stage reluctance launcher system. Two dimension finite element models of reluctance electromagnetic launcher are established based on the simulation environment of Ansoft Maxwell 2D. The effect of trigger position, initial velocity and their rational combination on multi-stage reluctance launcher are simulated and discussed. It can be seen from the results of simulation that different initial velocities have their optimum trigger positions in multi-stage reluctance launcher system. And then, their rational combination can improve their performance effectively.

Keywords: Reluctance electromagnetic launcher · Trigger position · Initial velocity

1 Introduction

Electromagnetic emission technology can convert electrical energy into electromagnetic energy, which has many advantages, such as high efficiency, excellent performance and good controllability. So, it has a tremendous practical value in the military and civilian areas.

The theory and control scheme were carried out by Electromechanical Research Center on the University of Texas at Austin campus, in the 20th Century [1]. Poland's B. Tomczuk and M. Sobol have analyzed reluctance launcher's magnetic field [2]; Malaysia's M. Rezal has done some excellent work on single-stage reluctance launcher by simulation and experimental [3]. In recent years, China has also carried out researches on reluctance launcher. Meng Xueping and Zhi Binan conducted some experiments, such as research on energy conversion efficiency of the single-stage reluctance coil launcher [4–6].

The above research mainly focuses on single-stage reluctance launcher. In this article, it mainly focuses on dynamic research on multi-Stage reluctance Launcher.

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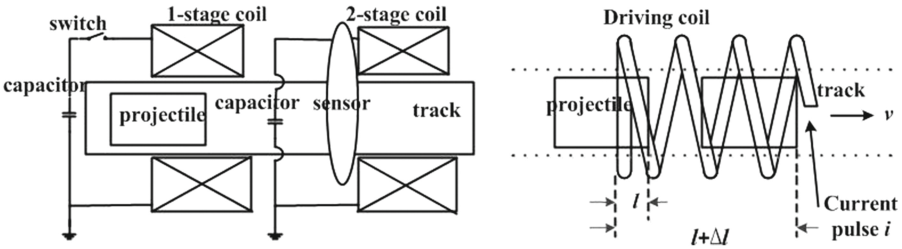
2 Theoretical Analysis

Reluctance launcher consists of solenoid-driven coils and ferromagnetic material Projectiles. Figure 1(a) is the 2-stage reluctance launcher schematic. When the switch is closed, Pulsed magnetic field is produced by capacitors discharge through switch to 1-stage driving coil. The projectile is sped up by changing reluctance in reluctance coil launcher. When the projectile moves to the center of the driving coil, the magnetic flux is easy to pass because of the smaller air gap of the magnetic circuit, the smaller reluctance of the magnetic circuit leads to the less force that acting on the projectile. When the projectile passes through the center of the driving coil, the attraction turns to tension. So some measures must be taken to prevent the projectile from pulling back. When the projectile just achieved the 2-stage driving coil, the photoelectric switch is turned on, so that the 2-stage pulse storage capacitor begins to discharge.



(a) 2-stage reluctance launcher schematic (b) Force analysis of projectile

Fig. 1. Reluctance launcher schematic and force analysis of projectile

Then, the force applied to the projectile in solenoid can be obtained by using the principle of virtual displacement [7]. As shown in Fig. 1(b), defining the distance from the top of the projectile to the bottom of the driving coil is l, the displacement is Δl. The calculation of force applied to the projectile does not need to calculate the magnetic field energy of the entire system according to the principle of virtual displacements, only need to calculate magnetic field energy's difference between the two positions of the projectile in Fig. 1(b).

Magnetic energy difference is:

$$\Delta W_m = \frac{1}{2}\int_{A\bullet\Delta l} (\mu - \mu_0)H^2 dV \tag{1}$$

Then the force applied to the projectile can be obtained:

$$F_p = \frac{\Delta W_m}{\Delta l} \approx \frac{1}{2}(u - u_0)H^2 A = \frac{1}{2}(u - u_0)(\frac{Ni}{l_x})^2 A \tag{2}$$

Where u_0 is the permeability of the vacuum, H is the magnetic field intensity of solenoid. A is the cross-sectional area of the driving coil, u is the constant permeability, there is a current i through solenoid which the length is l_x, N is the number of solenoid turns.

It can be seen from Eq. (2) that the force applied to the projectile is mainly related to the parameters of external circuit, solenoid and projectile. When solenoid and projectile's physical parameters are determined, i is the key factor to determine the acceleration force.

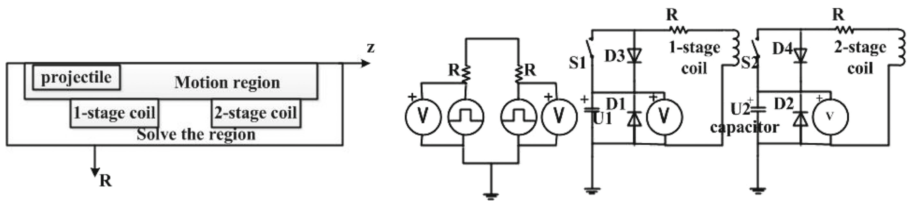
Equation (1) can only be a rough analysis of the force applied to the projectile. Then, we will analyze the relevant parameters of the force accurately by finite element analyzing software Ansoft Maxwell.

3 Simulation Study

3.1 Simulation Architecture, Parameters and External Circuit

In Ansoft Maxwell, inductance can be computed which is very different by analytic calculation [8]. So, this paper simulated 2-stage reluctance launcher system based on the 2D transient field solver of Ansoft Maxwell.

Figure 2(a) shows the simulation model of the 2-stage reluctance launcher, including the motion region, the solution region, the driving coil and projectile. The projectile is a solid cylinder with diameter of 20 mm and height of 50 mm, whose material and mass are iron and 124 g respectively; The two driving coils have exactly the same structure with inner radius of 12 mm, outer radius of 28 mm, height of 50 mm, a total of 200 turns, and the material is copper. And the driving coil resistance is about 0.133Ω. The material properties of the Motion and Solution fields are air. The mesh is taken by system default.



(a) Dynamic simulation model (b) External circuit model

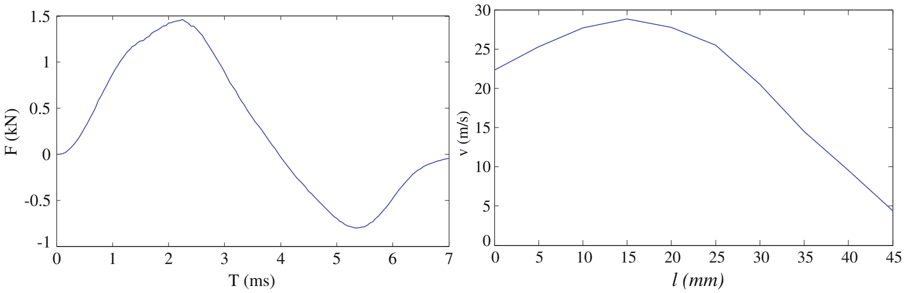
Fig. 2. Dynamic simulation model and the external circuit model

In Fig. 2(b), the external circuit model is made by Maxwell Circuit Editor software. And the parameter of capacitor is 600 v, 1000 uf. U_1 is the power of the 1-stage reluctance launcher and U_2 is the power of the 2-stage reluctance launcher; S_1 and S_2 are controllable switches which the discharge circuit is automatically altered by; D_1 and D_2 are free wheeling diodes that act as protection capacitors to prevent reverse voltage reversal. The roles of D_3 and D_4 protect the switch.

3.2 Effect of Trigger Position on Reluctance Launcher

In the process of simulation, the external circuit which shown in Fig. 2(b) provides excitation power for the launcher. It can be seen from Fig. 1(b) that l is 0 when the top of the projectile just enters the coil, l is 50 mm when the projectile just completely enters the coil and l is 100 mm when the projectile completely leaves the coil.

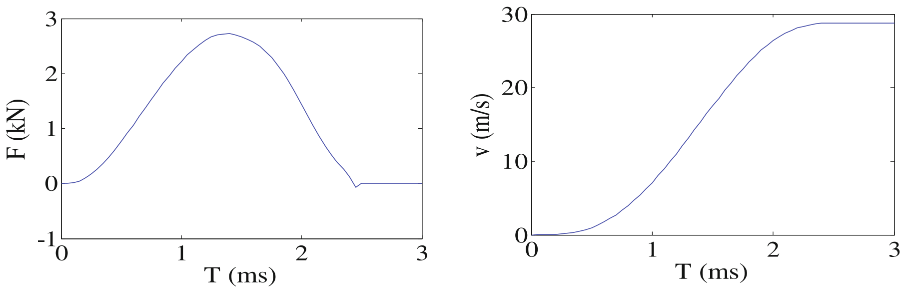
Due to the complexity of the dynamic process, the projectile is affected by both the accelerating force of the magnetizing current and the deceleration force generated by the eddy current magnetic field during the simulated process. According to Fig. 3(a), the launcher provided with an optional power, when the projectile is close to the center of the driving coil, the reverse force begins to appear. Therefore, when the projectile moves to the center of the driving coil, the switch should be turned off immediately.



(a) Electromagnetic force curve (b) Exit velocity curve

Fig. 3. Dynamic simulation curve

According to the dynamic simulation analysis of the force, trigger position can be selected in the range of 0-50 mm, and the step length is 5 mm. As shown in Fig. 1(b), the trigger position is l. Change l and keep other model parameters invariant, the dynamic simulation results are shown in Fig. 3(b). It can be seen that the outlet velocity gradually increases with the increase of displacement, and then decreases.



(a) Electromagnetic force curve (b) Velocity curve

Fig. 4. Dynamic simulation results

Figure 4 is the electromagnetic force and velocity curves when l (*trigger position*) = 15 mm. The above analysis shows that a series of best discharge positions which can make the projectile get the maximal velocity exist in a given reluctance launcher.

3.3 Initial Velocity of the Projectile

In fact, the projectile can posses arbitrary initial velocity. But, initial velocity of the projectile will have an impact on the performance of launcher. At the same time, trigger position will be greatly changed with different initial velocities. The initial velocity is chosen as the exit velocity $v_0 = 28.86$ m/s which is shown in Fig. 4(b), the simulation results are shown in Fig. 5.

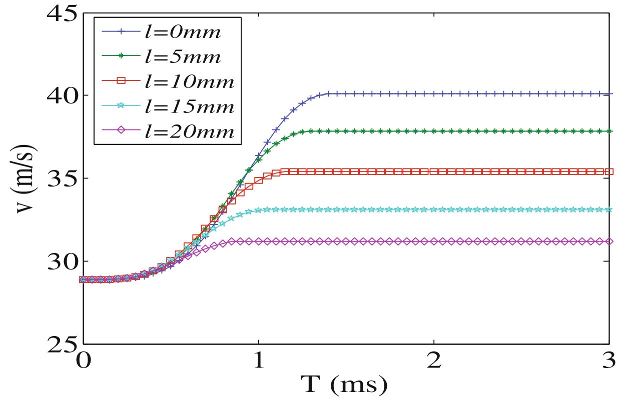


Fig. 5. Simulation results of exit velocity at $v_0 = 28.86$ m/s

When the initial velocity is 28.86 m/s, the best trigger position is $l = 0$ mm. And so on, when other parameters remain unchanged, we can get the initial speed of the best trigger position (as shown in Table 1). It can be seen from Table 1 that with the increase of projectile initial velocity, the best trigger position changes a little. When $v_0 \geqq 15$ m/s, the best trigger position is almost always fixed at $l = 0$. This is because the time of operation is too short to complete, the rising edge of the current is not yet fully act on. So, force does not reach the peak but the projectile has separated itself from the effective magnetic field. It can be seen that the initial velocity of the projectile has a great influence on the performance of the reluctance launcher.

Table 1. Simulation results vary with the initial velocity

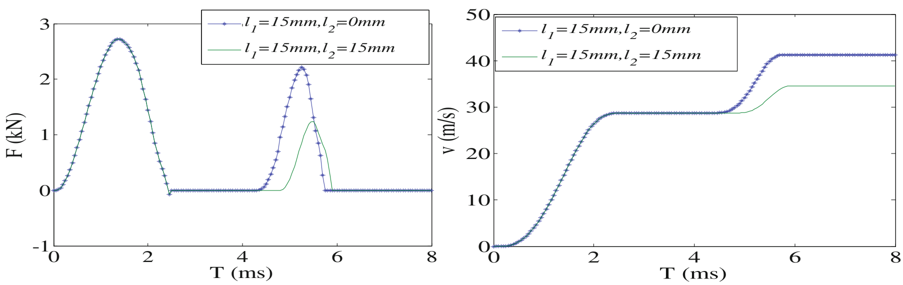
v_0(m/s)	Δv(m/s)	l (mm)	v_0(m/s)	Δv(m/s)	l (mm)
0	28.55	15	25	13.2	0
5	25.2	10	30	11	0
10	12.55	3	40	6.6	0
15	19.8	0	50	3.35	0
20	16.7	0	100	0.45	0

The spacing between 2-stage coil and 1-stage coil which we named relative space is s. The flight time and relative space have a proportional relationship when projectile flies in the primary and secondary coils. Relative space s can't be too small, otherwise the primary and secondary coils will work together on the projectile ($s \geqq 50$ mm). But, the flight time will be too long if relative spacing is too large, and the overall efficiency will be reduced. So the best spacing can be set as $s = 50$ mm. The above simulation can be summarized as two points. (1) Multi-stage reluctance launchers have a optimal trigger position and an initial velocity which is numerically equal to the exit speed of the previous stage. (2) The stage number of multi-stage reluctance launcher need to be choose carefully. Although the exit velocity of projectile will increases with the raise of the stage number. But, the speed increments will be smaller and gradually approach zero when the speed exceeds a critical value.

3.4 Combination Triggering Position with Initial Velocity

It can be seen that different initial velocities of projectile should choose corresponding trigger positions which has great influence on the performance of reluctance launcher. Without loss of generality, 2-stage reluctance launcher will be analyzed in this article. All parameters are the same except for trigger position. Therefore, we discuss in two cases: (1) The first and second launchers discharge at the optimal trigger position, namely $l_1 = 15$ mm, $l_2 = 0$ mm; (2) The two discharge position are set to $l_1 = 15$ mm, $l_2 = 15$ mm.

Simulation results are shown in Fig. 6. Figure 6 (a) is the diagram force-time. Obviously, in the first case, the drive current of the second launcher is larger, leading to force applied to the projectile is larger. Figure 6(b) is the diagram speed-time. In the first case, when $t \approx 5.65$ ms, the projectile reaches the outlet of the second stage driving coil, at which time the exit velocity is 41 m/s. In the second case, when $t \approx 5.90$ ms, the projectile reaches the outlet of the second driving coil, at which time the exit velocity is 39 m/s. Thus, it can be seen that the performance in the first case is better than in the second case.



(a) Force-time curves

(b) Speed-time curves

Fig. 6. Simulation results

4 Conclusion

The trigger position and initial velocity of projectile have great influence on the performance, and their rational combination can improve the efficiency in the 2-stage reluctance launcher. Some methods on how to improve the exit speed of the two-stage reluctance launcher can be get. (1) Make sure that the projectile injection speeds (equivalent to a single stage of the initial velocity) at all levels have corresponding optimal trigger positions, and the driving coil begins to discharge in this position; (2) The relative space need to be selected reasonably. (3) The stage number of multi-stage reluctance launcher must be selected carefully.

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