Effect of the Permanent Magnet Location to Magnetic Forces in Maglev System with Hybrid Magnets

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Abstract

In a maglev vehicle of traditional electromagnetic system (EMS), the electrical magnets are used on the vehicle to produce attractive levitation force. Due to limitation by the capacity, volume, weight and heat-dispersion condition of the exciting power system, the magnetomotive force is limited. To improve the performance of maglev system, a better choice is to use the hybrid magnet, which is formed with the permanent magnet and the electromagnetic coils, to provide exciting energy[1][2][3]. This paper presents the analysis results calculated with FEM about the effect of the permanent magnet position to a hybrid maglev vehicle system in our Lab. The results of the lift, thrust and lateral resilience forces can provide important guidance to the design of a hybrid maglev vehicle system.

I. Introduction

A long-stator linear synchronous motor (LSM) with iron cores is used to drive the high-speed maglev vehicle in Transrapid (TR) system. At the same time, the electromagnet poles of the LSM provide lift and guidance forces to control the vehicle. Since the exciting winding turns of electromagnet and current are limited by the size, weight of the pole, the lift force is limited, and the air-gap length is only 10mm.

Compared with an electromagnet, a permanent magnet has higher energy density. At present, high energy level of NdFeB can meet the need of most motor performances. If permanent magnets and electromagnets are combined to form hybrid magnets, the lift force could be increased effectively with the same air-gap length, and the vehicle weight could be decreased.

In a maglev system with hybrid magnets, permanent magnets may provide the base lift force required for levitation while electromagnets produce adjustable lift force to stabilize the levitation system. It is known the position of the permanent magnet in this vehicle system will have effects on the lift, thrust and lateral resilience forces. How to locate the permanent magnet for the three forces to satisfy the system requirements should be considered first. In this paper, we use the finite element method (FEM) to calculate the magnetic field, then the forces along the X (thrust), Y (lateral resilience force) and Z (lift) axis with the virtual work principle. The calculation results of the force at a different distance of the permanent magnet to the slot bottom of the exciting windings are obtained. These results give us some guidance in the vehicle design.

II. Hybrid Levitation Model Vehicle

Fig.1 shows the cross section of the hybrid levitation model vehicle with permanent magnets and electromagnets combined in our Lab. Similar to Transrapid, the vehicle is driven by two LSM located in two tracks. The long-stator core and windings are arranged along the tracks, the hybrid magnets are located at the vehicle [1].

Fig.2 is the schematic drawing of the LSM. Since there are slots for linear generator coils on the surface of magnet iron core, it is impossible to locate the permanent magnet on the surface, thus the core is divided into two parts, and the blocks of permanent magnets are sandwiched between the upside and underside of the core. The concentrated windings are set in the slots. The letter "b" is used to show the distance between the undersurface of the permanent magnet and the slot bottom of the exciting winding, which is a position variable used in this research of magnetic forces.

The experimental model vehicle has four units of hybrid magnets placed along double-side tracks whose center to center distance is 280mm, and each unit is composed of two full and two half magnets shown as Fig.2. The distance of two units is two pole pitches along the length direction. The rated air gap is 10mm, pole pitch is 87mm, rated lift weight is 120kg, and the thickness of the permanent magnet is 5mm.

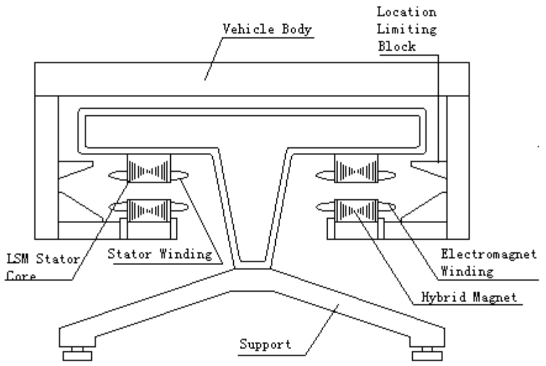


Fig. 1 Hybrid levitation model vehicle

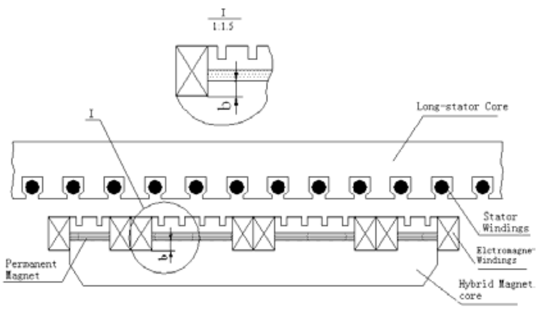


Fig. 2 Structure of the LSM (One unit of hybrid magnet)

III. Calculation Model of Magnetic Force and Results

Compared to a general rotation synchronous motor with air gap about 3mm, the LSM of our model has bigger air gap due to mechanical structure requirements, which can lead to bigger flux leakage. Therefore 3D finite element method is used to calculate the lift force and lateral resilience force to avoid a bigger calculation error. After analysis, we know that the transverse leakage flux has less effect on the thrust force, thus 2D FEM is used.

Fig. 3 shows the region used in 2D FEM calculation. Since the units and nodes for 3D FEM calculation will increase greatly, and need too much computer time, one pole region is adopted with the consideration of field symmetry.

For the field of the LSM with nonlinear ferromagnetic material mentioned above, vector potential **A** is used as the field function, the question can be described as (3-1):

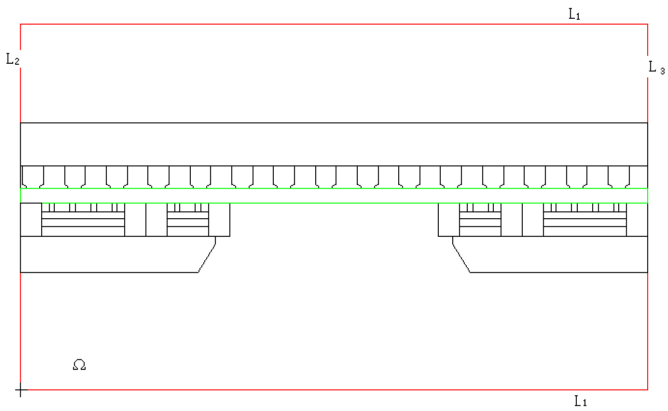
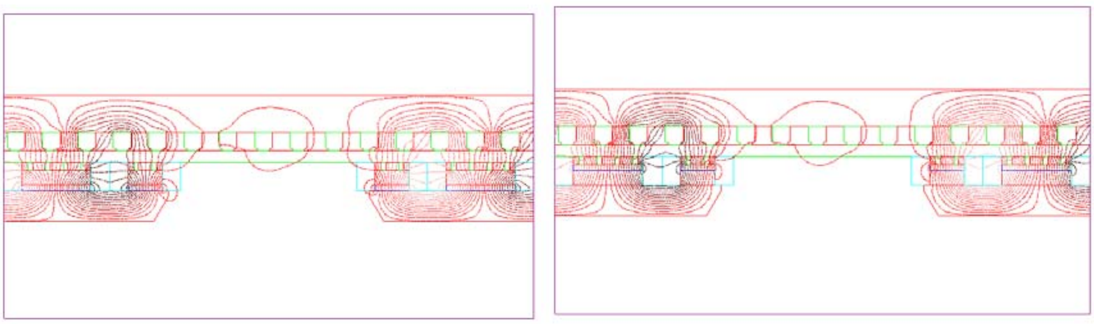


Fig. 3 2D FEM calculation domain

$$\begin{cases} \Omega : \nabla \times (\frac{1}{\mu} \nabla \times \mathbf{A}) = \mathbf{J}_c \\ L : \frac{1}{\mu_1} (\nabla \times \mathbf{A}_1)_t \big|_{L^-} - \frac{1}{\mu_2} (\nabla \times \mathbf{A}_2)_t \big|_{L^+} = \mathbf{J}_{sm} \\ L_1 : \mathbf{A}\big|_{L_1} = 0 \\ L_2, L_3 : \mathbf{A}\big|_{L_2} = -\mathbf{A}\big|_{L_3} \end{cases} \quad (3\text{-}1)$$

Here, **A** : vector potential, μ : material permeability, $\mathbf{J}_c$: armature current density in a stator slot, $\mathbf{J}_{sm}$: equivalent current density of a permanent magnet, and satisfy $\mathbf{J}_{sm}=\mathbf{M}\times\mathbf{n}$, **M** is the magnetization of permanent magnetic material used. Ω is the domain of solution. L is the interface of permanent magnetic material and other material. L_1 is the outer boundary away a distance from the long stator and hybrid magnets, L_2 and L_3 are the boundaries satisfied half periodic relationship.

The magnetic field can be obtained with FEM by solving the field equation (3-1), then the magnetic forces can be solved using Maxwell Stress Method. Fig. 4 shows the field distribution when the permanent magnet is located at two typical position: b=0mm, that is the under surface of the permanent magnet is at the slot bottom of the exciting windings, and b=12mm, that is the upper surface of the permanent magnet is at the slot bottom of the linear generator.



(a) b=0mm (b) b=12mm

Fig. 4 Magnetic field distribution

Fig. 5 to Fig.7 show respectively the variation of lift, maximum thrust and lateral resilience forces with b varying when exciting current-turn is at 510, 0 and -510. The windings of long-stator have no-current for calculating lift and lateral resilience force, while they have rated phase current 13A for calculating thrust.

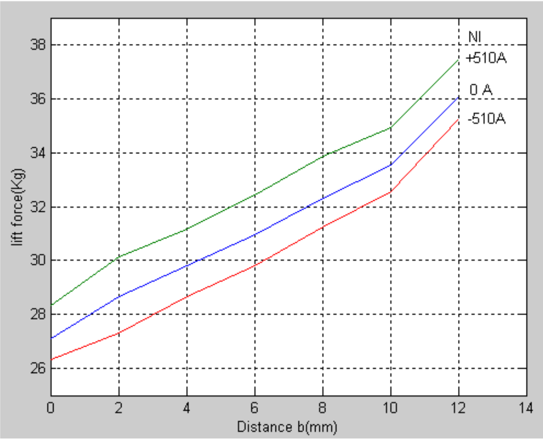


Fig.5 Lift force to permanent magnet position

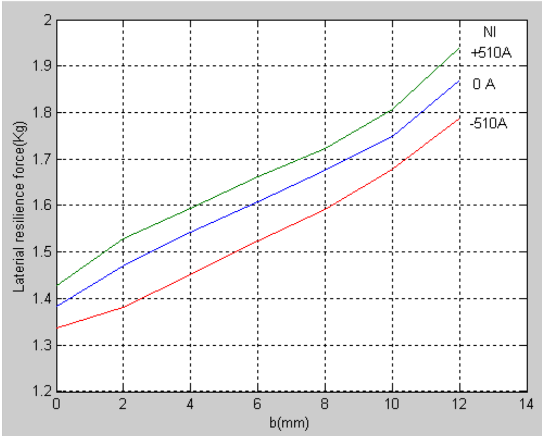


Fig.6 Lateral resilience force to permanent magnet position

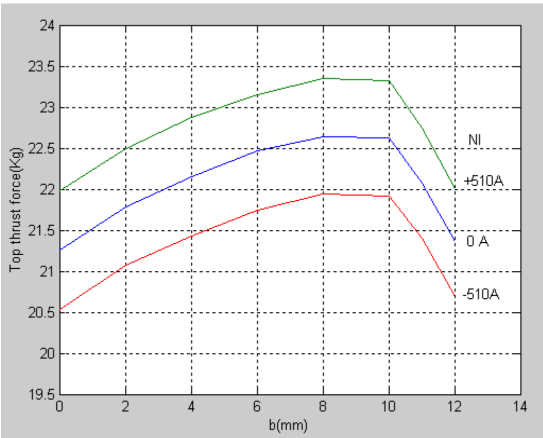


Fig.7 Thrust to permanent magnet position

It is indicated that with different exciting current, the lift and lateral resilience force rise monotonically with b increasing, and they will get the maximum at b=12mm. While Fig. 7 shows that the thrust curve varying with b is similar to a parabola, and it arrives the maximum at b=8mm.

To understand quantitatively the force variation with b, the ratios of the three forces to their maximum respectively are solved as follows:

1. The ratio of the lift increases from 0.74 to 1 when b changes from 0 to 12mm.
2. The ratio of the lateral resilience force increases from 0.73 to 1 when b changes from 0 to 12mm.
3. The ratio of the thrust is bigger than 0.93 and has less change to the maximum when b changes from 0 to 12mm.

But the thrust curve is similar to a parabola not a monotonically rising curve. Before b gets the maximum (12mm), a maximum thrust displays. In our model vehicle, when b=8mm, the thrust gets the peak.

The above results can be obtained since the location of the permanent magnet has effects on the leakage flux. When the permanent magnet is near the slot bottom of the exciting windings (b=0mm), the body leakage of the hybrid magnet increases, the magnetic forces decrease. Along with the permanent magnet near the slot bottom of the linear generator (b=12mm), the body leakage of the hybrid magnet lessens, but the slot leakage of the linear generator arises. And it makes the effective flux decreases to produce the thrust. So the trust curve with b is a parabola not a monotonically rising curve. Therefore the position of permanent magnet should be optimized to fully utilize permanent material and make the forces along three directions get the maximum.

Ⅳ. Conclusion

In a hybrid maglev vehicle design, it is necessary to optimize the position of permanent magnet in order to fully use permanent magnetic material, lessen flux leakage, reduce the vehicle weight and obtain bigger magnetic forces. In this paper, the effect of the permanent magnet position on magnetic forces is calculated by FEM based on the model maglev vehicle. It is conformed that more near, the lift and resilience forces become larger because the leakage flux through the slots of exciting coils decrease. But the thrust force varies with a parabola curve with the leakage flux alternation.

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