Research on Permanent Magnet Linear Synchronous Motor for Rope-less Hoist System

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Abstract—**Permanent magnet linear synchronous motor (PMLSM) for rope-less hoist system, which has the advantages of simple structure, small volume, high force, unlimited hoisting height and speed, is a research focus and difficulties in the vertical hoist field. In this paper, according to the key technical problems of PMLSM for rope-less hoist system, a design scheme of direct driving high-speed elevator is proposed, and then a small-sized home elevator prototype drove by PMLSM is built. Experimental results show the safe and stable operation performance of the experimental device, with good prospects for the development and application of PMLSM rope-less hoist system.**

Index Terms—**permanent magnet linear synchronous motor (PMLSM), rope-less hoist system, high-speed elevator, home elevator; application research**

I. INTRODUCTION

Linear motor with the advantages of simple structure, low noise, high precision, easy maintenance etc., directly implements linear motion without gears, chains, connecting rod and other intermediate conversion. So, linear motor has been widely used in transportation, industrial equipment, logistics, military, modern high-precision machine tools and other fields, gradually into people's daily life [1, 2].

With the high-rise building higher and higher, mining more and more deep, it needs higher requirement for hoist system to save energy and space, enhance capacity, improve safety and performance. The traditional wire rope hoist system will encounter insurmountable problems. In view of this, it urgently needs to develop a new hoist model instead of the traditional model. The rope-less hoist system driven by linear motor is the best choice, which is proven as the hot research topic to solve the hoisting problems for the high-rise buildings and ultra-deep mine [3, 4].

Permanent magnet linear synchronous motor (PMLSM) combining the advantages of permanent

magnet motor and linear motor, is generally acknowledged as one of the best driving sources for rope-less hoist system. PMLSM rope-less hoist system shows a novel hoist mode without rope, balance weight, intermediate drive, restriction of the hoisting height and speed. With the advantages, such as simple structure, small volume, high-efficiency, high hoisting capacity, easy to realize the multi-car, PMLSM rope-less hoist system can be widely used in high-rise buildings and the mine hoist [5, 6].

In the beginning of 90's in the Twentieth Century, the vertical hoist system driven by linear motor was proposed firstly, used in the high-rise building and mine hoisting system, which becomes the research focus and difficulties in the vertical hoist field. According to the driving structure types, there are tow sides: one is driven by linear induction motor; the other is driven by linear synchronous motor, which can increase the system efficiency and operation performance. In fact, the vertical hoist system driven by PMLSM is most commonly used.

Research and development about the linear-motor-driven elevator in Japan has been done very well in the world. As early as 1990, a video of an elevator driven by PMLSM was shown by the famous linear motor expert Yamada in a symposium about the linear motor held in Beijing. An elevator prototype driven by PMLSM, load 16 persons, was developed in Mitsubishi. In Japan, the research works about linear motor elevator also carried on in Kyushu University, Fuji Electric, University of Muroran, Shinshu University, and so on [7~10].

In USA, Magnemotion Company has established a direct drive carrier lifts driven by PMLSM, and its video information can be got in the website. In Germany, the research focus on the high-rise building elevator driven by PMLSM, and some fruitful achievements were got. The research team in RWTH Aachen University built a elevator prototype driven by PMLSM. In South Korea, South Africa, Russia, some research teams also attend to the development and application of rope-less hoist system driven by PMLSM [11, 12].

According to the key technical problems of PMLSM rope-less hoist system, in this paper, a design scheme of direct driving high-speed elevator is proposed, and then a small-sized home elevator prototype drove by PMLSM is

built. Experimental results show the stable operation performance of the experimental device, having good prospects for the development and application.

II. BASIC STRUCTURES AND THE KEY TECHNICAL PROBLEMS OF PMLSM ROPE-LESS HOIST SYSTEM

A. Basic Structures

The basic topology structures of PMLSM rope-less hoist system depend on the driving source motor and arrangement mode. PMLSM with single or double side structures is the core of the rope-less hoist system. The driving PMLSM can be arranged in two types: one is located on one side of the car; the other is arranged symmetrically on both sides of the car. In the operation mode, short-primary long-secondary or long-primary short-secondary PMLSM can be chosen depended on the actual situation.

B. Key Technical Problems

It is the basic idea for PMLSM rope-less hoist system to erect the locomotive of horizontal movement. PMLSM rope-less hoist system eliminates the wire rope, using direct-drive electromagnetic force. From the current research status, PMLSM rope-less hoist system is still in the experimental research and application development stage, facing a number of major technical problems.

If the following key technical problems can be solved, it will be realized for PMLSM rope-less hoist system to use truly in the industrial applications.

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Firstly, the best overall solution for industrial applications of PMLSM rope-less hoist system should be further research, including the best topology of the main structure, design of the PMLSM with large force and good performance, reliable air-gap positioning system, etc.

Secondly, practical development of the safety braking device is the bottleneck problem. It is the focus to solve the key technical problems, such as the braking in the system operation, emergency parking, security, and so on.

Furthermore, PMLSM rope-less hoist system needs the optimal control methods in order to solve the problems, such as the precise positioning, air-gap detection, flexible braking, controlling of multi-car, fault diagnosis, the best mode of operation, and so on.

Finally, the lightweight design of moving parts, using the solutions of the optimized structure and new high-strength lightweight materials, is one of the important technical problems to reduce the drive power.

III. STRUCTURAL OPTIMIZATION DESIGN AND DEVELOPMENT APPLICATION

A. Practical Expeience

As early as in 1994, the research team haven carried out the work about PMLSM rope-less hoist system in Henan Polytechnic University (HPU), which is one of the earliest research institutes in China, and then two sets of PMLSM rope-less hoist experimental system were built in 1998 and 2003, respectively, shown in Figure 1 [13~15].

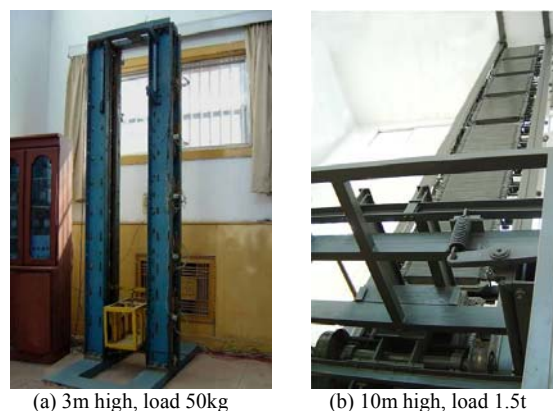(a) 3m high, load 50kg   (b) 10m high, load 1.5t

Figure 1.   PMLSM rope-less hoist system in HPU.

Figure 1 (a) shows the first-generation PMLSM rope-less hoist experimental system driven by a short primary multi-segment long secondary double-side PMLSM.

The second-generation PMLSM rope-less hoist experimental system adopted multi-segment long primary short secondary single-side PMLSM as the driving source, shown in Figure 1 (b).

It is clearly to accumulate abundant theoretical and practical experience through researching on the above two sets of PMLSM rope-less hoist system.

B. Design Scheme of Direct Driving High-speed Elevator

The third-generation machine of PMLSM rope-less hoist system, named direct driving high-speed elevator, has been studied since 2008 in Institute of Linear Electric Machines & Drives of Henan Polytechnic University. At present, the whole scheme demonstration and engineering design has been done. The design scheme of direct driving high-speed elevator, which is driven by two PMLSM with double-side structures, is shown in Figure 2.

The main characteristics of direct driving high-speed elevator are as follows.

Firstly, the scheme demonstration combines with the mechanical simulation. Dozens of design schemes were proposed in the early development of the direct driving high-speed elevator. After repeated demonstration, the optimum scheme was determined, drawn by 3-D design software.
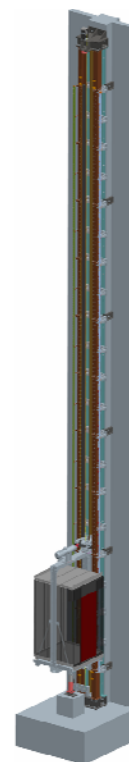

Figure 2.   High-speed elevator.

Secondary, the driving motor is designed using unitization method. With 16-pole 15-slot as one unit, the driving motor was designed by finite element method. In order to decrease the length of the winding end and minimum the fluctuation of the thrust force, the fractional slot concentrated winding was adopted.

Thirdly, the caliper brake with the force amplifier was designed and developed independently. The proposed caliper brake has smaller size and larger braking force, operating faster and more reliably than the existing ordinary brake. With a smaller driving force, the larger braking force can be obtained.

Finally, the direct driving high-speed elevator has four security protection measures. In the conditions of system power failure or other emergency, excepting three conventional protection measures, working brake, safety gear over-speed protection and buffer protection, there is the fourth power failure generation protection, which is the inherent character of PMLSM with winding shorted.

C. Design of Driving Motor

In addition to minimizing the length of the winding end, improve the air gap flux density, inhibit the thrust force fluctuations, fractional-slot concentrated winding is used in the design of the driving motor, which improves the stability of the whole system.

The driving motor is designed, 16-pole 15-slots as a unit, shown in Figure 3. Precondition the thrust force to be ensured, this type of unit motor minimizes the axial length in order to reduce the normal force of the PMLSM. This type of structure can effectively suppress the impact of the inherent normal force of PMLSM.

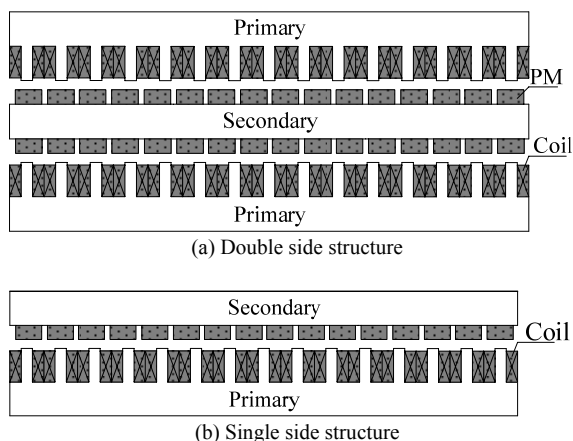(a) Double side structure

(b) Single side structure

Figure 3.   16p15s PMLSM physical structure model.

The physical structure model of a unit motor shown in Figure 3(a) is double side structures. In fact, this model can change to single structures in the actual application, shown in Figure 3(b).

The hoisting capability of whole rope-less hoist system can be enhance by increasing the number of the unit motors. For whole system, the sub-station power supply is used, not only saving, but also reduces the power capacity requirements. Figure 4 shows an application of rope-less hoist system driven by PMLSM with single multi-segment structures, named MP-PMLSM.
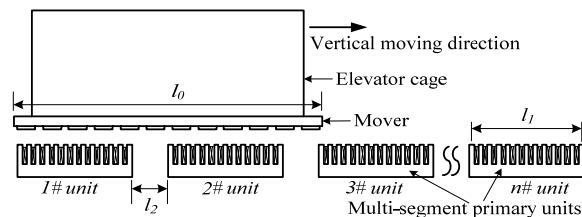

Figure 4.   Physical model of MP-PMLSM

The MP-PMLSM is composed of n# unit motor. In Figure 4 l_2 is primary segment space length. It is important in rope-less elevator operation and satisfies the following equation.

$$l_2 = 2k \cdot \tau \geq 0 \qquad (1)$$

where τ is the pole pitch, k=1, 2, 3, ….

In order to reduce force ripple and run stably, the mover length l_0, segment primary unit length l_1, segment space length l_2 and number of segment primary unit n must satisfy the equations as follow.

$$l_0 = 2 \cdot (l_1 + l_2) \qquad (2)$$

$$nl_1 + (n+1)l_2) \leq 10 \qquad (3)$$

The winding arrangement of 16-pole 15-slots is shown in Figure 5. The electrical angle α of the adjacent two teeth is calculated through the following equation.

$$\alpha = 16 \times 360/15 = 384 \text{ deg} \qquad (4)$$

The vector diagram of electromotive force (EMF) generated by the primary winding is shown in Figure 5.
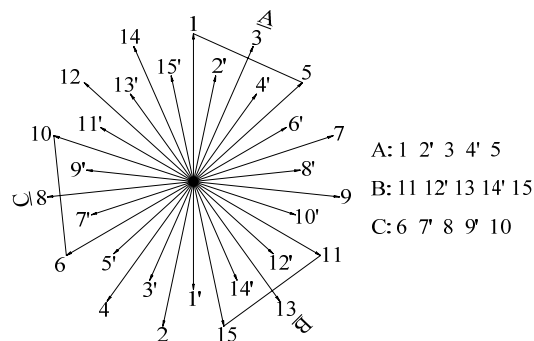

Figure 5.   Winding arrangement of 16p15s PMSM

As Figure 5 shown, the EMF vectors of the 15 stator coils are named consecutively from 1 to 15, and 1′ represents the reverse vector of 1, then numbering successively. The 15 EMF vectors are divided into symmetric three groups, and then per phase in series, the three phase winding will be got. This type of winding configuration has high winding factor and low loss.

Figure 3 shows the PMLSM physical structure model, while Figure 5 shows the winding arrangement. This type of PMLSM has two salient features. The one is that the slot pitch is close to the pole pitch. The other is that the fractional-slot concentrated winding is adopted in the stator design. This unit motor with 16-pole 15slots has lower cogging force and high thrust force density.

D. FEM model

The finite element method (FEM) is adopted to build the model of 16-pole 15-slot unit motor. Based on the analysis of the FEM model, the characteristic waveform of the thrust force with different power angle is got.

In order to save the calculation time, the 2D FEM analysis is used, based on the following simplifying assumptions.

a. The exterior magnetic field of motor is neglect.
b. The current density in the conductor is evenly distributed.
c. The non-linearity and eddying effect of the iron-cored are considered through the curve of magnetization and damage curve, with no view of the magnetic hysteresis effect.
d. Taking into account the actual operation condition, the even symmetry boundary condition is adopt to assume the primary infinitely.

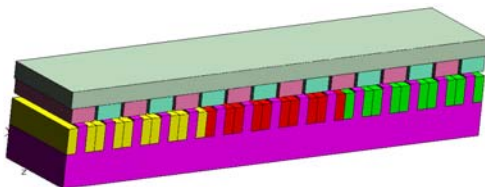The specifications of 16p15s unit motor are shown in Table I.

TABLE I.
SPECIFICATIONS OF 16P15S UNIT MOTOR

Parts	Items [units]	Value
Primary	Yoke height [mm]	20
	Pole pitch [mm]	24
	Axial height [mm]	100
Air-gap	Air-gap length [mm]	2.6
Secondary	Number of PMs	16
	PM height [mm]	8
	PM length [mm]	18

The FEM model is shown in Figure 6.
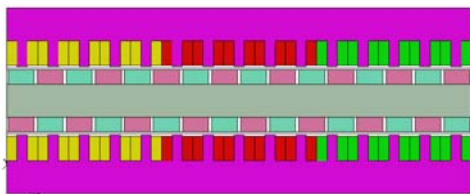
(a) Double side structure FEM model

(b) Single side structure FEM model

Figure 6.   16p15s PMLSM FEM model.

The relative movement of the primary and secondary can be processed by a moving edge boundary, i.e., a moving line in the air-gap. In order to improve the solving precision, the method of self-adaptive time stepping is adopted to adjust the space length of FEM. After moving for a time stepping, the size of the mesh between the primary and secondary isn't changed, but

only the grids in the moving region, which will be meshed again for each time stepping, is changed. The layering research and the adaptive method are adopted to choose the proper time-stepping in the area where the magnetic density changes heavily.

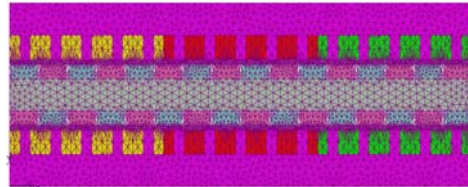Using self-adaptive movable grid meshing, the mesh generation at a certain time is shown in Figure 7.

Figure 7.   Mesh generation of 16p15s PMLSM.

E. Finite Element Analysis

Based on the FEM model with double side structure, the FEM analysis is done. While the correlative solving results of single FEM model can be converted through the solving results of double side structure FEM model.

The magnetic flux distribution and air-gap induction spatial distribution are the precondition to check FEM model and accurate calculation.

Figure 8 and Figure 9 show the two-dimensional magnetic field lines distribution of armature reaction magnetic field and the resultant magnetic field of 16p15s unit PMLSM respectively, when the A-phase current reaches the maximum.
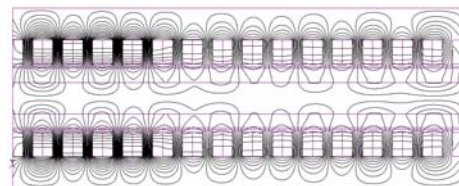

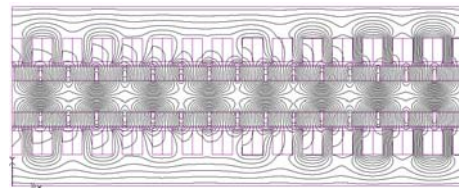Figure 8.   Armature reaction magnetic field.

Figure 9.   The resultant magnetic field

When the A-phase current reaches the maximum, the currents of B-phase and C-phase are the half of the A-phase current.

As Figure 8 shown, the armature reaction magnetic field is dense at the A-phase winding, corresponding air-gap induction higher. The air-gap induction is well-proportioned at the A-phase and B-phase winding, because the corresponding armature reaction magnetic field is even.

In the Figure 9, the resultant magnetic field has a little asymmetry, because the armature reaction magnetic field is smaller than the permanent magnetism excitation magnetic field.

Because of the even symmetry boundary condition in the primary, the two-dimensional magnetic field lines distribution of armature reaction magnetic field and the resultant magnetic field, shown in Figure 8 and Figure 9, are consecutive at the end of the FEM model, which takes into account the actual operation condition.

The EMF is an important parameter for the analyses and calculation of the motor performance. For the 16-pole 15-slot unit PMLSM with double side structure, when the air-gap is 2.6mm, the EMF waveform is got at the speed 0.5m/s, shown in Figure 10.
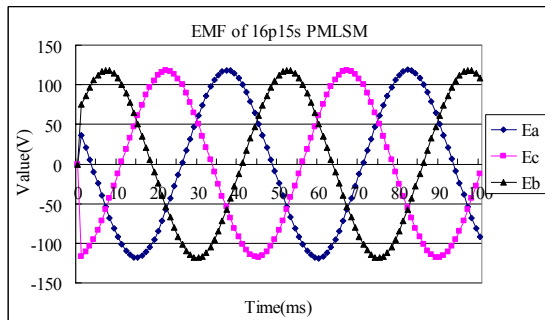

Figure 10. Waveform of EMF.

As Figure 10 shown, the EMF waveforms of A-phase, B-phase and C-phase are very sinusoidal, with 120^0 phase mutual deviation. The amplitudes of E_a, E_b and E_c are accordant. Then the EMF constant K_e can be got through the following equation.

$$K_e = \frac{E_a}{v} = \frac{80.7}{0.5} = 161.4 \text{ Vp-nrms/m/s} \qquad (5)$$

Based on the analysis of the FEM model with double side structure, the characteristic waveform of the thrust force with different power angle is got, shown in Figure 11.
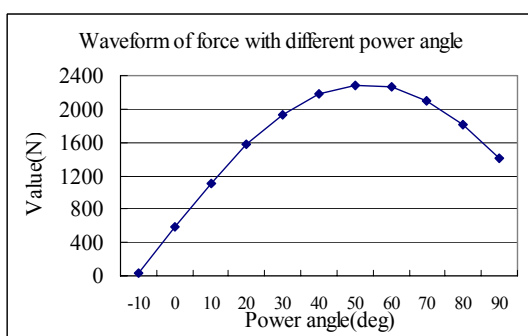

Figure 11. Waveform of force with different power angle.

In general, because primary resistance of permanent magnet motor r_s is much smaller than the synchronous reactance X_t, the impact of primary resistance can be negligible. So, the power angles 0^0 and 90^0 correspond to $0Nm$ and the maximum thrust force. However, the $0Nm$ and the maximum thrust force aren't at the power angle 0^0 and 90^0 respectively in the Figure 11, which maybe due to the low simulation operating frequency of the unit motor.

When the frequency is low, the voltage drops in the primary resistance increases significantly, and the unit motor has the characteristic of the small reactance and large resistance, which results that the power angle is negative when the thrust force is zero. Furthermore, the interval of the positive thrust force becomes narrower.

In Figure 11, considering 1.25~1.5 time of overload magnification, the best operating force of the double-side structure unit driving motor with 16-pole 15-slot, namely the rated force, is 1700N, and the corresponding current is 3.6A. Then the force constant of unit motor K_f can be got through the following equation.

$$K_f = \frac{F_N}{I_N} = \frac{1700}{3.6} = 472.2 \text{ N/Arms} \qquad (6)$$

F. Cogging force Analysis

For permanent magnet linear synchronous motor, the cogging force results from the interaction between the permanent magnets mounted on the secondary yoke and primary anisotropic, due to the slotting, it is undesirable and may cause thrust force ripple, vibration, noise, and deteriorates the characteristics of speed control at low speed as well as position control. So it is important to design the unit motor with low cogging force.

In the case of no exciting current in primary winding, force which is named cogging force is generated because of the PMs and tooth. So, the cogging force is the function of the relative position between the primary and the secondary.

Theoretically, the number of cycles of the cogging force in motor one rotation is the least common multiple of the pole number, and the slot number. So, for PMLSM, the theoretical ripple period of cogging force can be calculated through following equation.

$$T = 360 / (\frac{q \times 2p}{HCF(q, 2p)}) \qquad (7)$$

where q and $2p$ are the slot number and pole number of a PMLSM, respectively.

For the proposed 16-pole 15-slot unit motor, theoretical ripple period of cogging force is

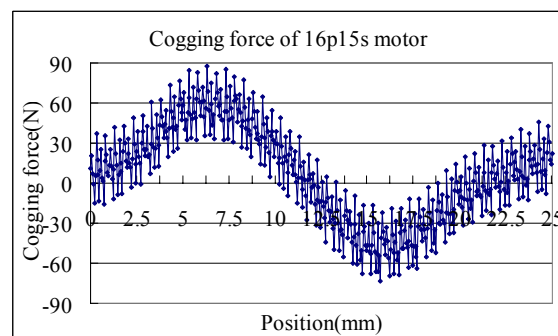$$T = 360 / (15 \times 16) = 1.5 \text{ deg} \qquad (8)$$

Figure 12. Cogging force of 16-pole 15-slots motor.

As Figure 12 shown, the cogging force waveform of unit motor has one main chain cycle, including many minor cycle. In fact, for PMLSM, the cogging force of the unit motor is composed of the end component and slot component. The end component of the cogging force is main component, with the period of one pole-pitch. The slot component is the harmonic content.

For the slot component, the analysis ripple period is agreeing with the theory in Figure 12. And it is known that fundamental harmonic of slot component is the least common multiple between the slot number q and the pole number $2p$. So, this 16-pole 15-slot PMLSM teed to have less cogging force of slot component because its bigger values of the least common multiple of the pole number and slot number. It is obvious that the peak value of slot component, shown in Figure 12, is very small.

For the end component, the analysis ripple period is one pole-pitch, and the end component is the main component. In fact, any one PMLSM has only two ends. So, the end component doesn't increase with the PMLSM lengthening.

IV. EXPERIMENT

A. Experimental Platform

In order to verify the feasibility of direct driving high-speed elevator, a small-sized home elevator prototype drove by PMLSM is built, shown in Figure 13.
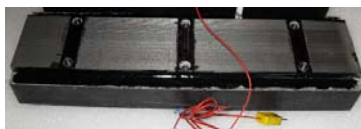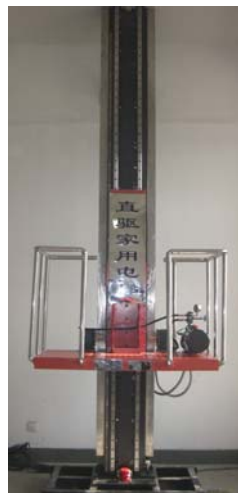

(a) Primary of a unit driving motor

(b) Secondary of unit motor

(c) Shop drawing   (d) Experimental platform

Figure 13. Home elevator prototype.

Figure 13 (a) and (b) are the primary and secondary of the 16-pole 15-slot unit motor, respectively. Figure 13 (c) is the cubic effect picture of the home elevator prototype drawn by Pro/Engineer software. Figure 13 (d) is the prototype of the home elevator prototype.

It should be noted that this home elevator prototype uses single side structure PMLSM as the driving source, arranged on one side of the shaft. This type of single driving scheme has the simplest principle, which can be adequately imposed to develop the small type rope-less hoist system used in home or low-rise buildings. If the design scheme is proper, this type of elevator will have a certain degree of feasibility and practical value.

The primary of the prototype is the stator, composed of 10 primaries of the 16-pole 15-slot unit motor; while the secondary of the prototype is the mover, composed of 4 secondary of the 16-pole 15-slot unit motor.

Table II shows the performance indices of the home elevator prototype.

TABLE II.
PERFORMANCE INDICES OF THE HOME ELEVATOR PROTOTYPE

Items [units]	Value
Power [W]	1000
Hoisting height [m]	4
Rated hoisting load [kg]	300
Max. hoisting load [kg]	450
Speed [m/s]	0.3
Note: The driving motor is single side PMLSM with fractional-slot concentrated winding.	

B. General Testing of Single Side Structure Unit motor

For single side structure unit motor with 16-pole 15-slot, the insulation, pressure, resistance, inductance, EMF, K_e and K_f testing is done, shown in Table III.

TABLE III.
RESULTS OF GENERAL TESTING

Items [units]	Value
Insulation resistance [GΩ]	2
Pressure-resisting values [V]	1500
Leakage current [mA]	1.5
Resistance of A phase R_a [Ω]	6.75
Resistance of B phase R_b [Ω]	6.71
Resistance of C phase R_c [Ω]	6.68
Inductance of A phase L_{aa} [mH]	57.24
Inductance of B phase L_{bb} [mH]	56.54
Inductance of C phase L_{cc} [mH]	57.02
EMF constant K_e [Vp-nrms/m/s]	82.5
Force constant K_f [N/Arms]	238.7

As Table III shown, the EMF constant K_e and force constant K_f of single side structure unit motor are the half of the double side structure unit motor. The results of the FEM analysis are agreed with the testing.

C. Load Experiment

The thrust force and speed are got at the rated hoisting load, shown in Figure 14 and15. The results show the home elevator prototype has fast response of the thrust force and speed.
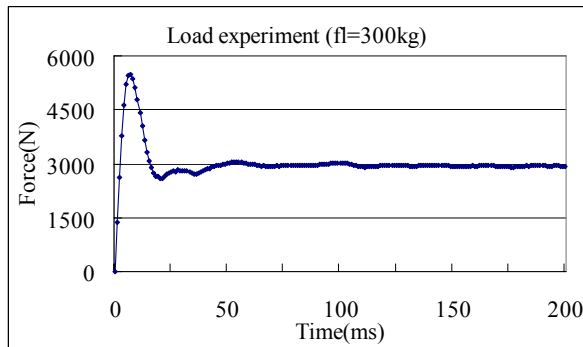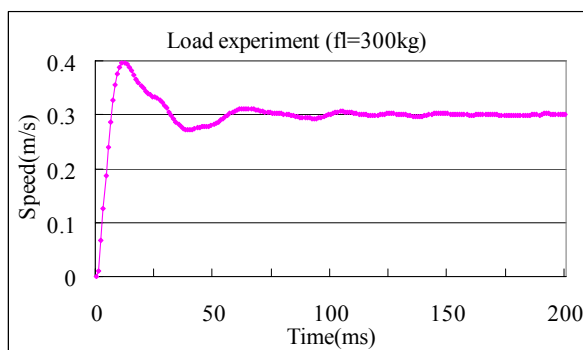

Figure 14. Force waveform of load experiment.

Figure 15. Speed waveform of load experiment.

In figure 14, the steady-state thrust force is 3000N, and the corresponding steady speed is 0.3m/s, shown in Figure 15. The fluctuation of the thrust force and speed is relatively small.

D. Power Fail Interrupts Protection Experiment

It is known that the PMLSM can generate force at a certain speed if the primary winding shorted. For this home elevator prototype, there is the power failure generation protection, which is the inherent character of PMLSM with winding shorted.

The experimental results of the power fail interrupts protection are shown in the following Figure 16 and 17.
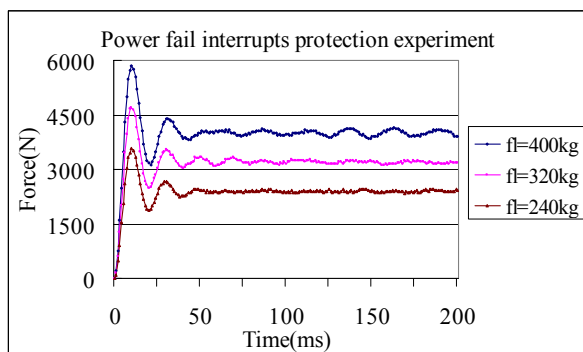

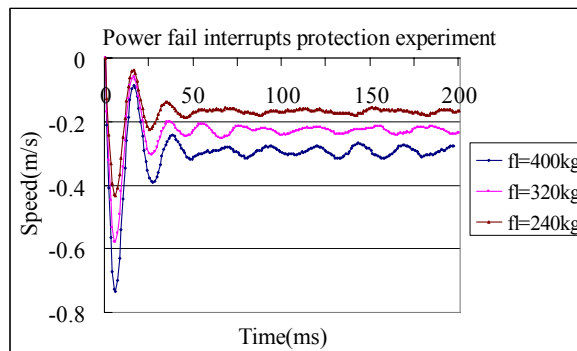Figure 16. Force waveform with different load.

Figure 17. Fall speed with different load.

In fact, there are four security protection measures in the home elevator prototype. Working brake, safety gear over-speed protection and buffer protection are the three conventional protection measures. Moreover, the power fail interrupts protection is the fourth measure.

As the experimental results show that the prototype operates safely and stably, and can be falling down at a constant low speed in the case of power failure.

V. CONCLUSION

In this paper, a design scheme of direct driving high-speed elevator is proposed, and then a small-sized home elevator prototype drove by PMLSM is built. The testing results show the safe and stable operation performance of the prototype, and then verify the feasibility of the direct driving high-speed elevator.

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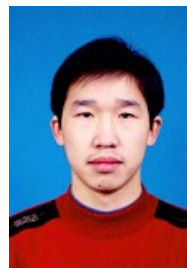
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