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Novel permanent magnet linear motor with isolated movers: Analytical, numerical and experimental study

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This paper proposes a novel permanent magnet linear motor possessing two movers and one stator. The two movers are isolated and can interact with the stator poles to generate independent forces and motions. Compared with conventional multiple motor driving system, it helps to increase the system compactness, and thus improve the power density and working efficiency. The magnetic field distribution is obtained by using equivalent magnetic circuit method. Following that, the formulation of force output considering armature reaction is carried out. Then inductances are analyzed with finite element method to investigate the relationships of the two movers. It is found that the mutual-inductances are nearly equal to zero, and thus the interaction between the two movers is negligible. A research prototype of the linear motor and a measurement apparatus on thrust force have been developed. Both numerical computation and experiment measurement are conducted to validate the analytical model of thrust force. Comparison shows that the analytical model matches the numerical and experimental results well. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4899236>]

I. INTRODUCTION

Linear machines can generate linear motion directly without rotation-to-translation conversion mechanisms. Due to their inherent advantages such as high power density and high efficiency, they have wide applications in robotics,^{1,2} manufacturing,^{3,4} transportation,^{5,6} medical operation,^{7,8} aerospace industry,^{9,10} and physics field.^{11–13} Permanent magnets (PMs) are applied in electromagnetic motors for their high flux density.^{14–17} The study on force output is one of the most important topics of PM linear machines. Analytical force formulation has been conducted by researchers for design optimization and control purpose of PM linear machines.¹⁸ For example, Zhu *et al.* developed finite element and analytical technique for the calculation of resultant cogging force of a slotted linear tubular brushless PM motor.¹⁹ Youn *et al.* proposed a new permanent magnet linear motor (PMLM) with 9-pole 10-slot structure and driven by three phases.²⁰ They derived the cogging force by applying vector addition and Fourier expansion. It was shown that the designed structure can effectively reduce the cogging force. Other similar methods were also proposed to decrease the cogging force and improve motor output performance.^{21–23} The thrust characteristics of double-side plate PM linear synchronous motor for electromagnetic launch system was studied.²⁴ The thrust and thrust ripple characteristics in different conditions, i.e., phase current and length of air-gap, were analyzed. However, it was simply calculated and analyzed with finite element software. Lu *et al.* designed two

novel PM transverse flux linear oscillating actuators, one with moving magnet and the other with moving magnet and iron core, for pump and compressor drives.²⁵ They investigated the thrust force output of the machine system by using equivalent magnetic circuit (EMC) method. However, so far most studies are more on electromagnetic motors with single stator and single mover. Many implementations require multiple motors to drive different components in the system. For example, in more-electric and all-electric aircraft systems, a certain quantities of electric actuators are needed to drive pumps.¹⁰ The improvement of power density of linear machines can certainly help to increase the performance of whole system.

Therefore, a novel PM linear machine with multiple isolated movers is proposed to increase the system compactness and improve the power density. The linear machine consists of one stator and multiple movers. Each mover can interact with the magnetic field produced by PM poles on the stator and generate independent linear motions. Compared with conventional multiple motor driving system, it helps to achieve compact structure, and thus improve the system working efficiency. The objective of this paper is to analyze the thrust force of the proposed linear motors with isolated movers. The design concept is presented. Following that, the magnetic field in the air gap is formulated analytically. The inductance is also analyzed to investigate the interaction of two movers. A research prototype and a measurement apparatus have been developed. Both numerical computation and experiment measurement are conducted to validate the analytical model of thrust force and the proposed design.

The rest of this paper is organized as follow. Section II presents the concept design of the novel PM linear motor.

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Section III obtains the analytical model of magnetic flux density in air gap by using EMC method and the formulation of thrust force according to the magnetic co-energy theory. Then the interaction of two movers are analyzed by calculating inductances, and the analytical model of thrust force is validated with numerical computation in Sec. IV. Section V presents the developed research prototype and measurement apparatus. Comparisons of analytical model, experimental data, and numerical results are also completed. The paper is concluded in Sec. VI.

II. DESIGN CONCEPT AND OPERATING PRINCIPLE

The assembly and exploded views of the proposed linear motor are illustrated in Figs. 1(a) and 1(b), respectively.

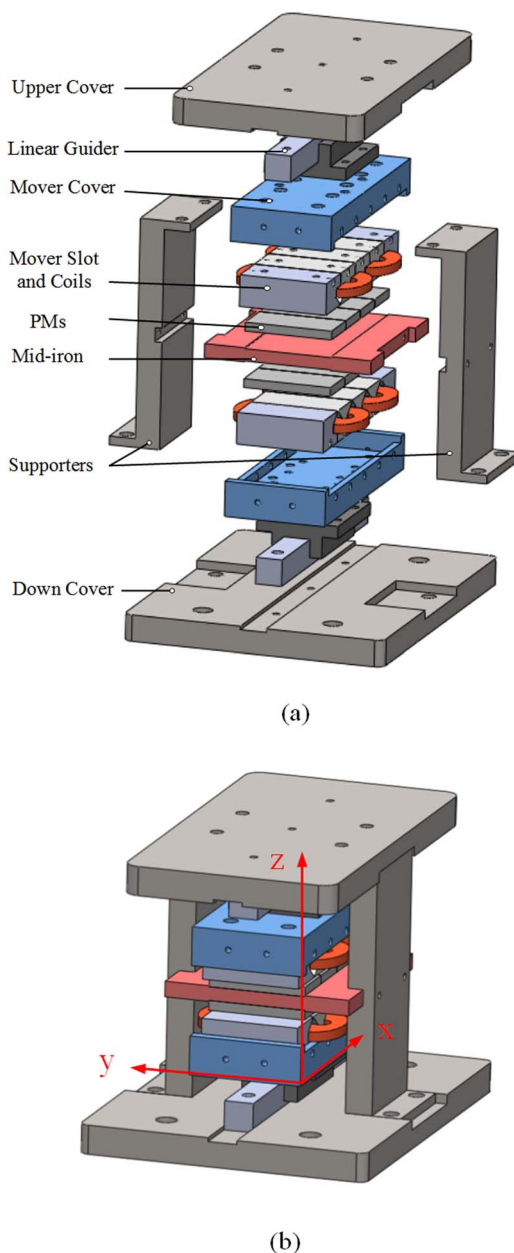


FIG. 1. Concept design of the novel PM linear motor. (a) Exploded view; (b) Assembly view.

The stator mounted with PM poles is placed at the center of the machine. It is fixed on the supporters on two sides of the machine. Two movers are placed on upper and down sides of the stator, and mounted on the mover covers. Windings are assembled on mover slots. The mover covers along with the mover can slide on the linear guiders. The linear guiders are installed on the upper and down covers that in turn are fixed on the supporters. The covers are made from ferromagnetic material to reduce the loss of magnetic energy, and thus improve the system performance.

The PM poles produce magnetic flux in the air gap, and current input in the mover windings interacts with the magnetic field to generate thrust force and linear motion. By varying the power supply in the windings, the two movers can create independent motions under control. It can be verified that the magnetic field distribution on both air gaps is similar. Therefore, the same control algorithm can be implemented for both movers. The similar design concept and operating principle can be extended to linear or rotary electromagnetic machines with multiple stators and rotors.

III. ANALYTICAL FORMULATION OF THRUST FORCE

The purpose of this section is to formulate the thrust output analytically based on magnetic field model. The result will be validated with numerical computation and experimental works.

A. Modeling of magnetic field

EMC method is utilized to obtain the analytical expression of the magnetic field distribution. The magnetic flux in the air gap is contributed by both PM poles and energized coils. Thus, this section will focus on the analytical formulation of magnetic field produced by PM and coil poles separately. The total flux field is equal to the superposition of these two parts. Figure 2 presents the stator pole configuration in which the two layers of PM poles are with the same magnetization pattern. Back iron is inserted in between these two layers of PM poles to reduce the magnetic energy loss and increase the flux density in the air gaps. It can also facilitate the system assembly. To decrease the system size further, single layer of PM poles could also be used for the design. The major design parameters of the linear motor are illustrated in Fig. 3.

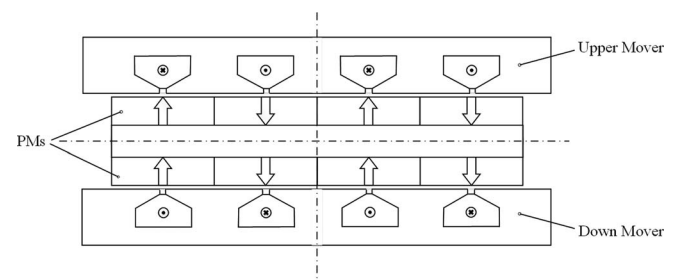


FIG. 2. Magnetization pattern of PM poles on the stator.

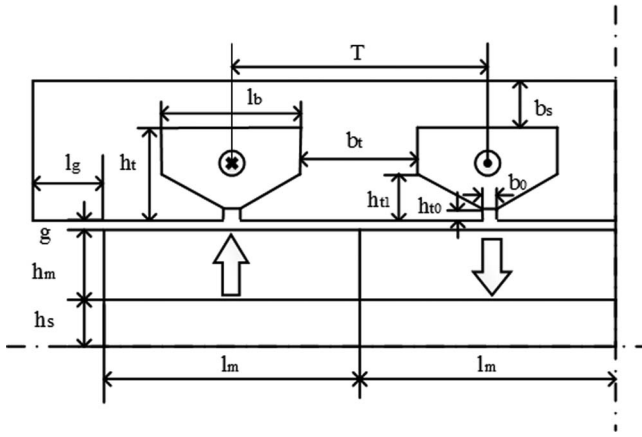


FIG. 3. Major structure parameters of the linear motor.

B. Magnetic flux field of PM poles

Figure 4 presents the equivalent circuit model of motor without payload based on EMC method. Only half side of these models are presented due to the symmetric structure. There are four magnetic reluctances in the magnetic circuit, i.e., PM reluctance R_{pm} , air gap reluctance R_g , saturation in the slot part R_s , and reluctance caused by fringing effect R_f . The last part of magnetic circuit is magnetic motive force (MMF) F_{pm} . The magnetic reluctances and MMF are given by

$$F_{pm} = H_c h_m, \quad R_m = \frac{h_m}{\mu_0 \mu_r l_m b}, \quad R_g = \frac{g}{\mu_0 l_m b}, \quad (1)$$

$$R_s = \frac{l_b}{\mu_0 \mu_{Fe1} b_s b}, \quad R_f = \frac{2(g + h_m + h_s)}{\mu_0 l_g b},$$

where H_c is PM coercivity, b is PM's width at vertical direction, and μ_0 , μ_r , and μ_{Fe1} are air permeability, PM relative permeability, and mover back iron permeability which can be

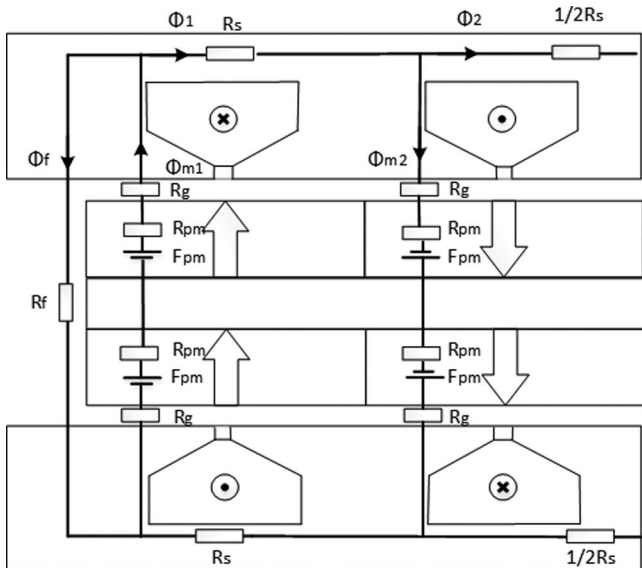


FIG. 4. Equivalent circuit model without payload.

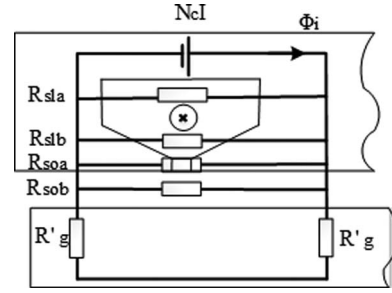


FIG. 5. Magnetic field model of armature reaction.

determined iteratively according to the nonlinear $B-H$ characteristic, respectively. Then the magnetic circuit flux can thus be obtained from

$$\Phi_{m1} = \frac{\left(\frac{1}{R_s} + \frac{3}{R_f} + \frac{1}{R_g + R_{pm}} + \frac{R_s}{R_f(R_g + R_{pm})} \right) F_{pm}}{2 + \frac{R_{pm} + R_g}{R_s} + \frac{R_s}{2(R_g + R_{pm})} + \frac{3(R_g + R_{pm}) + R_s}{R_f}},$$

$$\Phi_{m2} = \frac{2(R_f + R_s)}{R_f(R_{pm} + R_g)} F_{pm} - \left(1 + \frac{R_s}{R_g + R_{pm}} + \frac{2R_s}{R_f} \right) \Phi_{m1},$$

$$\Phi_f = \frac{2F_{pm} - 2\Phi_{m1}(R_g + R_{pm})}{R_f}. \quad (2)$$

Therefore, the air gap flux density is

$$B_{gi} = \frac{\Phi_{mi}}{l_m b}, \quad i = 1, 2. \quad (3)$$

C. Magnetic flux field by coils

Assume that there is no significant magnetic saturation in the stator core and the magnetic circuit is linear for consideration of the armature reaction. By removing all PM poles, the equivalent circuit model produced by the armature current is shown in Fig. 5. R_{sla} and R_{slb} are the slot leakage reluctances between the parallel and tapered slot walls, respectively. R_{soa} is the slot opening leakage reluctance, and R_{sob} is introduced for the large air gap length. The air gap reluctance is represented by R'_g as following:

$$R_{sla} = \frac{l_b}{\mu_0 b(h_t - h_{t1})}, \quad R_{slb} = \frac{2l_b}{\mu_0 b(h_{t1} - h_{t0})},$$

$$R_{soa} = \frac{b_0}{\mu_0 b h_{t0}}, \quad R_{sob} = \frac{4(h_m + g)}{\mu_0 l_g b}, \quad R'_g = \frac{2(h_m + g)}{\mu_0 b(T - b_0)}, \quad (4)$$

where b is PM's width at vertical direction and T is the distance between two coil slots. The magnetic flux due to the armature reaction is

$$\Phi_i = N_c i \left(\frac{1}{R_{sla}} + \frac{1}{R_{slb}} + \frac{1}{R_{soa}} + \frac{1}{R_{sob}} + \frac{1}{2R'_g} \right). \quad (5)$$

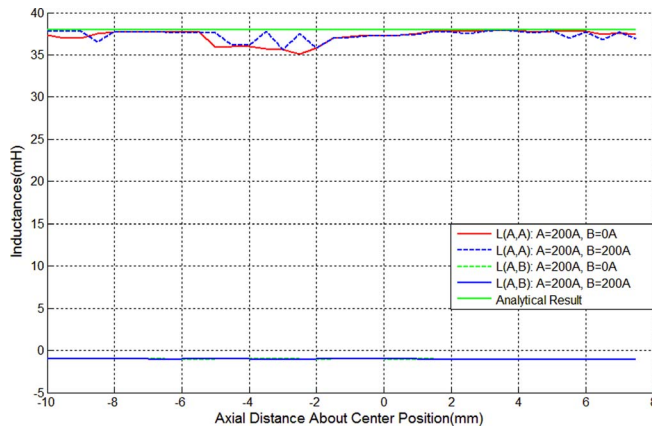


FIG. 6. Comparisons of inductances from numerical computation and analytical model

According to the above analysis, the whole magnetic circuit model can be obtained, taking magnetic saturation and flux leakage into account.

D. Formulation of trust force output

According to the theory of magnetic co-energy, the winding flux linkage is

$$\Psi(i, x) = \Psi_i + \Psi_{pm} = Li + K_e x, \quad (6)$$

where ψ_i and ψ_{pm} are induced by coils and PM poles, respectively. K_e is the back electromotive force coefficient. Then the magnetic co-energy in the air gap is

$$W_{com} = \int_0^i \Psi(i, x) di = \frac{1}{2} Li^2 + K_e xi. \quad (7)$$

The thrust force can be calculated from

$$F = \frac{\partial W_{com}}{\partial x} \Big|_{i=cons} = \frac{1}{2} i^2 \frac{dL(i, x)}{dx} + K_e i. \quad (8)$$

Generally, L is the function of winding currents and mover displacement. However, according to the finite element method (FEM) results shown in Fig. 6, the inductance does not vary much for different points with current inputs. The thrust is thus simplified as

$$F = K_e i. \quad (9)$$

When the mover has very small displacements Δx from the central position, the winding flux linkage due to PMs is

$$\Psi_{pm} \Big|_{\Delta x} = 2N_c B_g b \Delta x, \quad (10)$$

where N_c is the number of turns per slot. Then K_e and the trust force due to current at $x = 0$ are formulated as

$$K_e = \frac{\Psi_{pm} \Big|_{\Delta x}}{\Delta x} = 2N_c B_g b, \quad (11)$$

$$F = K_e i = 2N_c B_g bi.$$

TABLE I. Major parameters of the linear motor.

Symbol	Value	Symbol	Value
H_c	955 kA/m	b	50 mm
h_m	5 mm	b_s	6 mm
h_s	3.5 mm	b_0	1 mm
l_m	25 mm	g	1.5 mm
l_b	20 mm	μ_0	4×10^{-7} H/m
h_t	11 mm	μ_r	1.4
h_{t0}	6 mm	μ_{Fe1}	3×10^{-4} H/m
h_{t1}	1 mm	μ_{Fe2}	1.2×10^{-3} H/m

IV. INDUCTANCE CALCULATION

For linear motors with isolated movers, the study on interaction of movers is important. Inductances including self-inductance and mutual-inductance are good indexes for describing the interaction. Based on the equation of magnetic linkage caused by coils,

$$\psi_i = Li = N_c \Phi_i, \quad (12)$$

and combination with Eq. (5), self-inductance of the winding can be obtained

$$L = \frac{N_c \Phi_i}{i} = N_c^2 \left(\frac{1}{R_{sla}} + \frac{1}{R_{slb}} + \frac{1}{R_{soa}} + \frac{1}{R_{sob}} + \frac{1}{2R'_g} \right). \quad (13)$$

The mutual inductance is difficult to calculate analytically since the flux generated by other phase coils is unknown. Therefore, the numerical result is taken to replace the analytical data. Compared with analytical method, numerical result is more precise for calculating inductances because it takes saturation into account and no much simplification of the actual geometry is needed. Windings A and B represent upper layer and down layer windings, respectively. Figure 6 compares the self-inductances and mutual inductances with and without winding B current input. The relative coefficients used for the computation are listed in Table I. It is observed

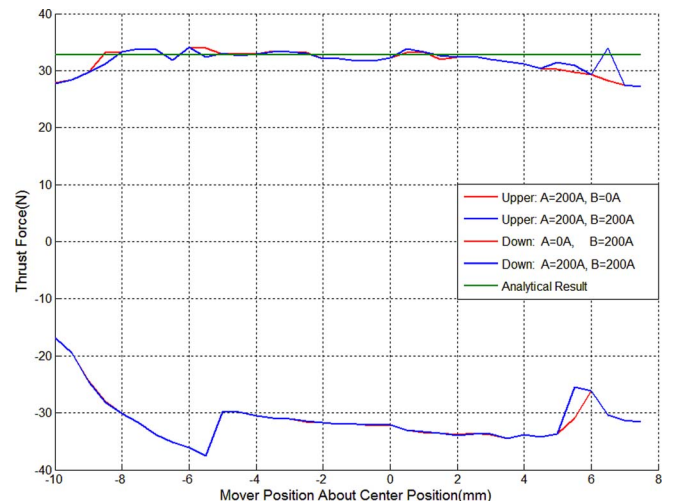


FIG. 7. Comparison of thrust forces from numerical computation and analytical model.

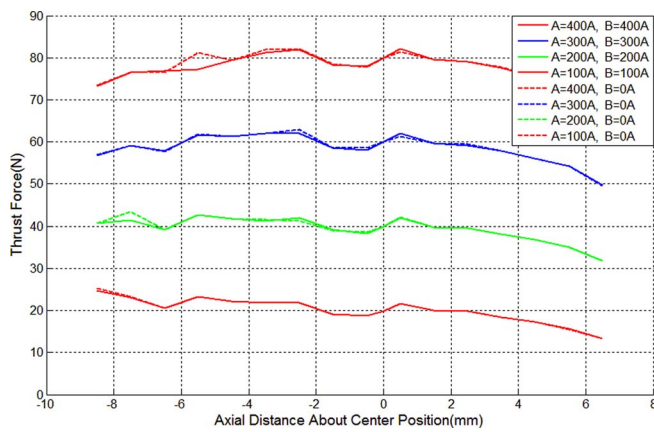


FIG. 8. Thrust forces under different current input.

that the two types of mutual inductances are almost equal to zero, and the self-inductances of winding A are almost equal, whether there is winding B current input or not. Therefore, it indicates that the two movers have no significant influence on each other.

The thrust forces generated by windings A and B with different pairs of current inputs, calculated by numerical method and analytical model, are compared in Fig. 7. It can be found that the force output generated by one mover with certain current input keeps the same value, even if the current input of the other mover changes. Furthermore, the force produced by the two movers with the same current inputs has similar magnitude and opposite direction, because the magnetic field distributions in two air gaps are similar but in opposite direction. The thrust output matches the analytical model closely. Figure 8 presents the thrust forces generated by upper mover with eight kinds of current input. It shows the linear relationship between thrust and current.

V. RESEARCH PROTOTYPE AND EXPERIMENTS

A. Research prototype

A research prototype of the linear motor with two isolated movers has been developed as shown in Fig. 9. The major parameters of the research prototype are shown in Table II. One stator with PM poles is mounted on the supporters at the center of the motor. Two movers are placed on upper

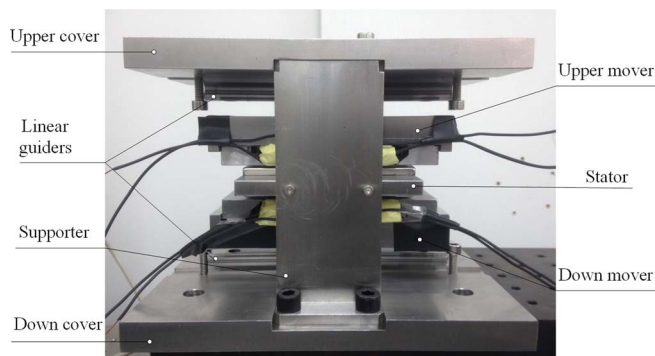


FIG. 9. Research prototype of linear motor with isolated movers.

TABLE II. Parameters of research prototype.

Parameter	Value
PM pole material	NdFeB N50
Number of stator poles (PM)	8/2 layers
Number of mover poles (coil)	8/2 layers
Number of coil turns	200
Mover length	137 mm
Mover height	28 mm
Mover width	58 mm
Stator length	100 mm
Stator thickness	19 mm
Stator width	50 mm
Air gap width	1.5 mm

and down sides of the stator, and fixed on the linear guiders through sliding blocks. The linear guiders are mounted on the upper and down covers that in turn are fixed on the supporters. The power supply in the windings of two movers is controlled separately, and thus the two movers can achieve independent linear forces and motions.

B. Experimental apparatus

An experimental apparatus has been developed to conduct measurements on the thrust force output of the research prototype with respect to different mover positions. As shown in Fig. 10, one power supplier is utilized to provide current input to windings mounted on the movers. The force sensor is installed between the mover and the supporter. The mover position can be adjusted with screw, and the thrust output can thus be measured accordingly.

C. Experimental results

The different pairs of current inputs are supplied into the windings on the two movers of the linear motor, and the thrust output of the two movers is measured accordingly. The

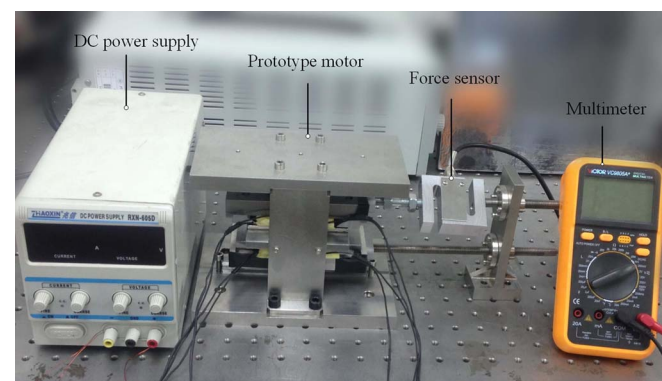


FIG. 10. Measurement system for thrust force output of linear motor with isolated movers.

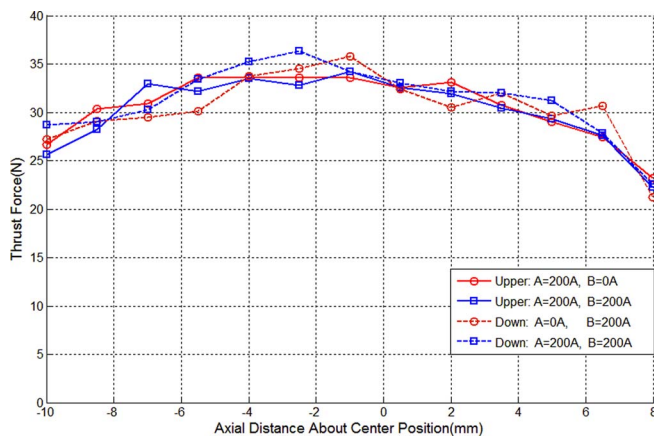


FIG. 11. Comparison of thrust forces produced by two movers with different pairs of current inputs.

experimental result with respect to different mover position is presented in Fig. 11. It indicates that the thrust output of upper mover keeps the same value, even if the power supply in down mover changes, and vice versa. Therefore, the employment of additional movers does not have significant influence on the output performance of the other mover, which in turn validates the proposed design concept of the proposed linear machine with isolated movers in this study.

Experiments are also conducted to verify the developed analytical model of the thrust output. Figure 12 presents the thrust output of the linear motor with respect to the mover's position. It is found that the analytical model fits with the numerical computation and experimental result well. Therefore, the analytical model could be employed for subsequent motion control of the linear motor. The analytical result is a little different from the numerical and experimental results at the beginning and ending parts, because flux leakage at the edges is ignored for the analytical calculation.

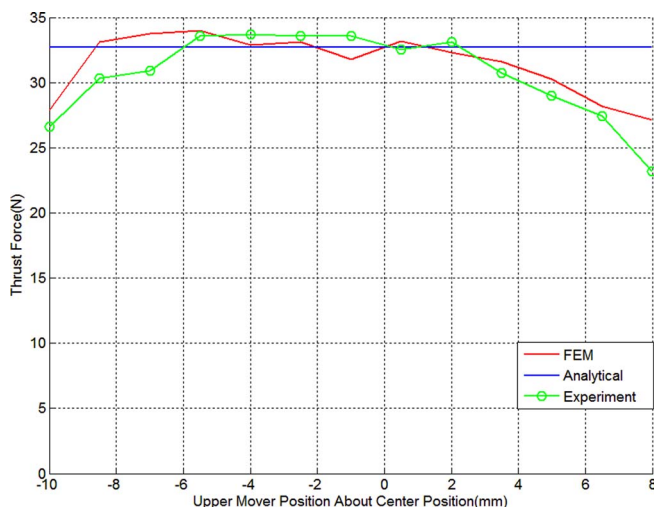


FIG. 12. Comparison of thrust forces by analytical model, numerical computation, and experimental result.

VI. CONCLUSIONS

This paper proposes a novel flat type PM linear motor with two isolated movers and one single stator. Each mover can interact with the PM poles on the stator to produce independent linear forces and motions. The proposed linear motor is especially useful for tasks requiring multiple motors. Compared with conventional multi-motor driving system, it helps to achieve compact size, and increase the system working efficiency. Mathematical model of the magnetic field distribution and thrust force are obtained based on EMC method. The inductance is also obtained analytically. It shows that the two movers have no significant influence on each other. A research prototype of the linear motor with isolated movers has been developed. Experimental apparatus is built up to measure the thrust force output of the system. The result validates the operating principle of the proposed design. Numerical computation and experimental data are employed to verify the analytical model of thrust force. The comparison shows that the analytical model fits with both experimental measurement data and numerical result well. The developed analytical model of the thrust output could be employed for the motion control of the linear motor in the subsequent study. The design concept and analysis approach is available for other rotary and linear machines with more movers or rotors.

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