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Research and Experiment on Electromagnetic Force Properties of LPMBLDCLM for Electromagnetic Launch

Huilai Li*, Xiaomin Li, Zhiyuan Li
Department of Unmaned Aircraft Vehicle Engineering, Mechanical Engineering College,
Shijiazhuang, P.R.China, 050003
*Corresponding author, e-mail: oec_ljw2009@163.com

Abstract

In order to improve the thrust characteristics of the moving-magnet type linear permanent magnet brushless DC motor (LPMBLDCM), the structural characteristics and magnetic field are analyzed. The influence rule of electrical parameters and structural parameters on the electromagnetic properties and thrust performance are researched by finite element analysis (FEA). The effect regularity of structural parameters to mover velocity and thrust are researched as well as the electrical parameters. The LPMBLDCM system is established, and some relevant tests were taken to verify the correctness of simulation results. Simulation and experimental results show that the thrust and velocity of mover are affected by some key parameter. The results will surely provide the reference and guidance for the optimization of electromagnetic and thrust characteristics of LPMBLDCM.

***Keywords**: LPMBLDCM, structural parameters, electrical parameters, velocity, thrust*

1. Introduction

Linear permanent magnet brushless DC motor (LPMBDCM) has the advantage of high flux density, large thrust, high energy efficiency and simple structure, which is very suitable to be applied to UAV launch for electromagnetic catapult [1-2]. Different with the chemical launcher, linear motor for electromagnetic launch generally require high voltage, high current, high and constant thrust. The variation range of transient vocility for mover is very large, and the terminal velocity can reach several tens metres per second. All those special conditions require high thrust output and energy efficiency for LPMBDCM. Therefore, the research of structural parameters and electrical parameters effect rule are necessary to promote performance for LPMBDCM design.

The optimization design of structural parameters and back-EMF waveforms are two main ways to promote thrust performance for LPMBDCM. The research of single structural parameters to improve the performance concerns pole/arc coefficient, slot width, thickness of iron yoke, winding mode, poles structure. However, this optimization method has its shortage. For the other non-objective parameters, they can't be optionally changed in simulated process. It must be recalculated when other parameters have been changed. The influences of gap length, thickness of magnet, pole arc coefficient, number of pole pairs to the average thrust have been already discussed for a double-sided linear synchronous motor used for electromagnetic catapults in [3], and some results are consistent with the computed results in [4]. For LPMBLDCM, the optimazation of structural parameters can increase the flat width of trapezoidal back-EMF, so the thrust output will be smooth [5].

In this paper, the rule of structural parameters and electrical parameters to thrust performance for LPMBLDCM are researched by simulation and experiment. The parameter matching and optimizing design problem for LPMBLDCM are explored to apply small and middle scale UAV launcher, and also to provide references to catapult design.

2.Electromagnetic Field Model Analysis

Figure 1 shows the simplified diagram of two dimensional solution area for LPMBLDCM. To calculate the flux density in the air-gap, the symmetry boundary conditions between

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permanent magnet is setted. The permanent magnet region, air gap region, and slotted stator region are divided in turn along the y-axis direction with three boxes alveolar layers boundary. The moving-magnet mover could only slip along x-axis direction.

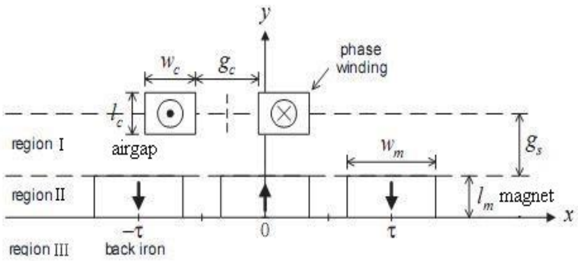

Figure 1. The Diagram of Two Dimensional Solution Area

The distribution equations of magnetic field for each layer are given as follows [6]:

$$\begin{cases} \dfrac{\partial^2 A_{\mathrm{I}}}{\partial x^2}+\dfrac{\partial^2 A_{\mathrm{I}}}{\partial y^2}=0 & Regin\,\mathrm{I} \\ \dfrac{\partial^2 A_{\mathrm{II}}}{\partial x^2}+\dfrac{\partial^2 A_{\mathrm{II}}}{\partial y^2}= jv_x\dfrac{\pi}{\tau}(n-1)\sigma_m\mu_m A_{\mathrm{II}}-\mu_0 J_m & Regin\,\mathrm{II} \\ \dfrac{\partial^2 A_{\mathrm{III}}}{\partial x^2}+\dfrac{\partial^2 A_{\mathrm{III}}}{\partial y^2}= jv_x\dfrac{\pi}{\tau}(n-1)\sigma_s\mu_s A_{\mathrm{III}} & Regin\,\mathrm{III} \end{cases} \tag{1}$$

Where A is the curl of magnetic vector; σ_s and σ_m respectively denotes the conductivity of permanent magnet and iron yoke; τ denotes the pole pitch; v_x denotes the velocity of mover along the x-axis direction; n is the multiple of the space harmonics to fundamental field. J_m is derived from the formula (2).

$$J_m = \nabla\times M = B_r / \mu_0 \cdot e^{j(\omega_0 t - at)} \tag{2}$$

Where B_r is the remanence of permanent magnet, ω_0 is the equivalent angular velocity. Magnetic obtained out of position and the winding currents, according to Ampere's law, the mover thrust have been suffered as formula (3).

$$\vec{F}=\int_V J\times B dV=\int_V J\times\left(i\frac{\partial A}{\partial x}+j\frac{\partial A}{\partial x}\right)dV \tag{3}$$

However, this method results were not accurate, for the non-linear magnetic flux leakage has not been taken into the model. To accurately calculate the field and parameters for LPMBLDCM, the ideal choice is the finite element analysis(FEA).

3. Finite Element Analysis and Results

3.1. Model Analysis And Parameter Settings

The transient process of electromagnetic launch is a highly coupled process. The eddy current loss and hysteresis loss are serious at high speed. The mutual inductance of mover and winding will present non-linear changes with the different position and velocity, which is difficult to establish the exact mathematical model. Maxwell Ansoft software can automatically consider part shape, material properties, relative position and other parameters, which could solve the problem of direct calculation. The transmit dynamic process of electromagnetic launch for

LPMBLDCM is researched using Maxwell Ansoft 2-D transient solver in this paper. The influence of structural parameters and electrical parameters to the thrust performance for LPMBLDCM are investigated, which provide foundation for optimal design.

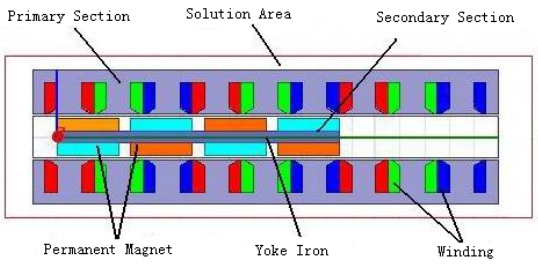

Figure 2. Dynamic Simulative Model of LPMBDCM

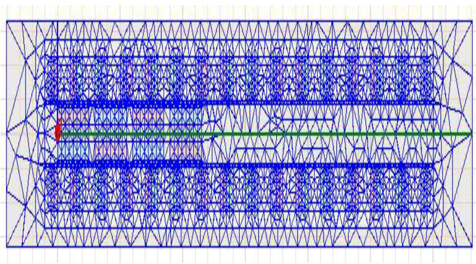

Figure 3. Section of the Meshed Model of LPMBDCM

Figure 2. shows the model of LPMBDCM, including mover, stator, winding, translation domain and solution domain. Figure 3. shows the meshed model of LPMBDCM by FEA. It can be seen that the mover, drive coil and translation domain are relative intensive so as to ensure the accuracy of simulation. The winding coil is setted as serial multilayer, a total of 4 layers. The material of solution domain is vacuum, and the external drive circuit is established, as shown in Figure 4. The current in the winding is added by external drive circuit, and the voltage and resistance values can be setted as required. The simulation time is from 0 ms to 150 ms with 0.05 ms step-size change.

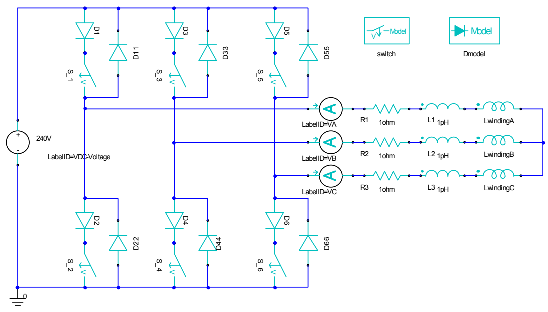

Figure 4. The External Drive Circuit

The pole pitch (τ), length of air-gap (gs), size of slot dimension (wc, lc, hs), size of PM dimension (wm, lm, hm), and the length of primary and secondary section should be adjusted properly. Some motor parameters and PM characteristic have been shown in Table 1.

Table 1. Motor Design Data and PM Characteristic

Symbol	*Item*	*Value*
τ	pole pitch	60mm
g_s	length of air-gap	2mm
w_c	width of slot	15mm
l_c	length of slot	20mm
h_s	depth of slot	100mm
w_m	width of PM	50mm
l_m	length of PM	90mm
h_m	thickness of PM	12mm
L_p	primary length	1.8m
L_s	secondary length	235mm
PM	material	Nd-Fe-B

3.2 Structural Parameters Effect And Analysis
3.2.1. The Influence of Pole/Arc Coefficient

For LPMBLDCM, the pole/arc coefficient is defined as:

$$\alpha = w_m / \tau \qquad (6)$$

To research the influence of pole/arc coefficient on the cogging force, some conditions have been located as follow: the initial velocity of the mover is 20 m/s; the atuating voltage is 0 V; the mass of mover and load is 10kg. The eddy current effect has been ignored. The cogging force results under different pole/arc coefficient have been obtained, as shown in Figure 5. As can be seen from Figure 5, the cogging force almostly remains stationary and they are quite small compared to thrust force output. The average of cogging force closely equal to 0 N, which does not produce any effect to thrust output, but it will cause thrust fluctuation and velocity fluctuations.

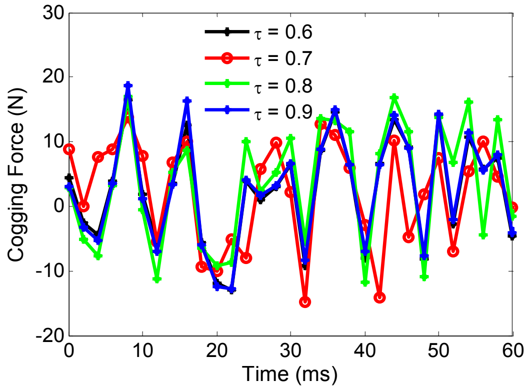

Figure 5. Result of Cogging Force considering Pole/Arc Coefficient

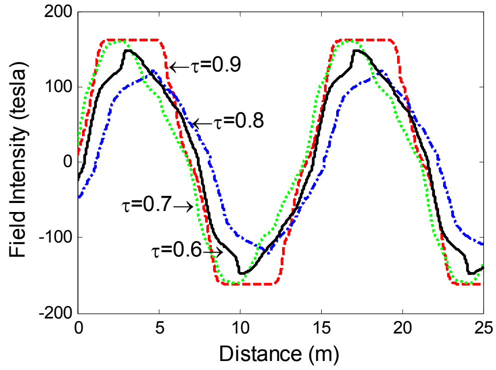

Figure 6. The Relationship of Back-EMF and Pole/Arc Coefficient

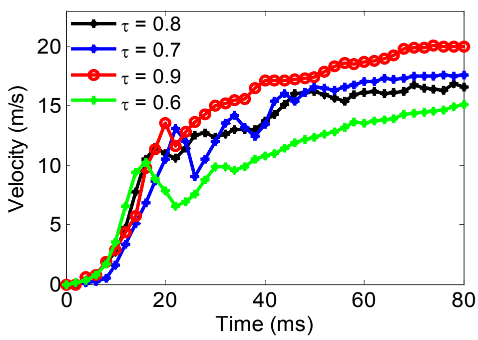

Figure 7. Result of Cogging Force Thrust considering Pole/Arc Coefficient

Figure 6 shows the back-EMF results under different pole/arc coefficient, when the atuating voltage is 300V. It can be seen that a rather large width of back-EMF waveshape occurs with a 100 degree electrical angle when pole/arc coefficient is 0.9. As the decrescence of pole/arc coefficient, the top width of back-EMF waveshape will become narrow down and the raised amplitud distortion will also appear. Figure 7 gives the basic law of acceleration change which different pole/arc coefficient are considered. The mover has different acceleration response when the pole/arc coefficient is respectively assumed at 0.6, 0.7, 0.8 and 0.9. The optimal acceleration response occurs when the pole/arc coefficient approximate at 0.7.

3.2.2. The Influence of Airgap Width

As some literature have been reported that the airgap width could impact the distribution of magnetic field, so the analysis of airgap length is very important for estimating the actual performance. The simulation conditions have been located as follow: the atuating voltage is 240V; the mass of mover and load is 10kg. The airgap width gs is setted from 2mm to 4mm with 1mm step-size change, and the eddy current effect has been ignored.

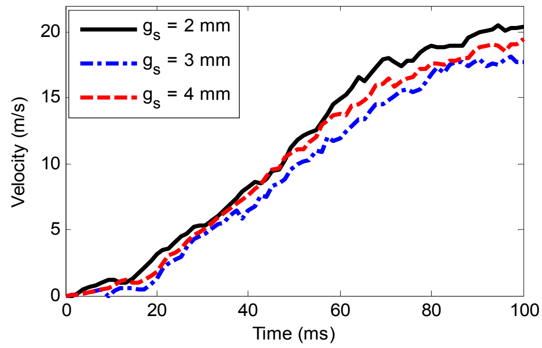

Figure 8. Results of Acceleration considering Airgap Width

The velocity changes of mover are presented in acceleration time with different airgap width, as shown in Figure 8. The acceleration curve shows that the mover has a rather larger acceleration from 0ms to 60ms and a gradual rolloff until to zero after 100ms. This can be explained that the short airgap will provided more larger field density, which the maximal velocity will become large and the acceleration time will also become short.

3.3. Electrical Parameters Effect And Analysis

3.3.1. The Influence of Actuating Voltage

Set the electrical parameters of external circuit as follow: the resistance R is 0.1ohm; the inductance L is 40mH; the voltage is setted from 60V to 240V with 60V step-size change. Figure 9. shows the velocity acceleration results considering actuating voltage.

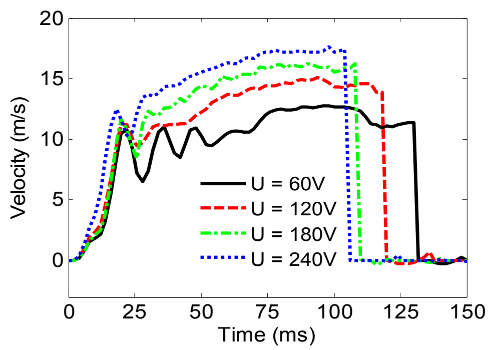

Figure 9. Results of Acceleration considering Voltage

The transient acceleration response does not show linear rule with the increase of voltage. The mover acceleration evidently present increasing at first and then decrease to zero in the process. When the voltage exceeds 180V, the addition of thrust in the x-axis direction and acceleration response are not obvious. The Ampere force can not increases linearly due to the saturated field in the air gap. The electromagnetic force is decided by current, magnet and position according the Ampere's law, so the maximum thrust doesn’t occurs near the maximum drive current point. The thrust fluctuation appeared during the transient start procedure and this can be explained that the influence of eddy current resistance makes the mover decelerate, which concernes with the change rate of coil current. For the greater of the change rate, the greater of the eddy current resistance, but the Ampere force still plays a leading role in the start procedure, so the thrust increases with the enhancement of the voltage despite a little fluctuation associated.

3.3.2. The Influence of Actuating Current

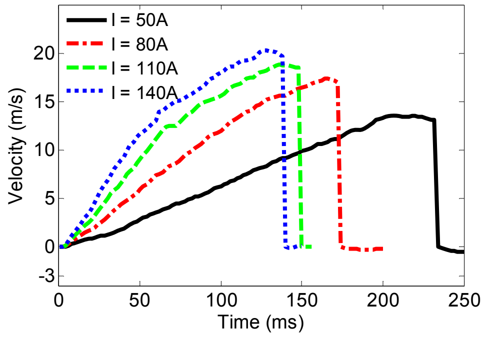

Figure 10. Results of Acceleration considering Current

Figure 10 shows the mover velocity curve when the actuating current alters some atypical value. With the enhancement of actuating current, the max velocity increases from 12.73m/s to 19.52m/s, when the actuating current is 50A to 140A. It can be seen that the mover velocity almost show linear relation when the number of ampere turns is below 400. The rate of mover acceleration is not evidently when the actuating current exceeds at given value, such as 200A for concerned model machine. According to the schematic model, a subscale long primary LPMBDCM system are established, as shown in Figure11.

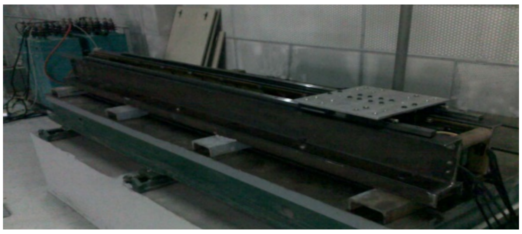

Figure 11. Prototype machine of a subscale long- primary LPMBDCM.

Table 2. Experiment and Simulation Results for Measured Thrust and Velocity

Voltage $U(V)$	48	96	144	180	216	240
Average simulation thrust (N)	288	446	639	883	1265	1432
Average measured thrust (N)	255	415	588	850	1186	1304
Max simulation velocity (m/s)	5.24	9.26	15.32	18.06	20.66	21.28
Max measured velocity (m/s)	4.95	8.84	13.85	17.09	19.25	20.06

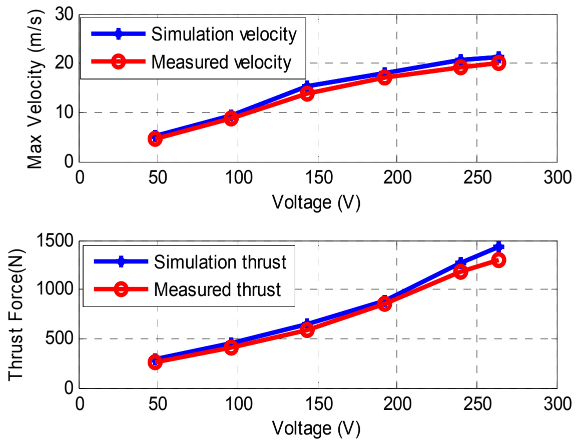

Figure 12. The Mover Velocity change to Voltage

Simulation and experimental results obtained are shown in Table 2. Figure 12 shows the comparative chart of measured and simulation velocity for the mover, and also the curve of average measured thrust and simulation thrust, when the voltage value changes from 48V to 240V.

It can be seen that the thrust output and mover velocity almost show linear accretion when the actuating voltage is blew 200V. However, it does not appear exactly as a linear relation. For the magnetic field is saturated, the thrust output cann't be promoted if the enhancement of the voltage. The variation rules obtained from the experiment and simulation results are basically consistent. Meanwhile, it can be seen that the measured results are a little smaller than simulation results due to the sliding resistance, which verify the correctness of simulation analysis.

4. Conclusion

The impact rule research of structural parameter and electrical parameter on electromagnetic force properties for LPMBLDCLM are the basic work for multi-parameter optimization design and segmented design. The theoretical working principle and magnetic field for LPMBDCM are analyzed in this paper. The influence rule of structural parameter and electrical parameter on electromagnetic properties and thrust performance for LPMBLDCM are researched by FEA and experiment. Simulation and experiment results show that the enhancement of actuating voltage can apparently increase the mover velocity when the voltage is less than 200V and the minimal single primary length for multi-stage launcher can be designed as 1.65m for proposed LPMBLDCM.

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