Research on Performance Influence of External Circuit Resistance in Synchronize Induction Coil Catapult

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Abstract. The external circuit of synchronize induction coil catapult can be equivalent to R-L-C circuit with freewheeling diode, the resistance directly affects the current and efficiency. In order to improve the performance of the catapult, the final launching speed can be increased in a certain range by the means of reducing the resistance of discharge circuit or increasing the resistance of freewheeling circuit. In this paper, Maxwell two-dimensional transient simulation model and single-stage coil ejection test of two kinds of coils with different turns was used to verify the influence of the external circuit. The research show that, the driving coil current and the electromagnetic force on armature can be increased effectively by reducing the resistance of discharge circuit, the launch speed which the armature is separated from the load is improved; the armature drag effect can be reduced by putting resistance in freewheeling circuit according to coil resistance, the final speed which the armature is connected to the load is improved, so the ejection performance is optimized.

Keywords: Induction coil catapult · Discharge circuit · Freewheeling circuit · Launching performance

1 Introduction

The synchronous induction coil ejector has the characteristics of no mechanical contact between the projectile and the drive coil, and has the advantages of large propulsion mass range, high propulsion efficiency, long service life and good controllability under the same current condition. It is one of the effective ways to achieve medium-high speed propulsion at present, and has a very broad application prospect in military and aerospace [1–3].

At present, the volume and weight of the power supply system are larger because of the efficiency of the ejection system is lower than the theoretical value, which once became the restriction condition of the electromagnetic ejection weapon production. The factors affecting the performance of the ejection system include the structural parameters of the drive coil and the armature, the relative position between the armature and the driving coil, the electrical parameters of the energy storage power supply, etc. A

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number of domestic universities and institutions have carried out relevant research on the coupling effects of single parameter and multiple parameters and the optimization of magnetic field configuration [4–10], the research on the influence of power supply parameters mainly focuses on the voltage and capacitance value, and the research on the influence of external circuit on performance is less. In this study, the finite element simulation software is used to model the induction coil gun, and the effective method to improve the firing speed is explored through simulation analysis, and verified by experiments.

2 System Working Principle

2.1 Working Principle

Coil ejection system is composed of energy storage power supply, driving coil, launching component (including armature and projectile), high-voltage trigger switch and other components [9]. During the launch, the driving coil is fixed and the armature is initially located at the right of the driving coil center. Switch on the high voltage trigger, charging capacitor bank feed pulse high current to driving coil. The current flowing through the driving coil generates a strong pulsed magnetic field, and induces a large pulsed current in the armature. The current is in opposite direction between the driving coil and the armature, which generates a mutually exclusive electromagnetic force. The driving coil is stationary, and the armature propels the projectile into accelerated motion until it reaches a predetermined speed, so the launch is complete.

2.2 Circuit Equation

In the transmitting process, the uneven distribution current along its axial direction of aluminum armature is ignored, and the single-stage induction coil coupling circuit is established, as shown in Fig. 1C is pulse power supply capacitance; D is continuous diode; S is the thyristor and its control assembly; R_c is the resistance of capacitor; R_D is the continuous loop resistance, which including the diode resistance and series consumption resistance; R_1 is the resistance of the discharge circuit, including the resistance of the cable and the connecting interface; R_d is the resistance and L_d is the inductance of the driving coil. M is mutual inductance between driving coil and armature [11].

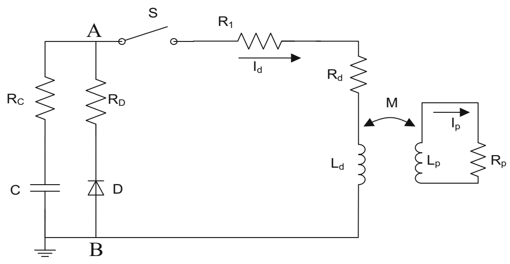


Fig. 1. Coupled circuit of single-stage

1) When discharging the coil, the voltage UAB ≥ 0 which from point A to point B, and the equivalent circuit equation is as follows:

$$L_d \frac{dI_d(t)}{dt} + (R_c + R_1 + R_d)I_d(t) + \frac{d}{dt}[MI_p(t)] = U_B \tag{1}$$

Among them $U_B = U_0 - \int_0^t I_d(t)dt$, In the formula

$$R_p I_p(t) + L_p \frac{dI_p(t)}{dt} + \frac{d}{dt}[MI_d(t)] = 0 \tag{2}$$

2) After discharge, the driving coil is continued through the diode, and the equivalent circuit equation is as follows:

$$L_d \frac{dI_d(t)}{dt} + (R_D + R_1 + R_d)I_d(t) + \frac{d}{dt}[MI_p(t)] = 0 \tag{3}$$

According to the magnetic flux coupling and mutual inductance law, $I_d M = I_P L_P$, substitute the expression of armature current I_P into Eq. (3) get:

$$(R_d + R_1 + R_D - R_p \frac{M^2}{L_p^2})I_d(t) + (L_d - \frac{M^2}{L_p})\frac{dI_d(t)}{dt} = 0 \tag{4}$$

Solving the equation results in:

$$I_d(t) = c \exp[-(R_d + R_1 + R_D - \frac{M^2}{L_p^2})t \Big/ (L_d - \frac{M^2}{L_p})] \tag{5}$$

3) The force F on the armature in the process of movement is:

$$F_p = I_d I_p \frac{dM}{dx} = I_d^2 \frac{M}{L_p}\frac{dM}{dx} \tag{6}$$

In order to improve the performance of the catapult, it is necessary to increase the force in the coil discharge stage and reduce the armature drag force in the continuation stage. According to the force formula (6), the current should be increased or decreased under the corresponding circumstances. The current can be increased when the equivalent resistance of the discharge circuit is reduced, corresponding to the increasing of the thrust peak value. The current of the loop during the continuous flow can be reduced when the equivalent resistance of the continuous loop is increased, correspondingly reduce the peak value of the armature drag force, which can increase the efficiency of the catapult to a certain extent.

2.3 Computing Efficiency

During the launching process, the total energy of the system remains unchanged, including the electrical energy of the capacitor bank, electromagnetic energy in the coil, kinetic energy of the load, and thermal loss of the resistance, etc. The efficiency of the system is defined as the ratio of the kinetic energy acquired by the load and armature to the initial energy of the capacitor bank.

$$\eta = \frac{\frac{1}{2}m(v_2^2 - v_1^2)}{\frac{1}{2}CU^2} \tag{7}$$

In the formula, m is the mass of armature and load, V_2 is fire velocity, V_1 is initial velocity, C is the capacitance value of the circuit outside the coil, U is the initial voltage of the capacitor.

3 Simulation Analysis

The external circuit of coil ejector has great influence on the ejection performance, among which the resistance value of the discharge loop affects the highest launching speed, and the resistance value of the continuation loop affects the final launching speed. In order to analyze the influence of resistance value on transmission efficiency, Ansoft Maxwell was used for transient simulation calculation for two kinds of coils with different turns. The capacitance of the pulse capacitor is 4.2 mF, and the initial voltage is 7.5 kV. The projectile armature is an aluminum cylindrical entity with external radius of 184 mm, thickness of 18 mm, axis length of 340 mm, and mass of 8 kg. The mass of armature and load is 110 kg, initial speed is zero, the initial trigger position is the axial center of the coil. The simulation model is shown in Fig. 2.

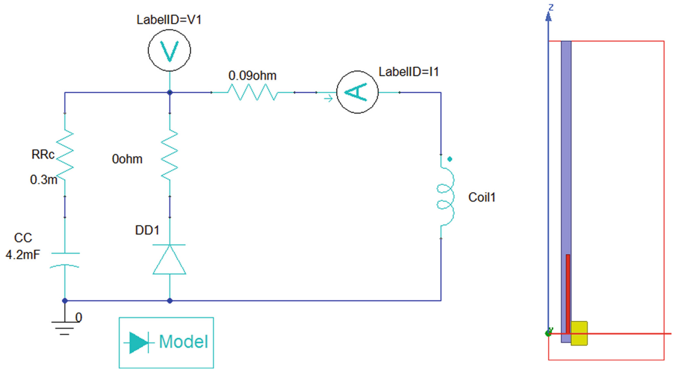


Fig. 2. Simulation model of single stage coil catapult

Table 1. The simulation parameters of coil

Parameter	coil1	coil2
Turns	140	70
Inner diameter/mm	186	186
Eternal diameter/mm	260	230
Axial length/mm	100	100

3.1 Effect of Equivalent Resistance of Discharge Circuit on Emission Performance

The equivalent resistance of the drive coil discharge circuit includes coil resistance, modulated inductance resistance, cable resistance and contact connection resistance. Since the resistance of the drive coil is obtained by combining the number of turns, current carrying capacity, strength and other factors, it is not within the scope of this study. This paper mainly studies the line resistance of other parts of the circuit, which is 10 mΩ, 50 mΩ, 100 mΩ and 200 mΩ in sequence, conducts transient simulation calculation for them.

It can be seen from Fig. 3 and 4 that, with the decrease of the resistance of the discharge circuit, the peak time of the current and thrust of the driving coil is advanced, and the value of the peak velocity increases significantly. For the ejection system composed of coils with different turns, the speed and efficiency change to different degrees. The load speed of the catapult of coil 1 increases from 10.32 m/s to 13.47 m/s, and the speed increases by 30.5%, the efficiency increases from 4.96% to 8.45%, and the efficiency increases by 70.36%. The load speed of coil 2 catapult increases from 8.91 m/s to 17.17 m/s, the speed changes 92%, the efficiency changes from 3.70% to 13.73%, and the efficiency increases 271%. On the whole, it can be seen that the equivalent resistance of the discharge circuit has a great influence on the performance of the catapult, and the resistance with fewer turns has a higher degree of influence under the condition of the same discharge resistance.

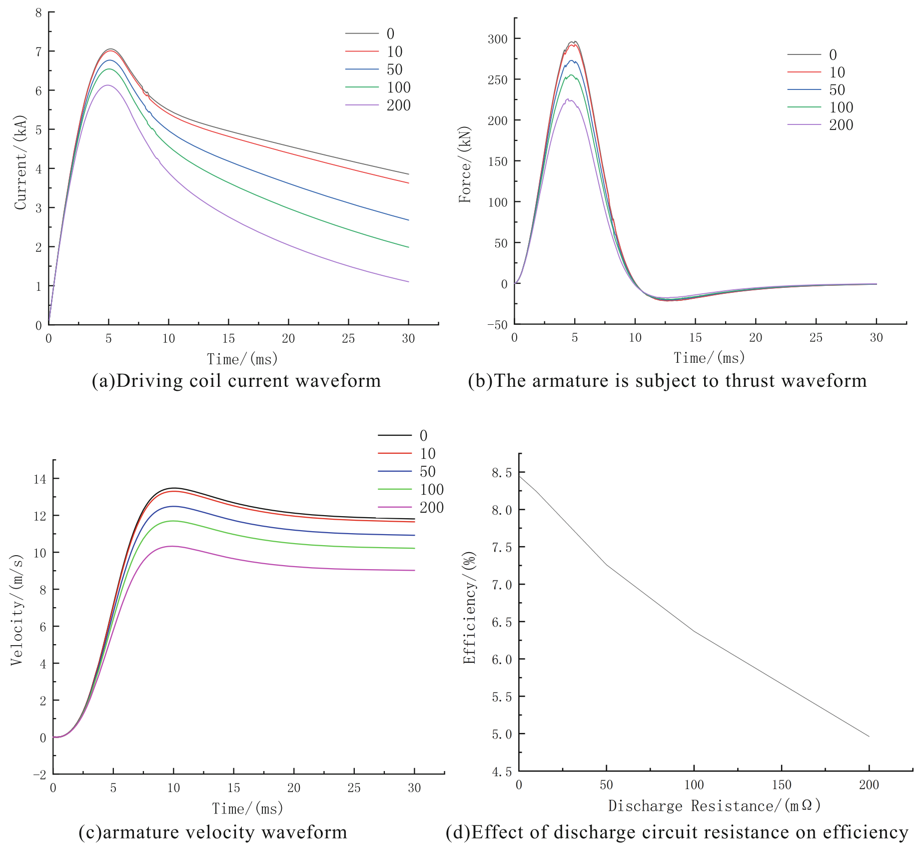


Fig. 3. Transient simulation Results of coil1 with different discharge resistance

3.2 Effect of Equivalent Resistance of Continuous Circuit on Emission Performance

According to the impedance value of the coil itself, the resistance of coil 1 continuous loop is 0 Ω, 0.1 Ω, 0.8 Ω and 10 Ω, and the resistance of coil 2 continuous loop is 0 Ω, 0.03 Ω, 0.5 Ω and 10 Ω. Transient simulation calculation is performed.

Figure 5 and 6 show that the value of the continuation resistance does not affect the current waveform and thrust waveform at the discharge stage. With the increase of circuit resistance, the current attenuation speed is accelerated, and the time of negative force on the armature is shortened. When the continuous loop resistance reaches a certain value, the driving coil current is reversed and the thrust changes from negative to positive, which is conducive to the acceleration of the armature. The speed can be increased by 13%, and the efficiency can be increased by 26.06% or even higher. However, in this case, the capacitor is reverse charged, which affects the life of the pulse capacitor.

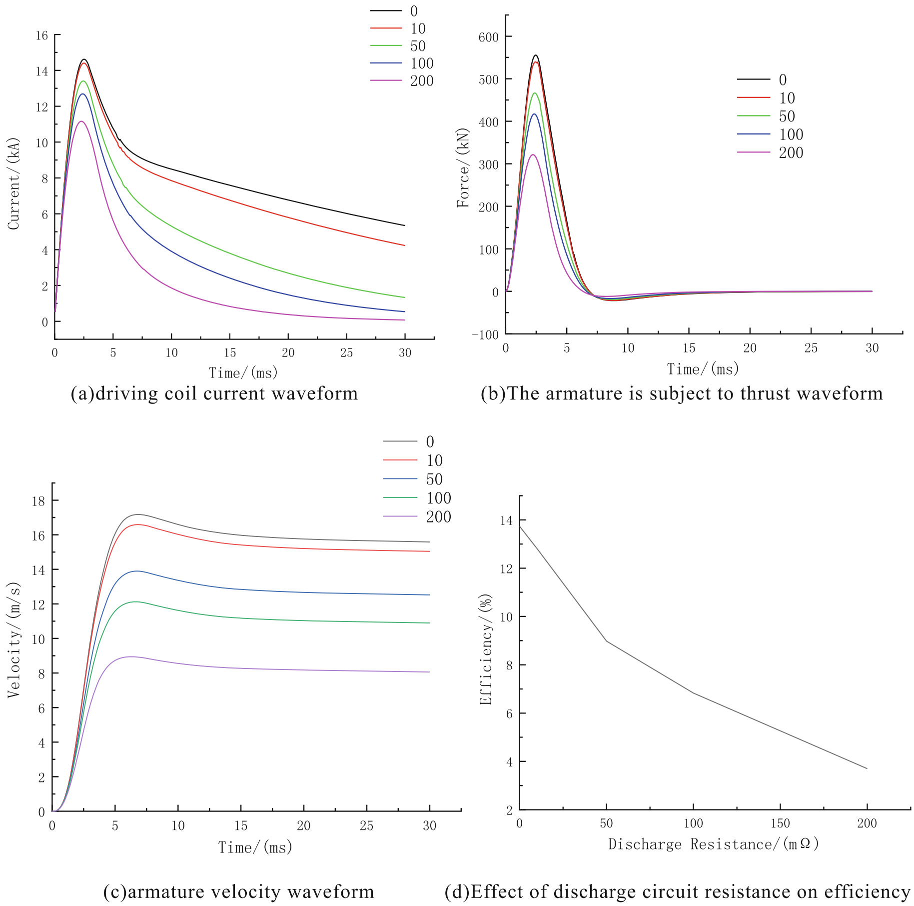
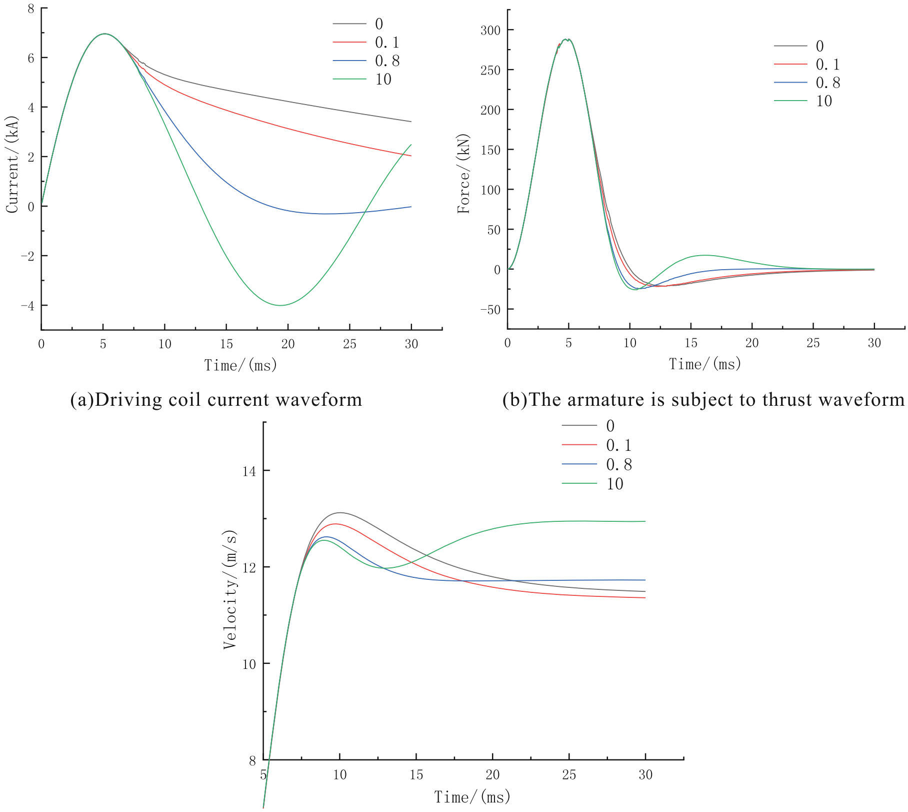


Fig. 4. Transient simulation Results of coil2 with different discharge resistance

Therefore, the selection of the resistance of the continuation circuit combined with the value of the resistance of the discharge circuit itself, it is not the larger the better. The speed of the armature is 11.42 m/s when the resistance of the discharge circuit of coil 1 is zero, and the speed is 11.93 m/s when the resistance is 0.8 Ω, the speed is increased by 4.5% and the efficiency is increased by and 9.23%. When the resistance of the discharge circuit of coil 2 is 0, the speed of the armature is 12.42 m/s, and when the resistance is 0.5 Ω, the speed is 12.73 m/s, the speed is increased by 2.5% and the efficiency is increased by and 5.15%. The serial resistance of the continuous loop can reduce the armature drag effect to a certain extent and improve the final speed, especially for the coil with larger resistance value.



(a)Driving coil current waveform

(b)The armature is subject to thrust waveform

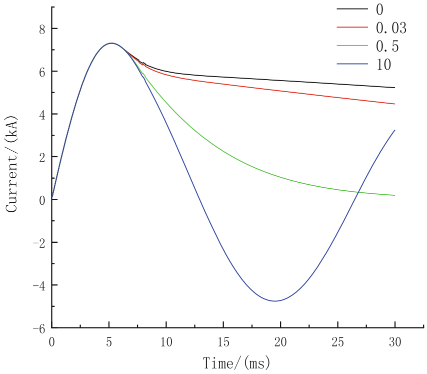
(c)armature velocity waveform

Fig. 5. Transient simulation results of coil1 with different freewheeling resistance

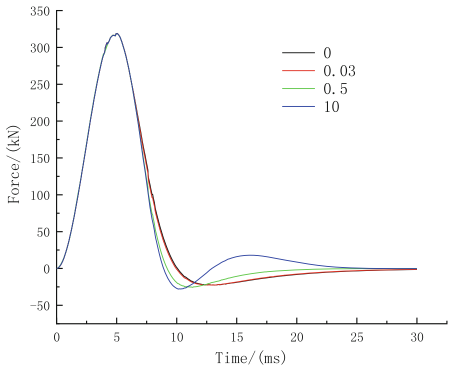
4 Experimental Verification

In order to verify the accuracy of the theoretical and simulation results, two kinds of coil specimens were processed according to the parameters in Table 1, and a single-stage coil catapult was built. The pulse power parameters were capacitance value 4 mF, voltage 7.5 kV, and resistance of the optimized external circuit discharge circuit was 20 mΩ. The mass of armature is 8 kg and the mass of load is 100.4 kg.

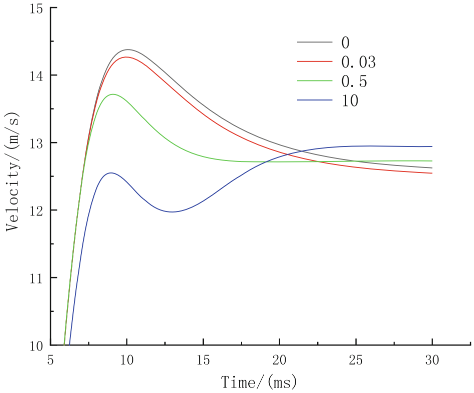
During the test, the armature is placed in the middle axial position of the coil, and the armature and load contact is placed without fixed connection. After charging the pulse capacitor to the required voltage with a high voltage charger, control signals are sent to the thyristor drive circuit through the optical fiber, so that the pulse capacitor discharges the driving coil and the armature is emitted. During the launching process, infrared laser velocity measurement is placed at the tail for the speed test of the armature, and a scale is laid under the front end of the load to complete the load speed test through high-speed photography (Fig. 7 and Table 2).



(a)driving coil current waveform



(b)The armature is subject to thrust waveform



(c)armature velocity waveform

Fig. 6. Transient simulation results of coil2 with different freewheeling resistance

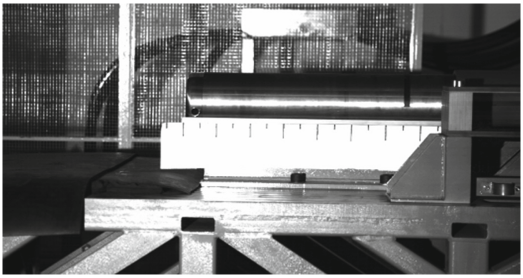


Fig. 7. Single-stage coil catapult

For the two coil parameters, the discharge resistance was set as 0.8 Ω and 0.5 Ω respectively. It can be seen from the results that after adding the resistance of the continuation loop, the exit velocity of the armature is improved, but the actual velocity is lower than the simulation due to ignoring the influence of friction and other factors during

Table 2. Muzzle velocity of armature with different freewheeling resistance

Parameter/Ω		The highest speed m/s	The drum speed m/s	Speed up%	Efficiency up%
coil1	0	13.247	11.04	4.6	9.5
	0.8	12.78	11.55		
coil2	0	14.29	12.25	3.2	6.67
	0.5	13.56	12.65		

launching. The speed of coil 1 with higher resistance is promoted greater than that of coil 2 with lower resistance, which is consistent with the results of simulation analysis.

5 Conclusion

In this paper, through theoretical analysis and simulation to calculate the discharge circuit and loop resistance change, on the influence of catapult performance including discharge current, electromagnetic thrust, maximum speed and the final speed, and two kinds of different specifications of a single-stage coil ejection experiments, the results coincide with the results of simulation, the results of the study has reference function to the catapult optimization.

(1) With the decrease of the resistance of the coil discharge circuit, the efficiency of the catapult is improved, and the effect of the coil catapult with fewer turns is greater. The loop resistance value can be further reduced from the following aspects, such as coil wire material selection, modulated inductance optimization, cable selection and interface design, so as to improve the transmission efficiency of coil ejection system.
(2) As the resistance value of coil continuation loop increases, the armature speed increases, but its value needs to be matched with the coil impedance design. When the current resistance reaches a certain value, the current will reverse to charge the capacitor. Considering capacitor safety, the value of the current resistance has a certain limit. The matching resistance value of coil continuation loop with large impedance is also larger, and the speed improvement effect is larger. If the pulse capacitor can withstand reverse charging, the final launch speed of the catapult can be greatly improved.
(3) The external circuit should be optimized according to the coil loop and the firing demand. When the armature and load are separately, the smaller the resistance of the continuation loop is the better. At this time, the load complete the firing at the highest speed, and the armature can be discharged or even recovered at a lower speed with the help of the armature dragging effect. In the integrated of armature and load, appropriate resistance should be connected in the continuous loop to weaken the influence of armature drag force and improve the final launch speed.

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