Structure Optimization of Permanent Magnet Linear Ejection Motor with Moving Armature

Guanglei Xie, Jun Wu* and Yongxiang He

College of Intelligent Science, National University of Defense Technology, Changsha, 410073, China

*Corresponding author’s e-mail: wujun2008@nudt.edu.cn

Abstract: In order to meet the needs of the battlefield, a double-sided moving armature permanent magnet linear ejection motor with high maneuverability is proposed. The structure of the permanent magnet linear ejection motor with moving armature is optimized. By designing the self-alignment guide structure, the air gap can automatically tend to be symmetrical and the normal force caused by the asymmetry of the actuator can be weakened. The eddy current resistance in the process of launch can be effectively reduced by replacing supporting frame materials and applying stiffeners. In addition, the braking effect of the brake segment can be improved and the impact force can be reduced by changing the brake structure to hydraulic damping brake.

1. Introduction

As a new type of combat weapon and equipment in the future unmanned, networked, informationized and intelligent battlefield environment, UAV cluster combat has been favored by more and more countries. As for the use of UAV, the take-off of fixed-wing UAV in different environments and places has created an urgent need for new launching methods[1-5]. At present, fixed-wing UAV launchers mostly use the land-based vehicle-mounted UAV electromagnetic launcher as shown in figure 1[6]. In order to meet the needs of the battlefield, UAV electromagnetic catapult requires high maneuverability, and the launcher needs to be transferred and transported quickly as the battlefield needs [7]. Therefore, the electromagnetic catapult needs to be small in size, light in weight and simple in structure. At the same time, the length of the track used for braking ejection platform at the end must be limited, while the braking performance is not affected [8-11]. The commonly used moving-magnetic linear motor, as the ejection motor for UAV, cannot meet the requirements of land-based vehicle mobility due to its heavy structure, large material consumption and low power density. Especially in the battlefield environment where space is limited, such as mountain and jungle, it will cause great difficulty in overall transportation and slow transfer and retreat, which will affect the effect of electromagnetic ejector.

Figure 1. Electromagnetic catapult model of land-based vehicle-mounted UAV
In order to improve the mobility of the electromagnetic catapult and facilitate transportation, transfer and expansion of capacity, it is an effective way to design the linear motor as a splicable assembly module. Therefore, the researchers chose the high-power density moving armature permanent magnet linear motor to achieve electromagnetic catapult [12,13]. This scheme adopts magnetic steel splicing and moving current receiver. Each part is loaded on the vehicle, which can be transferred and transported rapidly according to the needs of the battlefield. At the same time, the overall structure is simpler, greatly reducing the use of windings and the weight of electromagnetic catapulting system.

Unfortunately, because the moving structure is coil winding and adopts rubber damping brake structure, there is a problem that collision and impact easily destroy the moving armature and cause damage to the moving armature permanent magnet motor system. Reference [14] proposed a two-side eddy current braking device structure based on Halbach permanent magnet array, but the braking performance was not significantly improved. The metal supporting frame structure is added outside the coil winding to protect the moving armature, but a new eddy current resistance is introduced. Reference [15] analyzes the eddy current resistance introduced by the permanent magnet support sleeve. Such eddy current resistance can be effectively weakened by designing the stator core semi-closed slot structure and hollow aluminum support frame structure, but the eddy current resistance introduced by the metal support frame has not been analyzed. At the same time, in the process of operation, if the moving armature is offset, the double-sided permanent magnet linear motor will have a large normal force. The increase of normal force will lead to increased frictional resistance, which will hinder the motor operation and reduce the payload of the motor. Meanwhile, the magnetic steel and the fixed frame will be deformed. Reference [16] uses finite element analysis to obtain the allowable offset range of magnetic steel track splicing dislocation. Reference [17] analyzes the normal force caused by asymmetry of air gap on both sides, and designs a reasonable fixing way of magnetic steel. When the magnetic steel is offset by 4mm, the deformation of magnetic steel can be less than 0.3mm, thus ensuring that collision fault will not occur between magnetic steel and moving iron core during ejection, but the normal force caused by bias cannot be fundamentally reduced.

Therefore, aiming at the special structure of high power density moving armature permanent magnet linear motor, this paper analyzes the resistance during the ejection process and optimizes the design of the structure.

2. Structure and resistance analysis of permanent magnet linear motor for electromagnetic ejection of UAV

2.1. Structure analysis
The structure of the double-sided permanent magnet linear motor is shown in figure 2. According to the different structure of the mover, it can be divided into moving magnet type and moving armature type. The moving part of the moving magnet type permanent magnet linear motor is a permanent magnet and the stator is a coil winding. The moving part of the moving armature permanent magnet linear motor is the coil winding, and the stator is the permanent magnet array. In the new UAV electromagnetic ejection system, in order to improve maneuverability and flexibility, a moving armature permanent magnet linear motor structure is adopted.

Figure 2. The structure of the double-sided permanent magnet linear motor
Figure 3 shows the basic structure of the moving armature permanent magnet linear motor used in electromagnetic launch of UAV. Among them, the ejection platform consists of the moving armature, which pushes the UAV to launch. In order to overcome the normal force, the moving armature adopts a bilaterally symmetrical structure. As long as the air gaps on both sides are equal, the force of the moving armature is balanced. At the same time, a reinforcement structure is used outside the moving armature to prevent normal force from damaging the stator structure and affecting the performance of the motor. The magnetic steel array is the stator track, and the thin-walled aluminum alloy frame is fixed on the outside. The conductor rail is in sliding contact with the collector shoes on both sides of the mover to supply power to the moving armature. The rubber cushion is used as the end brake structure to brake the mover.

![Figure 3. Schematic diagram of permanent magnet linear motor with moving armature](image)

2.2. Resistance analysis

In the ejection process of the linear motor, the thrust force is the electromagnetic force received by the mover armature. To achieve accurate control of the ejection process, the resistance of the ejection process must be accurately analyzed. Under the condition of correct commutations, there are three main kinds of resistance in the moving armature permanent magnet linear motor: friction resistance caused by normal force, eddy current resistance introduced by supporting frame and rubber brake damping force.

2.2.1. Normal force. The permanent magnet linear motor adopts a flat-breaking structure, so that there is a large normal force between the primary iron core and the secondary magnet, and its value can reach 2 to 10 times the horizontal thrust. Although the moving armature linear motor adopts a bilateral symmetrical structure to offset the normal force, it is impossible to achieve the ideal symmetrical size in the actual machining process. Therefore, the moving armature linear motor still has a large normal force. According to reference [17], when there is deviation in the assembly, the normal force on the dynamic structure is

\[
F_n = \frac{1}{2} \mu_0 I \left[ \left( \frac{H_m l_m}{l_m + \delta - y} \right)^2 - \left( \frac{H_m l_m}{l_m + \delta + y} \right)^2 \right]
\]

2.2.2. Eddy current resistance. When the mover structure moves on the magnetic steel track at a certain speed, the supporting frame structure of the mover coil cuts the magnetic field lines in the magnetic field generated by the permanent magnet, and induces electromotive force and eddy current. The existence of eddy current makes eddy current resistance between the moving armature structure and the permanent magnet, which prevents the mover from moving forward.

The eddy current loss generated by the metal plate in the traveling wave magnetic field is expressed as
\[ P_e = \frac{qp^3}{2\sqrt{2\sigma\mu_\tau}} (K_z e^{-qb})^2 \]  

(2)

Where \( P_e \) is the eddy current loss of the support framework; \( p \) is defined as \( \frac{\tau}{\delta} \); \( q \) is defined as \( \frac{\pi}{\delta} \); \( \delta \) is the skin depth of the support framework; \( \sigma \) is the electrical conductivity of the support framework; \( \mu \) is the relative permeability of the support framework; \( K_z \) is the linear density of the equivalent current slice of the traveling wave magnetic field; \( b \) is the distance from the current sheet to the support framework.

Then the eddy resistance generated by the support framework during the movement of the mover is

\[ f_e = -\frac{P_e}{v} \]  

(3)

2.2.3. Damping braking force. At the end of the braking section, rubber pads are used for redundant braking to improve system reliability. The rubber damping braking analysis is the analysis of the collision and contact between the mover structure and the rubber. During the deformation process, the rubber exhibits strong geometric nonlinearity and material nonlinearity. Therefore, the Hunt nonlinear damping model is selected for the dynamic contact model, and the contact force expression is as follows

\[ F_z = KS^n + \mu S^n \dot{S} (S \geq 0) \]  

(4)

Where \( F_z \) is the contact force; \( K \) is the contact stiffness coefficient; \( S \) is contact deformation; \( \dot{S} \) is contact velocity; \( n \) is the rigidity index of the material; \( \mu \) is damping coefficient. The nonlinearity of the collision structure in the deformation range can be approximately expressed by the exponential term \( S^n \).

3. Structure optimization

In this paper, the structure of a new type of permanent magnet linear motor with moving armature is optimized, including the self-alignment guide structure, the moving armature supporting structure and the brake rubber damping structure.

3.1. Optimization of the self-alignment guide structure

A non-contact self-alignment guide structure as shown in figure 4 is designed. Two magnetic steel arrays are embedded in the pedestal. When the air gap of the rotor coil is symmetrical, the magnetic steel is opposite to the external support frame, and the moving armature supporting structure is at the minimum magnetoresistance position. When the moving armature is biased, the magnetic field near the magnetic steel and the support frame changes, which makes the magnetic energy between the magnetic steel and the support frame change. The change of magnetic co-energy will produce a normal suction to prevent the moving coil from shifting. Therefore, when the actuator bias leads to unequal air gap, the magnetic steel can make the air gap tend to symmetry automatically and reduce the normal force on the actuator structure.
The magnetic co-energy method can be used to solve the force between the magnet and the mover frame. Figure 5 shows the magnetic circuit analysis model of the self-alignment guide structure. The magnetic field lines pass through the permanent magnet, the air gap and the mover frame. It can be approximated that the magnetomotive force provided by the permanent magnet is consumed in the air gap. From the law of Ampere’s loop:

$$\sum_{n=1}^{N} l_n = 2H_c l_m = \frac{\delta}{\mu_0} Hdl = 2H_0(l_m + \delta)$$

(5)

Where $\sum_{n=1}^{N} l_n$ is the current passing through the magnetic circuit; $H_c$ is the coercive force of the magnetic steel; $l_m$ is the thickness of the magnetic steel; $l$ is the length of the magnetic steel; $\delta$ is the air gap size; $\mu_0$ is the relative permeability of air; $H_0$ is the air magnetic field strength.

The magnetic common energy of a single magnet is

$$W_m = \frac{1}{2} \mu_0 H_c^2 \cdot V = \frac{1}{2} \mu_0 \left(\frac{H_c l_m}{l_m + \delta}\right)^2 \cdot (l_m + \delta) \tau l = \frac{1}{2} \mu_0 \tau l \left(\frac{H_c l_m}{l_m + \delta}\right)^2$$

(6)

Taking the derivative of $W_m$ in the normal direction, we can get the suction which is affected by the blocking deviation when the moving armature structure offsets $x$:

$$F' = \frac{\partial W_m}{\partial x}$$

(7)

By simulating and analyzing the different offsets of the moving armature, the normal force of the motor load and the suction force of the self-alignment guide structure can be obtained. The results are shown in table 1. The simulation results show that the air gap can be automatically symmetrical when the moving armature offset is less than 2mm, thus eliminating the normal force. When the offset of the moving armature exceeds 3mm, the normal force exerted on the moving armature structure can be reduced by the self-alignment guide structure, thus reducing the friction caused by the normal force.
| Offset /mm | 0   | 1   | 2   | 3   |
|-----------|-----|-----|-----|-----|
| Motor load normal force /kN    | 0   | 0.60| 1.25| 1.90|
| The suction on the self-alignment guide structure /kN | 0   | 0.85| 1.41| 1.63|

### 3.2 Optimization of the moving armature supporting structure

The supporting structure of moving armature is divided into internal frame and external frame. The internal frame is used to fix the iron core and the coil winding, while the external frame is connected with the current receiving boots and the transmitting platform. The material is Q345B. After the prototype was made, there was a magnetic leakage phenomenon, which resulted in the decrease of the air-gap magnetic field and affected the performance of the ejection motor. Meanwhile, eddy current resistance would be introduced into the supporting frame during operation. In order to reduce the motor magnetic flux leakage, the frame material can be replaced by a low permeability material. At the same time, in order to weaken the eddy current resistance introduced by the frame structure, the area of cutting magnetic field lines of the supporting frame can be reduced, and the frame can be changed into a stiffener structure, as shown in figure 6.

![Figure 6. Schematic diagram of optimized unilateral support structure](image)

The frame structure material is changed to 7075-T6 series special aluminum profile for aviation. The structure before and after optimization is simulated and analyzed. The results are shown in figure 7. Before optimization, the maximum eddy current resistance of Q345B supporting frame is 196.3N, and the average eddy current resistance is 172.2N. After optimization, the maximum eddy current resistance of the aero-aluminum support frame is 41.74N, and the average eddy current resistance is 34.07N. By optimizing the supporting frame materials and structure, the average eddy current resistance was reduced by 80.2%. The results show that the maximum stress in the collision process is 184mpa, which is far less than 505mpa yield strength of 7075-T6 series aluminum profile for aviation. The structural strength after optimization meets the requirements.

![Figure 7. Optimize eddy current resistance before and after](image)
3.3. Optimization of brake rubber damping structure

It is easy to cause impact when the rubber pad damping braking is carried out at the end of the braking section. The end rubber damping braking can be changed to hydraulic damping braking, so that from the beginning of the braking section, the hydraulic damping braking will play a role in reducing impact, improving braking efficiency, and at the same time avoiding the rebound after the collision of the mover. The structural diagram of gradual damping type hydraulic buffer is shown in figure 8.

![Structure drawing of porous hydraulic buffer](image)

Figure 8. Structure drawing of porous hydraulic buffer

According to the flow equation

\[ Q = v A \eta_v \]  

Where \( A \) is the piston area; \( \eta_v \) is the volume efficiency of hydraulic cylinder.

The thrust of the hydraulic cylinder is

\[ F = (p_1 - p_2)(A_1 - A_2) \eta_m \]  

Where \( p_1 \) is the pressure within the bar cavity of the hydraulic buffer; \( p_2 \) is the pressure inside the bar cavity of the hydraulic buffer; \( A_2 \) is the area inside the rod cavity; \( \eta_m \) is the mechanical efficiency of the hydraulic cylinder.

Set the mass of the actuator at 30kg and the initial speed at 30m/s to simulate the braking section. The velocity curve during collision is shown in figure 9. When the rubber pad is used at the end for braking, the braking acceleration at the moment of impact is about 650g, and the braking time is 406ms. After being optimized into the hydraulic damper structure, in the collision process, the thrust of the hydraulic cylinder is the resistance of the actuator, which is about 45KN, the whole braking acceleration is 150g, and the braking time is 20ms. According to the analysis, by optimizing the brake structure into the full hydraulic damping, the impact force of instantaneous contact collision can be reduced by 76.9%, and the braking process is faster.

![Speed curve in the process of collision](image)

Figure 9. Speed curve in the process of collision

4. Conclusion

In this paper, the structure of a new generation of moving armature permanent magnet linear ejection motor is optimized. By designing the self-alignment guide structure, the air gap can be automatically symmetrical when the moving armature offset is less than 2mm, thus eliminating the normal force. When the moving armature offset is greater than 3mm, the normal force of the moving armature can be
effectively reduced, thus reducing the friction force and increasing the payload. Besides, the eddy current resistance of the moving armature supporting frame structure in the process of launch can be reduced by 80.2% through replacing the supporting frame material and applying the stiffener structure. At the same time, the structural strength meets the requirements. By replacing the rubber damper brake with a full hydraulic buffer brake, the impact force of instantaneous contact can be reduced by 76.9%. At the same time, it can also avoid damage to primary components and brake faster.

Acknowledgments
This subject is derived from the key technology research project of high-speed maglev transportation system in the National Key Research and Development Plan of the 13th Five-Year Plan (2016 YFB1200602-40) "Research on the comprehensive detection system of high-speed maglev track".

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