Study of the influence of electrical parameters on launch performance of projectile from the single-stage reluctance coil launcher

Zh Y Li, Y L Shen, H R Li and L N Song.

Equipment Support Department, Logistics University Of People's Armed Police Force, Tianjin 300309 China.

Email: lzyjxsjz@163.com.

Abstract. To increase the exit velocity of projectile from single-stage reluctance coil launcher, the theoretical analysis is conducted for the projectile acceleration principle. The influence law of the electrical parameters on the projectile velocity is obtained, by the imitation research about the influence rule of the variation of electrical parameters (including capacitor voltage and capacitance) in a single-stage reluctance coil emitter on the transmitting performance, using the two-dimensional transient field solver in the finite element analysis software of Ansoft. At the same time, the single-stage reluctance coil launcher is also set up to conduct relevant tests, and the correctness of simulation analysis is verified. The results show that increasing the voltage and capacitance of the capacitor is beneficial to increase the exit velocity of the projectile, in the condition that the relative position of the projectile and driving coil is constant, The capacitor voltage is less than 1000V, and the capacitor capacitance is less than 1500µF. The simulation and experiment results provide guidance for the related analysis and study of multi-stage reluctance coil launcher.

1. Introduction
Non-lethal kinetic energy weapon is a traditional antiriot weapon. It mainly depends on electromagnetic energy to fire projectiles to cause pain to the recipient and subdue them. But the traditional shot power is not adjustable and the velocity attenuation of the projectile is so fast that it causes the contradiction between the effective working distance and the minimum safe distance. To obtain the minimum safe distance, it is necessary to narrow the effective range, which causes the power of the weapon to be insufficient. However, to increase the effective range, the corresponding safe distance is therefore increased, and it is prone to cause serious damage to people. So it is urgent for our country to develop a new type of non-lethal kinetic energy weapon to solve the problem that the ballistic attenuation is too fast and provide our counter-terrorism forces with anti-terrorism and anti-riot weapon which has controllable power, long effective range, short safe distance and low price [1-9].

The reluctance coil launcher accelerates the projectile by electromagnetic force. When the current is introduced into the driving coil, the magnetization current in the projectile will be induced in the same direction, thus the attraction force will be generated to accelerate the projectile. As a new type of kinetic energy non-fatal anti-terrorism and anti-riot weapon, the reluctance coil launcher has the advantages of good controllability, safety, portability and so on. Good controllability means that the
exit velocity of the projectile can be conveniently adjusted by selecting different electric parameters (such as voltage, capacitance value, etc.), initial trigger position of the shot, trigger series and the like [10]. In this paper, the influence of electrical parameters (including capacitor voltage and capacitance) on the exit velocity of projectile from the single-stage reluctance coil launcher is studied by means of experiment. The study results will provide guidance for the optimization design of multi-parameter matching of single-stage reluctance coil launcher and the analysis and study of multistage reluctance coil launcher.

2. Analysis of acceleration principle of reluctance coil launcher

The reluctance coil launcher is mainly composed of driving coil, ferromagnetic projectile, emission tube, pulse capacitor, switch and so on. It uses the change of the magnetic resistance of the coil magnetic circuit to attract the projectile to move so as to accelerate the projectile. Given the initial position of the projectile, because the permeability of the air is much smaller than that of the ferromagnetic projectile, when the pulse capacitor is discharged through the coil, the projectile will move in the direction of reduced magnetic resistance [10-12].

Figure 1. Schematic diagram of a single-stage reluctance coil launcher.

The principle of a single-stage reluctance coil launcher is shown in figure 1. When the switch is closed, the pulse capacitor discharges to the driving coil to excite and produce the magnetic field. Because the projectile belongs to ferromagnetic material, magnetization current, vortex current and so on will be produced in the projectile under the action of the magnetic field from the driving coil. The analysis of the magnetic field of the projectile shows that the magnetic field of the projectile is produced by the interaction of free current, magnetization current, vortex current and displacement current. In the launch process of resistance coil launcher, the displacement current and vortex current are small, which can be ignored. Therefore, free current and magnetization current play a major role in the projectile movement. Therefore, the related equations indicating the magnetic field of the projectile are as follows [13]:

\[
\begin{align*}
\nabla \times B &= \mu_0 (J + J_M) \\
J &= \sigma E = \sigma \left( -\nabla \phi - \frac{\partial A}{\partial t} + v \times B \right) \\
J_M &= \nabla \times M \\
a_M &= M \times n \\
\beta_M &= n \times (M_1 - M_1)
\end{align*}
\]

In the equations (1), the free current density \( J \) is obtained by the conductivity \( \sigma \) of the driving coil material and the electric field intensity \( E \). The volume magnetization current density \( J_M \) is the curl of magnetization intensity \( M \). The magnetization current density of ferromagnetic surface \( a_M \) is obtained from magnetization intensity \( M \) and dielectric interface unit normal vector \( n \). The magnetization current density \( \beta_M \) of dielectric interface is solved by the unit normal vector \( n \) of dielectric interface and the difference of magnetization intensity between two media.

Because the direction of magnetization current is the same as that of free current, the magnetic field produced by the two interacts with each other, so that the projectile is subjected to the action of
The electromagnetic force and accelerates forward. The magnetic energy stored in the system of a hollow reluctance coil launcher is $W_m$, which is defined as follows:

$$W_m = -\int_0^\delta N_i d\phi = \frac{1}{2} \phi^2 R_m$$  \hspace{1cm} (2)

In the equation (2), $N$ is the number of turns of the driving coil, $i$ is the current of the driving coil, $\phi$ is the self-flux, and $R_m$ is the reluctance of the flux path. When the center of the ferromagnetic projectile coincides with the center of the drive coil, the reluctance of the system can be approximately expressed as:

$$R_m = \frac{4g}{\mu_0 \pi d_m l_s}$$  \hspace{1cm} (3)

In the equation (3), $g$ is the air gap between the drive coil and the projectile, $\mu_0$ is the vacuum permeability, $d_m$ is the diameter of the projectile, and $l_s$ is the length of the projectile.

At this point, the acceleration force obtained by the projectile is

$$F_p = -\frac{dW_m}{dx} = -\frac{1}{2} \phi^2 \frac{dR_m}{dx} \approx (N_i)^2 \frac{4g}{\mu_0 \pi d_m l_s}$$  \hspace{1cm} (4)

It can be seen from equation (4) that the acceleration force obtained by the projectile is mainly related to the driving coil current under the condition that the driving coil and the projectile parameters are certain, and the larger the driving coil current is, the greater the acceleration force is. So that the projectile outlet velocity can be increased by increasing the driving coil current. However, the result of this method is not accurate enough. It does not take into account the magnetic leakage and nonlinear problems. To accurately calculate the relevant parameters of the reluctance coil launcher, the Finite Element Analysis method is an ideal choice [9].

3. Simulation and Analysis

3.1. Structure and simulation parameter setting

In the single-stage reluctance coil launcher, the self-inductance and mutual inductance of the driving coil and the projectile will show nonlinear changes with the change of the driving coil current and the movement of the projectile. It is very difficult to calculate, and it is difficult to establish the mathematical model of the system. However, the electromagnetic field simulation software Ansoft can automatically take into account the influence of the component shape, the relative position and the material property on parameters such as the inductance, and solve the problem of calculating the parameters directly. Therefore, in this paper, with the help of 2D transient field solver in Ansoft, the launch process of the single-stage reluctance coil launcher is simulated and analyzed, which avoids the difficult problem of calculating the inductance parameters of the driving coil and the projectile, and lays a foundation for the research of the outlet velocity of the reluctance coil launcher and other researches.

Figure 2. Simulation Model Diagram.
Because the body of the single-stage reluctance coil launcher is axisymmetric, and can be simplified to a two-dimensional model, since the Ansoft software provides a column coordinate system simulation environment. And so that the calculation amount can be greatly reduced, while the calculation accuracy is ensured. Figure 2 shows a simulation model of a single-stage reluctance coil launcher, including a projectile, a driving coil, a motion domain, and a solution domain. The diameter of the projectile is 8 mm and the length is 25 mm. The material is set as A3 steel. The radial thickness of the driving coil is 6 mm and the length is 50 mm, with the total of 6 layers along the radial direction from inside to outside. The number of turns of each layer is 44, 44, 43, 43, 43, and 43, with a total of 260. The material is made of copper. The driving coil is arranged in a multi-layer series connection mode and is more practical, so that the simulation calculation is more accurate. The material property of the motion domain and the solution domain is set as air. Figure 3 shows the mesh parting of the simulation area. It can be seen from the diagram that the mesh parting of the projectile, the driving coil and the motion domain is relatively dense, which can ensure the accuracy of the simulation calculation.

In the simulation process, the driving coil is loaded by the auxiliary circuit. In the auxiliary circuit, the voltage value and capacity value of the pulse capacitor can be set according to the needs. The resistance of the driving coil is 0.408 Ω with a total of six driving coils. The connection mode between the coils is series. The starting time of the simulation is 0 ms, the termination time is 6 ms, and the simulation time step is 0.05 ms [14-17].

3.2. Results and analysis of the simulation

Fix the capacity of the pulse capacitor as 400 µf. We adjust the voltage and the voltage step is 100V. The following simulation results are obtained.

As can be seen from figure 4, as the charging voltage of the capacitor is increased, the exit velocity of the projectile increases continuously, from 2.73m/s at 200V to 29.25m/s at 1000V. The increase of the exit velocity is mainly due to the increase of the driving current causing that the electromagnetic acceleration force increases and that the projectile obtains the increasing acceleration force. When the acting time is basically the same, the velocity is increased continuously. When the voltage is 900V and 1000V, the velocity curve exhibits a tendency to increase firstly and then decrease. This is mainly due to the fact that the driving current still exists when the projectile passes through the middle of the driving coil, which makes the projectile subject to the reverse force and causes the projectile to decelerate.
Fix the voltage of the pulse capacitor as 600V. The capacitance is changed, and the step size of capacitance is 100µf. The simulation results are as follows.

![Simulation results](image)

**Figure 5.** Diagram of the effect of capacitance on projectile velocity.

It can be seen from figure 5 that with the increase of capacitance value, the exit velocity of the projectile increases continuously, from 7.60m/s at 200µf to 29.24m/s at 1000µf. With the increase of the capacitor capacitance, the electromagnetic force on the projectile increases obviously. At low velocity, the increase of electromagnetic force has more influence on the velocity of the projectile than the discharge time, so the exit velocity of the projectile increases continuously. When the capacitance is 800µF, 900µF and 1000µF, the velocity curve shows an obvious trend of first increasing and then decreasing. This is mainly due to the fact that the driving current still exists when the projectile passes through the middle of the driving coil, which makes the projectile subject to the reverse force and causes the projectile to decelerate.

4. Related Tests

According to the schematic diagram, the test device of a single-stage reluctance coil launcher is built. The test device is shown in figure 6.

![Test device](image)

**Figure 6.** Test device diagram of a single-stage reluctance coil launcher.

The pulse capacitor employs series and parallel connection to meet the test requirements. The switch is thyristor. The driving coil is wound by φ1 enameled copper wire. The projectile is made of A3 steel. The photoelectric pair tube is used to measure the average exit velocity of the projectile. The driving coil current is measured by open-loop Hall current sensor.

![Current measurement](image)

**Figure 7.** Velocity measurement diagram when C = 400µf, u = 600V.
The test is conducted in two parts. First, fix the capacitance of the capacitor \( C = 500 \mu F \). The voltage varies from 590V to 840V. The voltage increment is 50V. The projectile exit velocity is measured. Second, fix the charging voltage \( U = 600V \). The capacitance varies from 500\( \mu F \) to 1500\( \mu F \), and the capacitance increment is 250\( \mu F \). The projectile exit velocity is measured. The measurement of the velocity is shown in figure 7. Read out the time difference between the falling edges of the two square waves, and then calculate the average exit velocity of the projectile according to the distance between the two pairs of phototubes. The exit velocity of the projectile measured in figure 7 is 11.96m/s. The velocity obtained from the simulation and test results are shown in table 1 and table 2.

**Table 1.** The exit velocity of the projectile from the test and simulation results obtained by fixing the capacitance as 500\( \mu F \) and adjusting the voltage.

| \( U(V) \) | 590 | 640 | 690 | 740 | 790 | 840 |
|------------|-----|-----|-----|-----|-----|-----|
| Test velocity (m/s) | 18.20 | 19.50 | 21.00 | 22.18 | 24.00 | 25.50 |
| Simulation velocity (m/s) | 15.75 | 16.14 | 18.06 | 18.89 | 19.98 | 22.09 |

**Table 2.** The exit velocity of the projectile from the test and simulation results obtained by fixing the voltage as 600V and adjusting the capacitance.

| \( C(\mu F) \) | 500 | 750 | 1000 | 1250 | 1500 |
|---------------|-----|-----|------|------|------|
| Test velocity (m/s) | 18.34 | 22.68 | 27.41 | 28.96 | 29.45 |
| Simulation velocity (m/s) | 15.80 | 22.52 | 29.24 | 34.95 | 38.87 |

From the analysis of the test results in figure 8 and figure 9, it can be seen that the test results are basically consistent with the law obtained by the simulation results. Increasing the voltage and capacitance of the capacitor is beneficial to increase the exit velocity of the projectile. At the same time, there is a certain error between the test results and the simulation results. The main reasons for the error are the poor workmanship of the launching tube, the uneven material of the projectile, the friction between the launching tube and the projectile, the vibration of the projectile in the launching tube and the obstruction effect of the air resistance on the projectile movement, etc.

**Figure 8.** The variation diagram of the projectile exit velocity with charging voltage.
Figure 9. The variation diagram of the projectile exit velocity with capacitance.

According to the voltage, the capacitance, the mass and velocity of the projectile during the test, the energy conversion efficiency (from electric energy to kinetic energy of the projectile) of the single-stage reluctance coil launcher can be obtained. Figure 10 shows the energy conversion efficiency obtained by adjusting the voltage when the capacitance value is 500 µF. According to the energy conversion efficiency in figure 10 and test results of the change of the projectile exit velocity with charging voltage in figure 8, it can be seen that increasing the voltage of the capacitor is conducive to the increase of the projectile exit velocity, but reduces the energy conversion efficiency of the single-stage reluctance coil launcher.

Figure 10. The diagram of efficiency variation with voltage.

5. Conclusions
The study of the influence of electrical parameters on the exit velocity of the single-stage reluctance coil launcher is the basis of the design and test of multi-stage reluctance coil launcher. In this paper, the theoretical analysis of the single-stage reluctance coil launcher is carried out. The influences of two electrical parameters, voltage and capacitance, on the exit velocity of the projectile are simulated by applying the 2D transient solver in Ansoft simulation software. Finally, the test verification is carried out. The simulation and test results show that increasing the voltage and capacitance of the pulse capacitor is beneficial to increase the exit velocity of the projectile. At the same time, fixing the capacitance and increasing the voltage of the capacitor will reduce the efficiency of the single-stage reluctance coil launcher.

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