Analysis of the Force Characteristic on the Armature of Inductive Coilgun and its Trigger Strategy

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Abstract — The inductive coilgun utilizes the theory of magnetic coupling between the driving coil and the armature. The armature is accelerated when the direction of induced current in it is opposite to the current direction in the driving coil, or else it will be slowed down. By the finite element analysis, the relationship between the induced current and the position, the velocity of armature, and the waveform of current in the driving coil, is obtained, especially the moment and the position when the armature current reverses its direction or passes zero. The direction reverse position will be brought forward as the increase of the armature velocity, even the passing zero position of induced armature current will be ahead of the peak point of driving coil current. Thus, it is very important to cut off the current of driving coil in this moment, to avoid slowing down of the armature. Based on the movement and the location of passing zero position for multiple driving coils system, the trigger strategy of multiple coils can be designed.

I. INTRODUCTION

As a new launching technology, the electromagnetic launch has bright prospect as its advantages such as high initial velocity, easy to control, working steady, etc[1]. The electromagnetic field and force of coilguns have been analyzed by lots of scientists [2-6]. However, the efficiency and control strategy of multi-stage coilguns still need further study. In order to get higher velocity and efficiency, the trigger strategy is investigated in this paper, based on the analysis of the relationship between the electromagnetic force of armature and its velocity, as well as the current provided by the external circuit.

II. ANALYSIS OF FORCE CHARACTERISTIC ON ARMATURE

The principle diagram of three stages coilgun is shown in Fig 1, which consists of drive-coils, the integrated launch package (ILP) including the projectile and the armature, capacitor banks, synchronous control circuits, etc.

At first stage, the rear of the armature is just at the middle of the driving coil. The working process is as follows: the capacitor banks are charged by the external circuit, then the controller sends signals to each drive-coil trigger switch one by one to turn on the discharge circuits, so that the capacitor banks discharge to driving coil and stimulate pulse magnetic field which causes induction current and force in the armature. If the moment of trigger is suitable, the armature will be accelerated by the push force caused by the interaction of induction current. Oppositely, the armature might be decelerated by the pull force caused by the driving coil current. Therefore, as the armature moves forward, the present driving coil should be turned off to avoid the pull force, and the next driving coil should be turned on at an optimal position to accelerate the armature further, so that the armature can be accelerated continuously.

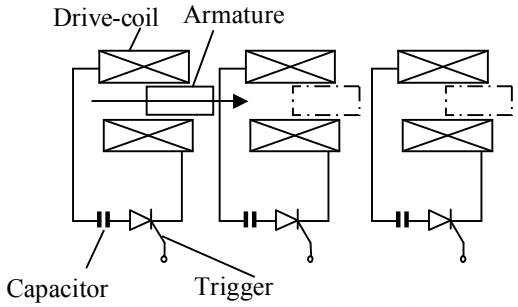

Fig. 1. Working principle diagram of three stages coilgun.

A. Analysis of the Induction Current of Armature

The magnetic force of armature can be defined as[1]

$$F_{\mathrm{p}} = \frac{\mathrm{d}M}{\mathrm{d}x} I_{\mathrm{d}} I_{\mathrm{p}} \tag{1}$$

where, $\mathrm{d}M/\mathrm{d}x$ is the mutual inductance gradient between the driving coil and the armature, I_{d} is the current of driving coil and I_{p} is the induced current in armature. The armature will be accelerated when the direction of induced current is opposite to the current direction in the driving coil, or else it will be slowed down. The typical contour of the current in driving coil and armature is shown in Fig 2.

At the beginning, as the increase of the current in driving coil, the magnetic flux in the armature is also strengthened, by which the current is induced in armature, whose direction is opposite to the current of driving coil, so that a push force upon the armature pushes it to move forward, according to Lenz's law and Faraday's law.

However, as the movement of the armature away from the driving coil, the magnetic flux in it will be decreased. When the decreasing is greater than the increasing of the field produced by the increasing current in the driving coil, i.e., the magnetic field in the armature decreases, the direction of the induced current in the armature will reverse, and so is the direction of the force. Actually, the current of driving coil also decreases afterward. Certainly, the rate of the decrease caused by the armature movement depends on its velocity.

Consequently, the direction of induced current in armature reverses from negative to positive during its movement. The point of direction reverse is point B as shown in Fig. 2. Actually, the position relationship between point A and B has three different cases: point B is ahead and behind of A, and they coincide. The reason why is point B behind of A is the intergradation phenomena of the equivalent resistor-inductor (R-L) circuit.

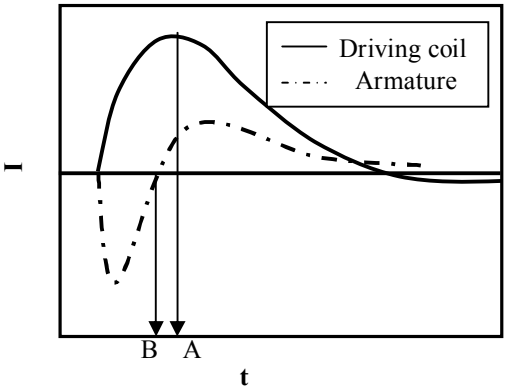

Fig. 2. Contour of the current in driving coil and armature

B. *Analysis of the Force Characteristic by the FEM*

In order to obtain the relationship between the current in the armature and the driving coils as well as the velocity of the armature, the model of coilgun can be simulated by the finite element software Ansoft. The parameters of the simulation model are shown in Table I. The value of the capacitor is 2000μF and the initial voltage is 10000V. We choose external circuit as the excitation source of the driving coil. The total mass of the projectile including the armature is 1kg. After the building of simulation model, we start to simulate at three different cases when the initial velocity of armature is 0, 100m/s and 200m/s. Then we obtain the force curves of armature as shown in Fig.3 and the relation curves of force and discharge current as shown in Fig.4.

TABLE I
PARAMETERS OF THE SIMULATION MODEL

Model	Length(mm)	Depth(mm)	Material
Armature	60	20	Aluminum
Driving Coil	80	30	Copper

Form the results shown in Fig.3 and Fig.4, we can see that as the increase of armature velocity, the reverse position of the induction current is brought forawrd, even ahead of the peak point of discharge current, which is completely consistent with the theory analysis in Section A.

III. TRIGGER STRATEGY OF MULTI-STAGE COILGUN

Launching efficiency is one of the most important indexes of coilgun. Therefore, it is better to keep the peak point of discharge current ahead of the zero point of the induction current for higher efficiency. There are two ways to improve launching efficiency.

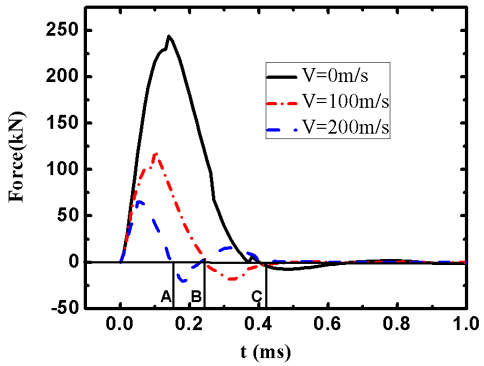

Fig. 3. Force curves of armature at different initial velocity

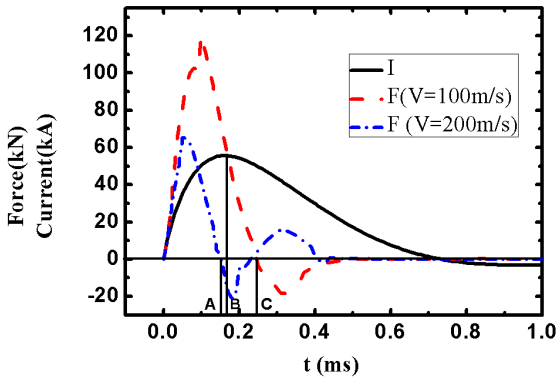

Fig. 4. Relation curves of force and discharge current

When the structure and circuit parameters of every stage are the same, it is better to trigger before the rear of the armature arriving at the middle of driving coil as the speeding up of the armature. The velocity of armature is higher, and the triggering time is earlier.

On the contrary, when the parameters of every stage are different, we can improve the discharge frequency by changing the parameters of the circuit as the speeding up of armature, which may keep the peak point of the discharge current ahead of the zero point of the induction current.

In order to get the optimal parameters of every stage of coilgun, we build a simulation model to analyze the influence on efficiency of different parameters. According to the simulation results, we optimize the parameters of multi-stage coilgun.

IV. CONCLUSION

The direction of the induced current in armature reverses during movement, which brings the direction of magnetic force on the armature reverse accordingly. The position of the reverse point is determined by the current of driving coil and the velocity of the armature. As the increase of armature velocity, the reverse point will be advanced. Thus, it is essential to simulate the fore characteristic and trigger multi-stage coilgun according to the reverse point and the position of the armature precisely, to increase the launching efficiency of coilgun.

V. REFERENCES

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