Thrust Performance Analysis of A Flux-switching Permanent Magnet Linear Motor for Electromagnetic Launch Systems

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Abstract — In the paper, a novel double-sides flux-switching permanent magnet linear motor (FSPMLM) is proposed for electromagnetic launch systems. The proposed motor has advantage of simple secondary structure, high power density, and is adequate for long distance linear motion. Firstly, the structure and operation principle of the FSPMLM are given. Secondly, the thrust force equation is derived. Two-dimensional (2-D) finite element method (FEM) is used to investigate the dynamic electromagnetic characteristics of the FSPMLM and the process of electromagnetic launch. Lastly, a single-side FSPMLM is employed to validate the thrust performance of proposed machine.

I. INTRODUCTION

Electromagnetic launch technology has attracted the attention of several researchers as the replacement of the steam propulsion technology [1]. The traditional linear induction machine used in electromagnetic launch systems (EMLS) has disadvantages of low efficiency and power factor [2]. The cost of traditional permanent magnet linear synchronous machine used in EMLS is extremely high because of complex secondary structure [3-4]. However, the FSPM machine has advantages over high power density and power factor, as well as simple structure of the secondary [5]. Therefore, a novel FSPMLM is proposed for EMLS. The 2-D FEM combined with an equivalent circuit is employed to analyze electromagnetic characteristics of the FSPMLM. The thrust force equation is derived and validated by finite element analysis (FEA). A single-side FSPMLM prototype is used to validate the results of FEA and thrust formula.

II. THE OPERATION PRINCIPLES

The configuration and cross-section of short primary FSPMLM is shown in Fig.1.

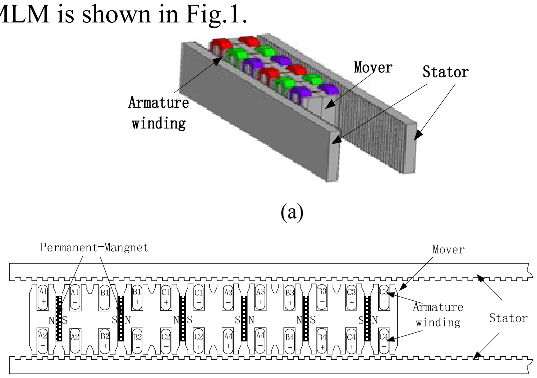

Fig.1 Configuration and cross-section of FSPMLM. (a) The configuration of FSPMLM.(b) The cross-section of FSPMLM.

The double-sides structure is considered because the attractive force, between mover and stator, can be counterbalanced to cancel the swing. The operation principle of the proposed machine is similar to the rotating machines. Flux linkage of armature coils change with magnetic reluctance at different position.

A small scale FSPMLM model is used to investigate the performance of this kind of machine. The no-load PM flux-linkages in three phase coils are shown in Fig.2.

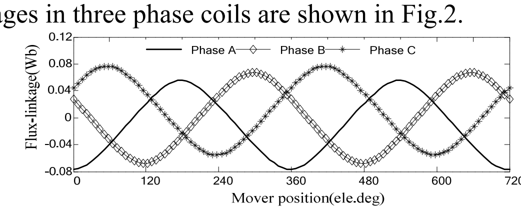

Fig.2 The no-load PM flux-linkage in three phase coils.

As the magnetic fields of end coils of linear machine are asymmetric, the flux of end phases has a value offset.

III. ANALYSIS OF THRUST FORCE

Thrust force is the most important parameter of linear machine for EMLS. Similar to the torque equation derived in [6], the thrust force can be expressed as follows

$$F_e = \frac{\partial W}{\partial x} = \partial[\frac{1}{2}\bar{I}^T \bar{L}\bar{I} + \bar{\Psi}^T_{pm}\bar{I}]/\partial v + F_{cog} = F_r + F_{pm} + F_{cog} \quad (1)$$

where, F_r is the reluctance force caused by inductions, F_{pm} is the permanent magnet thrust force, and F_{cog} is the cogging force generated by slot effect.

Based on the FEA results of inductions, the three-phase inductances can be expressed as follow

$$\begin{cases} L_{aa} = L_0 + L_m \cos(2\pi x/\tau) \\ L_{bb} = L_0 + L_m \cos(2\pi x/\tau + 2\pi/3) + L_1 \\ L_{cc} = L_0 + L_m \cos(2\pi x/\tau - 2\pi/3) \end{cases} \quad (2)$$

$$\begin{cases} M_{ab} = M_{ba} = M_0 + M_m \sin(2\pi x/\tau + 2\pi/3) \\ M_{bc} = M_{cb} = M_0 + M_m \sin(2\pi x/\tau) \\ M_{ca} = M_{ac} = M_0 + M_m \sin(2\pi x/\tau - 2\pi/3) - M_1 \end{cases} \quad (3)$$

where, L_0, L_1, $M_1$and M_0 are constant value of self- and mutual- inductances, respectively; L_m and M_m are the magnitude of the fundamental components of self- and mutual- inductances, respectively.

At operation, the i_d =0 control strategy is obtained by adopting the phase angle of current is in sync with the phase angle of no-load back EMF. The electromagnetic thrust force can be obtained by using the Park-transformation and expressed as

$$F_{pm} = 3\pi\psi_m i_q/\tau = 3\pi\psi_m I_m/\tau \quad (4)$$

$$F_r = \pi I_m^2((2M_1 - L_1)\cos(4\pi x/\tau + \pi/6) + 6M_m\cos(6\pi x/\tau))/2\tau \quad (5)$$

where, τ is teeth distance of stator; ψ_m and I_m are the magnitude of flux-linkage and armature current, respectively.

The cogging force decided by the slot effect is obtained by FEM. The harmonics analysis results of the cogging force waves show that the cogging force can be expressed as follow

$$F_{cog} = F_{c1} + F_{c2} = F_{cm1}\cos(6\frac{2\pi}{\tau}x + \theta_{c1}) + F_{cm2}\cos(12\frac{2\pi}{\tau}x + \theta_{c2}) \quad (6)$$

where, F_{cm1} and F_{cm2} is the fundamental component and second-order harmonic component of cogging force, respectively; θ_{c1} and θ_{c2} is the phase angle of fundamental component and second-order harmonic component.

According to the requirement of EMLS, the average thrust should be kept invariant. The process of electromagnetic launch (EML) can be expressed as follow

$$\frac{1}{2}mv^2 = \Delta W = \int_0^X F_e dx \approx \int_0^{N\tau} F_e dx = F_{pm}N\tau \quad (7)$$

where, m is the mass of moving part of EMLS; v is the speed of mover; N is an integer and $N*\tau$ approximately equal to X, the distance of launch process.

It can be seen that the speed of launcher is only decided by permanent magnet thrust force. The phase position of flux-linkage and no-load back EMF is decided by the position of mover. Therefore, the i_d =0 control strategy is achieved easily by keeping the current phase position angle changing with the mover position.

IV. THE SIMULATION RESULTS OF FEA

2-D transient FEM combined with equivalent circuit is used to investigate the thrust forces of proposed FSPMLM. The thrust of FEA at different current are shown in Fig.3.

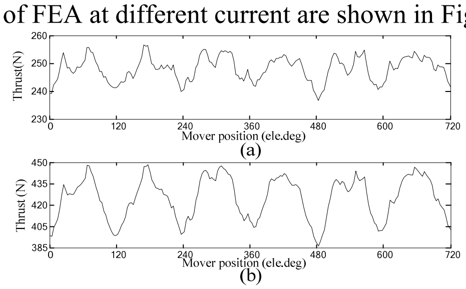

Fig.3.The thrust under different currents.(a) Thrust under 3A. (a) Thrust at current of 5A.

Suppose the mass of moving part is $20Kg$. The process of EML is simulated, and the results of simulation are shown in Fig.4.

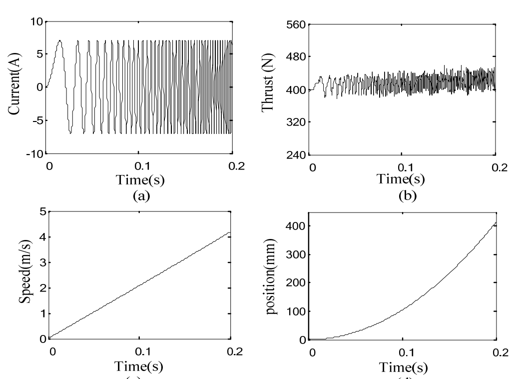

Fig.4 Transient results during the launch.(a)The current of phase A. (b) Thrust force. (c) Speed of mover. (d) Distance of mover.

From the results of FEA, it can be seen that, the thrust force of FEA agree with calculated ones through (4) to (6). During the process of EML, the acceleration of mover is double acceleration of gravity. Compared with The traditional linear induction machine, the control strategy of proposed machine is simpler, and the thrust is more stable.

V. EXPERIMENTAL VALIDATION

In order to verify the analysis results of thrust, a single-side FSPMLM is used to investigate the performance of this kind of machine. The experimental results of thrust force are shown in Fig.5.

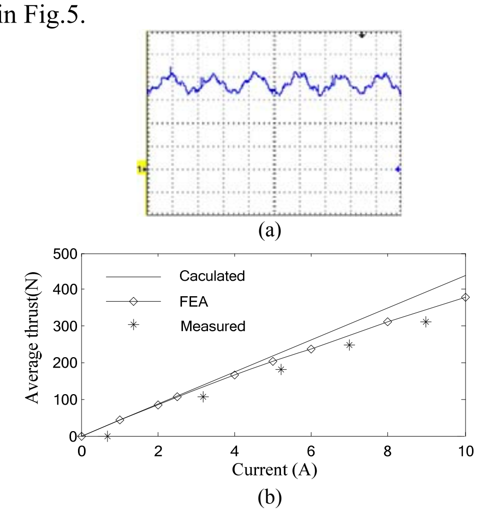

Fig.5 The thrust performance of a single-side FSPMLM. (a) Thrust at the current of 3A(40N/div,0.1s/div). (b) The thrust changing with current.

As shown in Fig.5, the results of FEA and calculated value through thrust formula agree with the Experimental ones. There is a difference between measured thrust and ones of FEA, because of friction force of single-side FSPMLM.

VI. CONCLUSION

In this paper, a novel double-sides FSPMLM is proposed for electromagnetic launch. All results of simulation and experiment manifest that the proposed motor has advantage of simple secondary structure minor cogging force and simple control strategy. This kind FSPMLM is well suitable for the application of electromagnetic launch.

VII. REFERENCES

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