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Reverse Force Suppression Method of Reluctance Coil Launcher Based on Consumption Resistor

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ABSTRACT When armature passes through the central plane of a driving coil in the process of reluctance coil launching, the magnetic force will reverse and slow down the armature speed. To overcome this problem, the principle of reluctance coil launcher is analyzed. Meanwhile, this paper establishes a finite element analysis model to calculate the electromagnetic force, velocity, displacement and other parameters of the armature while the reluctance coil launcher works. Based on the simulation results, dynamic characteristics of the reluctance coil launcher are summarized and two methods for reverse force suppression are discussed. Furthermore, an experiment system is established and some experiments are carried out. This research concludes that resistor consumption method can effectively restrain the generation of reverse force, with no obvious bad impact on other performance, which provides a practical approach to achieving higher speed and efficiency for reluctance electromagnetic launcher.

INDEX TERMS Consumption resistor, launching efficiency, reluctance electromagnetic launch, reverse force.

I. INTRODUCTION

Electromagnetic launcher is a kind of launching device which launches armatures by electromagnetic force. Compared with the traditional launching technology with chemical energy, it has the advantages of low launching noise, no smoke at muzzle, high muzzle speed, and etc, which has attracted much attention in recent years. There are rail launchers and coil launchers divided by the different structures and principle [1]–[3]. Furthermore, the coil launcher could be divided into induction coil launcher and reluctance coil launcher. Among of all, reluctance coil launcher has particular advantage in small-bore launch for its simple structure, repeatability and portability. Unlike other launchers, reluctance coil launcher uses ferromagnetic armatures as projectiles. When current passes through the driving coil, magnetic field is generated, and the armature is magnetized by the magnetic field [4], [5]. At the same time, traction force appears between the coil and the armature, which pulls the armature in a certain direction and launches it out. However, when the armature passes through the central plane of a coil, the force reverses and slows down its speed. In other words, the electromagnetic force on the armature changes into resistance force and reduces energy efficiency. Therefore, the method to improve the performance of coil launchers is necessary to restrain the effect of reverse force [6]. However, in past decades, the research on the speed and efficiency of reluctance coil launcher has mainly focused on the optimization of coil structure parameters, armature parameters design, trigger time controlling and etc [7]–[10]. The effective suppression method about the reverse force on the armature still needs further study. In this paper, the resistor consumption method is put forward to avoid the effect of the reverse force, which is a new and effective strategy to improve launch efficiency. At first, the finite element model of the reluctance coil launcher is established, and then the dynamic characteristics of the armature such as force, velocity and displacement are calculated and analyzed. Then, the reverse force suppression method based on consumption resistor is analyzed with the simulation model, the effect of which is proved with the simulation results. Finally, a multistage reluctance launcher is built, and then some experiments are carried out to verify the theoretical analysis and simulation results.

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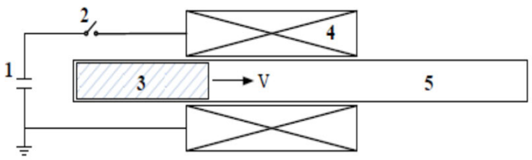
II. PRINCIPLE OF RELUCTANCE COIL LAUNCHER

Generally, reluctance coil launcher consists of driving coils, ferromagnetic armature, capacitor banks, and etc, as shown in Figure.1.



1-Capacitor banks, 2-Trigger switch, 3- Ferromagnetic armature, 4-Driving coil, 5-Barrel

FIGURE 1. Working principle of the reluctance coil launcher.

The capacitor banks provide initial energy for reluctance coil launcher. Generally, when the charged capacitor banks discharge to driving coils by trigger switch, the pulsed current and magnetic field will generate in driving coil. Thus, there will be magnetized current and eddy current in the ferromagnetic armature. As the discharge current and its frequency in the driving coil are low, the eddy current is much smaller than magnetized current. Thus, it can be seen that the magnetic field of armature is mainly caused by magnetized current and eddy current. It can be described as follows:

$$\begin{cases} \nabla \times B = \mu_0(J + J_M) \\ J = \sigma E = \sigma \left(-\nabla\varphi - \dfrac{\partial A}{\partial t} + v \times B \right) \\ J_M = \nabla \times M \end{cases} \tag{1}$$

where, the B is the magnetic induction, μ_0 is the permeability in the vacuum, J is the density of discharge current, J_M is the density of magnetized current, σ is the conductivity, E is the electric field strength, φ is displacement of the armature, A is the vector magnetic potential, v is the armature velocity, M is the magnetization.

When the pulsed current passes through the driving coil, the magnetic field energy is stored near the driving coil. The magnetic field energy storage W_m can be defined as follows:

$$W_m = -\int_0^{\phi} Ni\mathrm{d}\phi = \frac{1}{2}\phi^2 R_m \tag{2}$$

where, ϕ and i are the magnetic flux and current in driving coil, respectively, N is the turn number of driving coil, R_m is magnetic resistance.

Generally speaking, the magnetic resistance is mainly focus on the air gap between driving coil and armature, which can be defined as follows:

$$R_m = \frac{4g}{\mu_0 \pi d_m l_s} \tag{3}$$

where, the g is air gap, d_m and l_s are the diameter and length of armature. Thus, the electromagnetic force F_p on armature can be defined as follows [11]:

$$F_p = -\frac{\mathrm{d}W_m}{\mathrm{d}x} = -\frac{1}{2}\phi^2\frac{\mathrm{d}R_m}{\mathrm{d}x} \approx (Ni)^2\frac{4g}{\mu_0 \pi d_m l_s} \tag{4}$$

It can be seen from (4) that the electromagnetic force on armature is mainly determined by the discharge current in driving coil. Thus, the discharge current is very important to the performance of the reluctance coil launcher.

Furthermore, according to the principle of reluctance coil launcher, when the central section of armature passes through the central section of driving coil, the direction of electromagnetic force on armature will be reversed. On that condition, the armature will be decelerated. Thus, in order to alleviate the effect of reverse force, it should take measures to reduce the current in driving coil when the central section of armature has passed through the central section of driving coil.

III. MODEL OF RELUCTANCE COIL LAUNCHER

According to the working principle of reluctance launcher, when the discharge current of the driving coil is obtained, the electromagnetic force can be calculated. However, the discharge current is affected by the equivalent inductance of the discharge circuit. The equivalent inductance is also closely related to the armature. Thus, analysis of reluctance launcher involves nonlinear problems as the armature is usually made of ferromagnetic material. Therefore, it is difficult to analyze the reluctance launcher with the traditional mathematical method. The finite element method provides a suitable way to simulate actual work of a reluctance coil launcher. In this paper, dynamic characteristics of reluctance coil launcher are simulated and analyzed with finite element method by Ansoft Maxwell software.

Because of the axisymmetric structure of the driving coil and armature in the reluctance launcher, the 3D simulation model of the driving coil and armature can be simplified to a 2D axial symmetry model under the assumption that the armature and driving coils are coaxial and the pulse current in driving coil is uniformly distributed. Based on the transient magnetic field solution module, the finite element simulation model of single-stage reluctance coil launcher is constructed in R-Z axisymmetric coordinates, as shown in Fig. 2.

FIGURE 2. Simulation model of single stage reluctance launcher.

In Fig. 2, the length and the radial thickness of the driving coil is 50mm and 20mm, respectively. The inner diameter is 20 mm, and the turn number of coil is 400. The material of driving coil is copper. The armature is a hollow cylindrical structure. The length of the armature is 15mm, the outer diameter is 18mm, the inner diameter of the head is 16mm, and the inner diameter of the tail is 6mm. The length of the 6mm part is 8mm. The armature material is Q235, which is a kind of low carbon steel. The inner diameter of the moving area is 19mm, the length is 300mm, and the material is air. The internal diameter of the solution field is 120mm, the length is 350mm, and the material is air. The head of the armature is located just behind the driving coil. The boundary conditions are set as natural boundary conditions (as balloon boundary in the software). The mass of the whole projectile is set as 40g. After the establishment of the model, mesh generation is carried out, and the minimum mesh size is set as 0.1mm.

In order to improve the simulation accuracy, external circuit is used as the excitation source of driving coil. The excitation source circuit is designed in the circuit module of Ansoft Maxwell software, as shown in Fig. 3. The equivalent resistor of the discharge circuit is 0.5 Ω. In order to avoid reverse charging of capacitor banks, the freewheeling diode is set in discharge circuit.

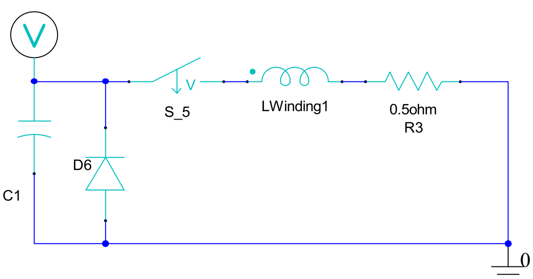


FIGURE 3. Excitation source.

In Fig. 3, the capacitor is used to simulate the pulse power supply of driving coil. The capacitance is 340μF and the initial charging voltage is 780V. The voltage-controlled switch in the circuit is used to simulate the trigger switch of the discharge circuit. When the voltage at the trigger pin of the switch is over 5V, the switch will be turned on. LWinding1 in the circuit is used to simulate the driving coil windings. D6 is the freewheeling diode in the discharge circuit. It can be used to avoid reverse charging of energy storage capacitors.

In this simulation model, the friction between the armature and the launch tube is ignored, the forward displacement of the armature is set as 240mm, and the initial speed of the armature is 0. In the solution parameter settings, the solution time is set as 10ms and the time step is set as 0.1ms. After building of the simulation model, the dynamic performance of the reluctance coil launcher can be calculated and analyzed by finite element method.

IV. DYNAMIC ANALYSIS OF RELUCTANCE COIL LAUNCHER

Through this model, magnetic field distribution in the driving coil, current distribution in the armature, discharge current and voltage of the driving coil, electromagnetic force on the armature, the armature speed and displacement can be calculated and obtained. Details about the simulation results are discussed in the following sections.

Fig. 4 shows magnetic field distribution of driving coil and armature at 2.2ms. It can be seen that the distribution of magnetic lines has changed due to skin effect. The magnetic lines distribute along the external edge of the armature, and they're relatively dense at head and tail of the armature. It can also be seen that magnetization of the armature will also be generated along the external edge, thus, the armature will be accelerated by electromagnetic force.

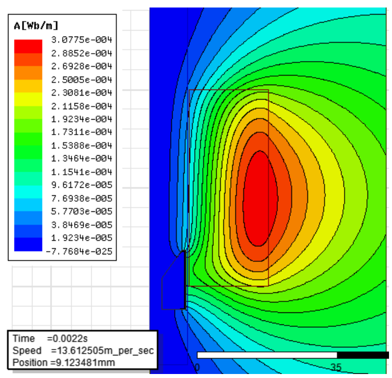


FIGURE 4. Distribution of the magnetic field.

Fig. 5 and Fig. 6 demonstrate curves of discharge voltage and current of the capacitor banks obtained by simulation. As shown in Fig. 5, the voltage of capacitors gradually decreases from 780V to 0V after 1.6ms. However, due to the freewheeling diode, the capacitors would not be reversely charged, the voltage remains 0V until power releases completely. From Fig. 6, we can see that discharge current in the driving coil increases gradually at first. At 1.4ms, the current reaches the maximum which is about 226A. Then, the current gradually decays to 0A.

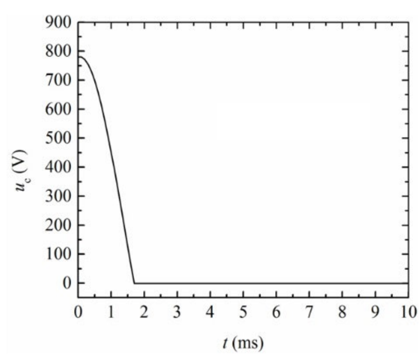


FIGURE 5. Discharge voltage.

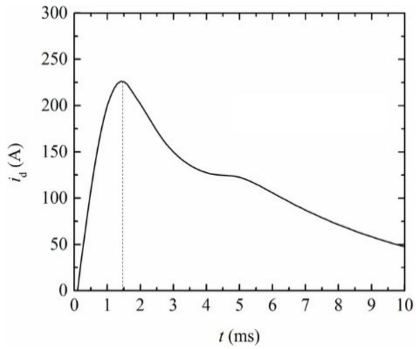


FIGURE 6. Discharge current.

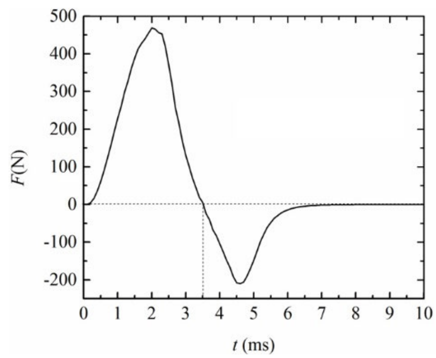


FIGURE 7. Electromagnetic force.

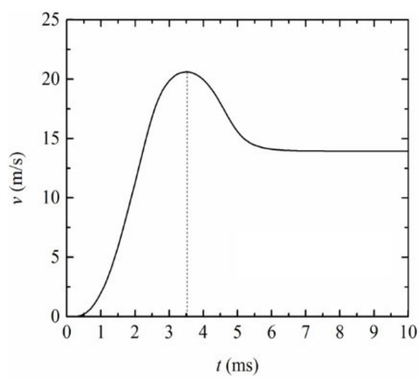


FIGURE 8. Armature velocity.

Fig. 7 and Fig. 8 show simulation results of armature electromagnetic force, armature velocity respectively. In Fig.7, it shows that electromagnetic force on the armature increases continuously to the maximum value at 2ms, and decreases to zero at 3.5ms. After that the electromagnetic force reverses, which changes into resistance force and slows down the armature. As shown in Fig.8, the armature speed increases at first and then decreases. The maximum value appears at 3.5ms. However, under the action of electromagnetic braking force, the armature speed decreases continuously and finally stabilizes at 13.9 m/ s.

Fig. 9 shows displacement curve of the armature. It can be seen that the displacement is about 33mm at 3.5ms. At this time, the armature moves to the central plane of driving coil.

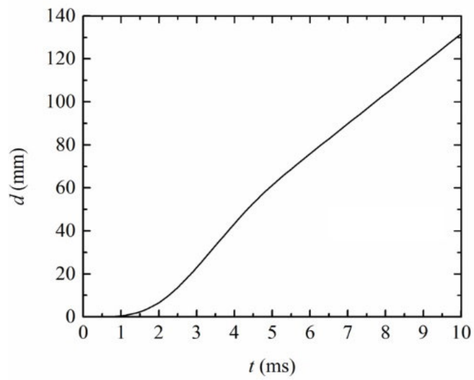


FIGURE 9. Displacement of the armature.

In other words, the central plane of armature coincides with that of driving coil. According to the working principle of reluctance coil launcher, the magnetic resistance is 0, and the inductance gradient between the driving coil and armature is also 0. Meanwhile, the electromagnetic force on the armature is 0N.

After that, the central section of armature moves away from the central plane of driving coil. According to the principle of minimum magnetic resistance, the armature will be subjected to electromagnetic braking force in the opposite direction of motion, which makes the armature slow down.

Additionally, when the central plane of armature moves away from the driving coil central plane, the coupling flux in the driving coil will decrease. According to Lenz's law, the driving coil will generate induced current in same direction. Therefore, the discharge current of driving coil fluctuates slightly. It can be seen from Fig. 6 that the discharge current fluctuates at 3.5ms.

Simulation results demonstrate that the direction of electromagnetic force on the armature changes from acceleration force to resistance at 3.5ms. In addition, from the electromagnetic force curve of armature, it can be seen that the electromagnetic braking force on the armature lasts until 6.5ms, and the deceleration of armature lasts for a long time. Eventually, armature speed decreases significantly. Therefore, it is necessary to take measures to eliminate the influence of electromagnetic braking force on armature for higher launching efficiency of reluctance coil launcher.

V. SUPPRESSION METHOD OF ELECTROMAGNETIC BRAKING FORCE FOR RELUCTANCE COIL LAUNCHER

According to the working principle and dynamic characteristics of reluctance coil launcher, two methods of restraining electromagnetic braking force are proposed. One of the methods is open circuit method; another one is resistor consumption method. Through numerical simulation, advantages and disadvantages of the two methods are compared and analyzed. Finally, the effective implementation method is proposed, so as to eliminate the adverse effect of electromagnetic braking force on armature acceleration and improve the launching efficiency of reluctance coil launcher.

A. OPEN CIRCUIT METHOD

According to the analysis of the dynamic characteristics of reluctance coil launcher, the best way to eliminate the influence of the electromagnetic braking force is to disconnect the discharge circuit of the driving coil at 3.5ms, and make current in the discharge circuit turn to be 0 A. Consequently, the electromagnetic force on the armature becomes 0 N, and the armature would no longer be affected by the electromagnetic braking force. However, it can be seen from Fig.6 that at 3.5ms, the current in the driving coil is about 136A which is still large. Thus, there are several problems in the forced turn-off of large current. At first, according to Lenz's law, the large current in the driving coil will produce a large reverse electromotive force in the driving coil, which will cause a serious impact on the insulation performance of the driving coil, as well as the electronic devices of the discharge circuit. Then, the forced turn-off of the large current does not conform to the high-voltage electrical safety regulations.

In order to verify the analysis above, the turn-off time of the trigger switch in the excitation source circuit shown in Fig.3 is set at 3.5ms, and then the simulation model shown in Fig. 2 is calculated again. Other parameters remain the same as before. The discharge current and electromagnetic force is shown in Fig.10 and Fig.11.

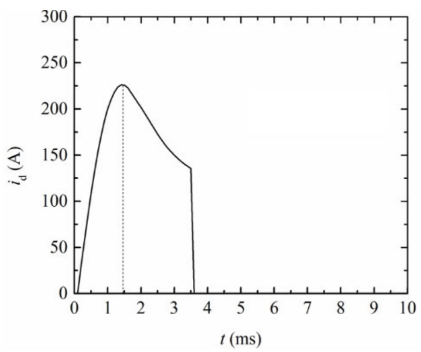


FIGURE 10. Discharge current.

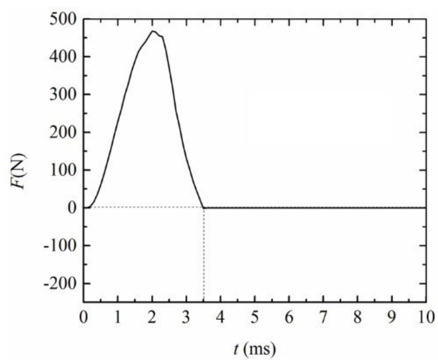


FIGURE 11. Electromagnetic force.

Fig.10. shows that due to the breaking of trigger switch in the discharge circuit, the current in the driving coil suddenly changes and decreases sharply at 3.5ms. Meanwhile, due to the influence of the response delay time of trigger switch, the current in driving coil finally declines to 0A at 3.6ms. Moreover, Fig.11 shows that electromagnetic force on armature stays 0N after 3.5ms, so there is no influence of electromagnetic braking force on armature. The forced turn-off realizes the elimination of electromagnetic braking force as expected.

The armature speed and the voltage of driving coil obtained by numerical calculation are shown in Fig.12 and Fig.13 respectively. According to Fig. 12, the final armature speed is about 20m/s. Compared with the armature velocity shown in Fig.8, the final speed of armature is significantly improved, and the launch efficiency is greatly increased. It is obvious that the brake force on the armature can be effectively eliminated by the forced turn-off method. However, as shown in Fig. 13, due to the large current in the driving coil when the switch is turned off, the forced breaking causes the sharp attenuation of the current in the coil, and finally generates large reverse induction electromotive force which is about 4000V in the driving coil.

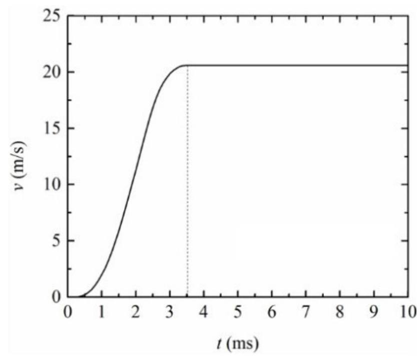


FIGURE 12. Armature velocity.

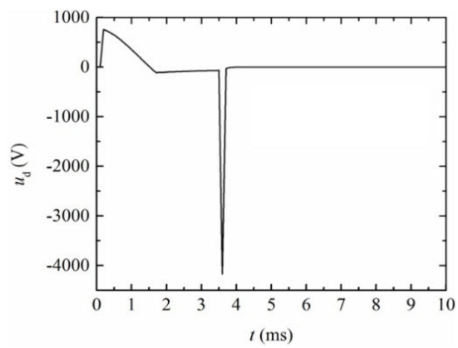


FIGURE 13. Voltage of the driving coil.

The induction electromotive force is far greater than the charging voltage of the capacitor banks, which is very unfavorable to the high voltage insulation performance of driving coil. In addition, the forced turn-off will cause persistent high-voltage pulse in the driving coil with the continuous fire of the reluctance launcher, which brings serious danger to the safety of the reluctance coil launcher. Therefore, though the open circuit method is relatively simple to realize, it cannot be used in engineering application.

B. CONSUMPTION RESISTOR METHOD

From the analysis of the open circuit method, it can be concluded that the open circuit method can eliminate the influence of electromagnetic braking force, but the reverse electromotive force caused by forced turn-off circuit will have bad effects on the reluctance launcher. Therefore, it is necessary to put forward another effect method. On one hand, it should eliminate the adverse effect of electromagnetic braking force; on another hand, it will not produce excessive reverse electromotive force, so as to avoid affecting the safety of the driving coil.

Through the analysis of the open circuit method, it can be summarized that the main reason of large reverse electromotive force is that current in the driving coil changes rapidly. It can be seen from Fig. 10 that within the 0.1ms, the current of driving coil suddenly decreases from 136A to 0A. The large current change rate leads to excessive induction electromotive force. Therefore, to solve the problem of excessive electromotive force, it is necessary to reduce the current attenuation rate on the basis of the open circuit method. Thus, the consumption resistor method is proposed.

The consumption resistor method adopts a suitable resistor in the discharge circuit of the driving coil at an appropriate time. The current in the driving coil can be reduced at a certain rate through the resistor to consume the current in the driving coil, so as to meet the needs of eliminating braking force and the adverse effects of reverse electromotive force.

Therefore, according to the analysis above, a consumption resistor branch is added to the excitation source circuit of the reluctance coil launcher simulation model. The improved excitation source circuit is displayed in Fig. 14.

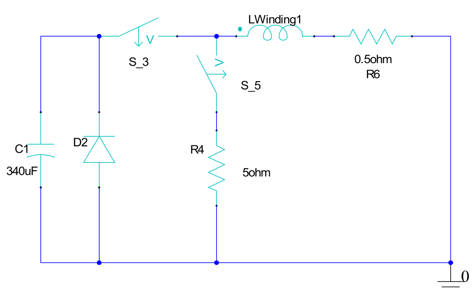


FIGURE 14. **Excitation source.**

In Fig. 14, the consumption resistor is 5 Ω which is obtained after trying. The switch S_5 and S_3 are voltage-controlled switches. Its working process is as follows. When the reluctance launcher begins to work, the switch S_3 is turned on and switch S_5 is kept off. Then, the capacitors discharge to the driving coil. After a quarter of discharge period, voltage on the capacitors decline to 0V. At that time, the current in the driving coil will continue to flow along the freewheeling branch. After that, turn on the switch S_5 and connect the consumption branches in parallel into the discharge circuit at 3ms. At 3.5ms, the switch S_3 turns off and discharge circuit changes from freewheeling branch to consumption branch. Meanwhile, the current in the driving coil will flow along the consumption branch. As the consumption resistor is far greater than other equivalent resistance of the discharge circuit, the current in the driving coil will rapidly decay.

Based on the finite element simulation model shown in Fig.2, numerical calculation is carried out by using the improved excitation source circuit with other parameters unchanged. The discharge current, electromagnetic force, armature velocity and voltage of driving coil are obtained by simulation, as shown in Fig. 15 to 18.

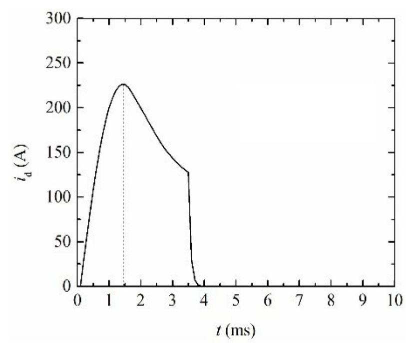


FIGURE 15. **Discharge current.**

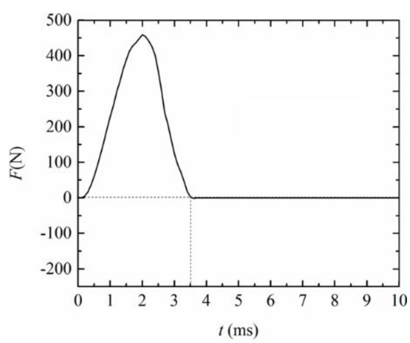


FIGURE 16. **Electromagnetic force.**

It can be seen from Fig. 15 that due to the existence of the consumption branch, as switch S_3 is turned off, the current in the driving coil decays to 0A in the period from 3.5ms to 3.9ms, and the decay rate is far lower than that shown in Fig.10. However, compared with the current curve shown in Fig. 6 without resistor consumption branch, the discharge current rate displayed in Fig. 15 is much higher. It can be seen from Fig. 16 that the electromagnetic force on the armature stays as a positive acceleration force, which is not affected by the braking force. Therefore, the consumption branch plays a role in restraining the electromagnetic braking force.

As demonstrated in Fig.17, the armature velocity does not slow down because there is no influence of electromagnetic braking force, and the final speed reaches about 20m/s. As shown in Fig. 18, reverse voltage is generated for current in the driving coil changes, which results in a reverse induced electromotive force on the driving coil. The maximum value is about 600V, which is far lower than that in the open circuit method, and also lower than the charging voltage of the capacitors. Therefore, the driving coil can withstand the reverse induced electromotive force.

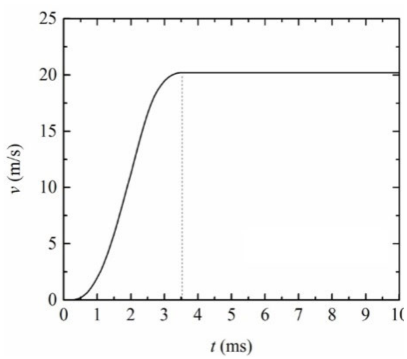


FIGURE 17. Armature velocity.

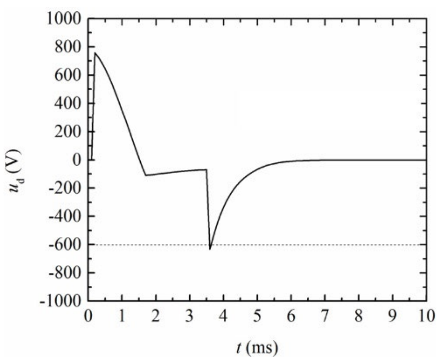


FIGURE 18. Voltage of the driving coil.

Moreover, the induced electromotive force of the driving coil could be further reduced by reducing the consumption resistor R4 in the consumption branch, for the decay rate of the discharge current of the driving coil declines correspondingly.

C. ANALYSIS OF MULTI-STAGE RELUCTANCE LAUNCHER

In order to further study the validity of the consumption resistor method, a finite element model of two stages reluctance coil launcher is built. The dimension of the second driving coil is the same as the first stage. The distance between the two driving coils is about 10mm. The excitation sources of two driving coils are the same as Fig.14 and both of the consumption resistance is 5ohm. Meanwhile, the turning on times of main switch and the consumption branch for the second stage is 4.1ms and 6.1 ms respectively. Finally, the discharge current and the armature speed are as shown in Fig. 19 and Fig.20.

It can be seen from Fig. 19 that the discharge current decreases sharply after reaching the maximum value with the effect of consumption resistor. Furthermore, the pulse width

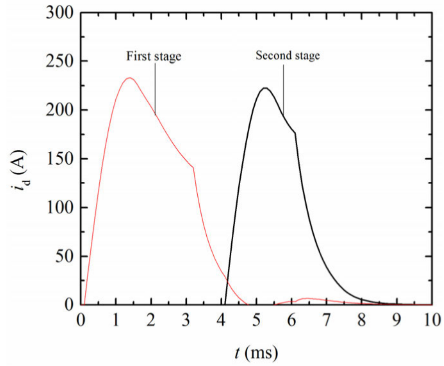


FIGURE 19. Discharge current.

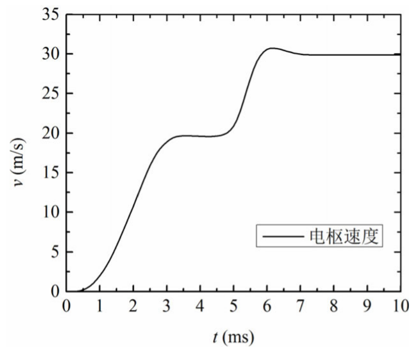


FIGURE 20. Armature speed.

of the discharge current in the second stage is less than it in the first stage, because the armature speed passing through the second stage is larger.

The Fig.20 displays the change of the armature speed. It shows that the armature increases gradually, and the muzzle speed is about 29.8m/s. The results indicate that the effect of reverse force on armature is insignificant, which proves the validity of the consumption resistor method.

Through the analysis above, it can be concluded that the resistor consumption method can effectively suppress the electromagnetic braking force, improve the armature speed and launch efficiency, and has no obvious impact on other performance of the reluctance coil launcher.

VI. VERIFICATION OF EXPERIMENT

In order to verify the results of theoretical analysis and simulation, an experiment system is established and some experiments are carried out.

A. ESTABLISHEMENT OF EXPERIMENT SYSTEM

Among all of the components of reluctance coil launcher, the pulsed power source and driving coils are the most important composite.

The driving coils are made of copper with insulation coating. Furthermore, the external surface of the windings is covered by heat shrink tube to improve the insulation performance of driving coils. The driving coils are shown in Fig.21, whose parameters are the same as the simulation model.

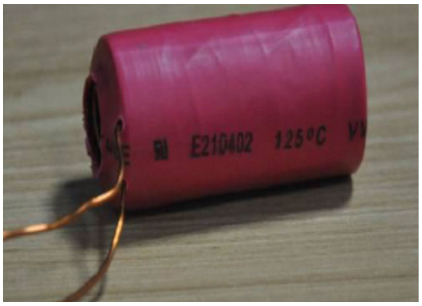


FIGURE 21. Driving coil.

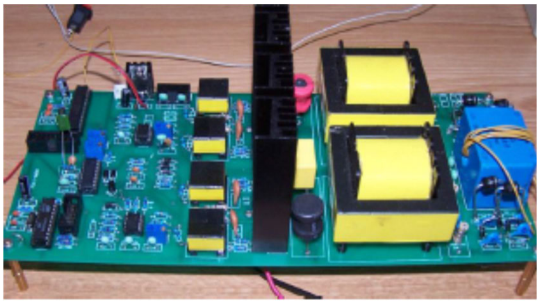


FIGURE 22. Charger of pulsed power source.

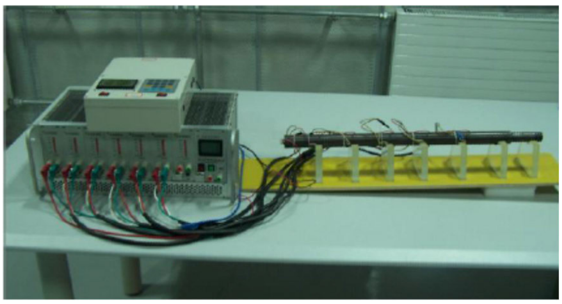


FIGURE 23. Experiment system of multi-stage reluctance coil launcher.

The charging power source of the reluctance coil launcher is shown in Fig.22. The maximum output voltage is 1000V, and the initial voltage of battery is about 48V. Considering the boost efficiency of the transformer, the boost ratio is set 26.

Finally, a multi-stage reluctance coil launcher is designed, which is shown in Fig.23. It can be seen that all the capacitor banks are set in the box under the charger.

B. ANALYSIS OF EXPERIMENT RESULTS

With the experiment device of the multi-stage reluctance coil launcher, some experiments are carried out. As the discharge current of each driving coil is difficult to monitor in the experiment, the muzzle velocity of armature are measured with photoelectric speed measurement method. In the Fig.23, the first and the second capacitor banks are charged, and the armature velocity is obtained and shown in Table 1.

It can be seen from Fig.20 that the armature velocity in simulation model for the first stage and the second stage are about 19.6m/s and 29.8m/s, respectively. Considering the deviation of the simulation model and the experiment, the experiment results is basically consistent with the simulation. It proves that the reverse force on armature is suppressed with the consumption resistor. The validity of the suppression method for the reverse force is verified.

TABLE 1. Armature velocity.

Experiment index	First stage (m/s)	Second stage(m/s)
1	17.9	27.5
2	17.7	27.3
3	17.7	27.5
Average	17.8	27.4

VII. CONCLUSION

In order to improve the launching speed and efficiency, two kinds of reverse force suppression methods are discussed based on analysis of dynamic characteristics of the reluctance electromagnetic launcher in this paper.

The open circuit method is characterized by high voltage pulse caused by sudden decline of the coil current as the switch turns off. Although the method has significant advantage in reverse force suppression, the high voltage pulse may bring serious danger to the safety of the reluctance coil launcher.

The improved method adopts consumption resistor instead of the switch suddenly turning off. The voltage pulse declines to a reasonable range, so it is much more practicable in engineering. Furthermore, the value of the consumption resistor should be determined with the electrical parameters of the discharge circuit. A suitable consumption resistor not only can improve the armature speed and launch efficiency, but also have negligible impact on other performance of the reluctance coil launcher. Thus, this method can effectively restrain the electromagnetic braking force.

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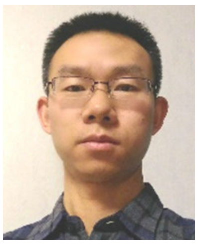

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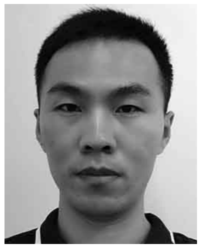

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