Thrust Characteristics of a Double-Sided HTSLSM with an HTS Magnetic Suspension System

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Electromagnetic design of a double-sided high temperature superconducting (HTS) linear synchronous motor (HTSLSM) with HTS bulk magnet secondary is introduced in this paper. An HTS magnetic suspension system is applied to replace the sliding rail to levitate the secondary mover which results in that the HTSLSM can move without any sliding friction force. The thrust model of the HTSLSM is built up by numerical analysis method, and the thrust characteristics obtained from it are compared with finite element analysis (FEA) results. Theoretical investigations are finally verified by the measurements.

I. INTRODUCTION

With the improvement of high temperature superconducting (HTS) material performance and application technologies, linear motor with HTS bulks or HTS coils have been developed. The developed HTS linear motors to date are mainly the HTS linear synchronous motor (HTSLSM), which can be further classified as: 1) HTS linear reluctance motor (LRM) with zero-field-cooling (ZFC) HTS bulk as secondary [1]; 2) HTSLSM with HTS bulk magnets or HTS coil magnets as secondary [2,3]; 3) HTSLSM with HTS coil winding as primary [4]. Comparing to the conventional linear motors, HTSLSM has many advantages like less weight, smaller size and higher efficiency etc. for using the no-resistance HTS tapes or strong-pinning HTS bulks with high trapped magnetic field.

In this paper, a double-sided HTSLSM with HTS bulk magnet secondary, which is levitated by an HTS magnetic suspension system, has been proposed and designed. The magnetic circuit analysis method is used to calculate the HTS bulk magnet flux linkage as to be the basic of the built thrust model. Finite element analysis (FEA) method is applied to build up the 2D FEA model of HTSLSM, and the thrust characteristics are obtained by transient analysis. Finally, the thrust characteristics of the HTSLSM are verified by experimental testing on a prototype.

II. MODEL OF HTSLSM LEVITATED BY HTS MAGNETIC SUSPENSION SYSTEM

The proposed model is shown in Fig. 1, which consists of double-sided long-primary as stator and HTS bulk magnet array as mover, and which is levitated by an HTS magnetic suspension system located on the bottom of the HTSLSM by connecting and fixing the levitator containing HTS bulks with the secondary mover. The permanent magnet guideway (PMG) of the HTS magnetic suspension system is installed on the track. This structure arrangement ensures the HTSLSM run without any sliding friction force. The main dimensions and parameters of the HTSLSM are listed in Table I.

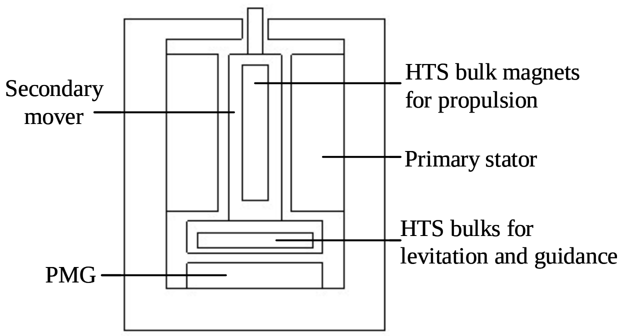

FIG. 1. Model of HTS magnetic suspension and propulsion system.

TABLE I. Primary dimensions and parameters of the HTSLSM.

Primary	Width w_t	150 mm
	height	140 mm
	Length l_t	2220 mm
	pole pitch τ	45 mm
	number of slots Q	72
	pair poles p	24
Secondary HTS bulk magnets	Length l_s	40 mm
	Width w_s	40 mm
	Height h_s	20 mm
	trapped magnetic flux intensity	0.5 T
	relative permeability μ_r	0.4
	number along longitudinal direction	6
	number along transverse direction	3

III. Magnetization Characteristics of HTS Bulk Magnet

The magnetic field trapping characteristics of HTS bulk by field-cooling (FC) and ZFC magnetization with D.C. magnet, ZFC pulse magnetization with pulse magnetizer are tested with the results as shown in Fig. 2. As it can be seen from the graph, the trapped flux density B_{trap} of HTS bulk magnet increases with the external magnetic field B_{ext} linearly, and then reaches saturation. The amplitude of B_{ext} for saturation magnetization using ZFC pulse magnetization is about double that for the ZFC D.C. magnetization, and four times that for the FC D.C. magnetization. The results have reference meanings to select appropriate methods to obtain HTS bulk magnets. For the low-field magnetization, using the FC D.C. magnetization is appropriate; however, ZFC pulse magnetization would be a better choice for the high-field magnetization for its lower cost and easier way to realize.

The B_{trap} of HTS bulk magnet attenuates with time due to flux creep is observed with the results plotted in Fig. 3. From the graph can be seen that the B_{trap} tends to steadiness 3 minutes later and the attenuation rate is very small after it, which tells that the HTS bulk magnets with steady B_{trap} can satisfy the requirement for long time working.

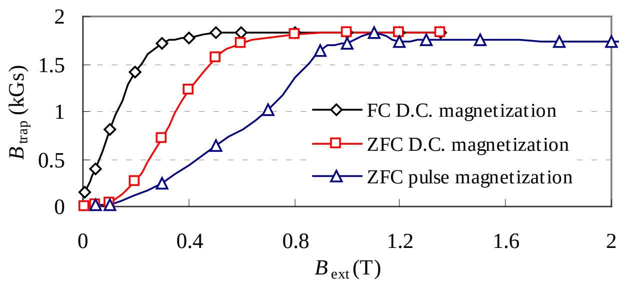

FIG. 2. HTS bulk flux trapping characteristics comparison within the different magnetization methods.

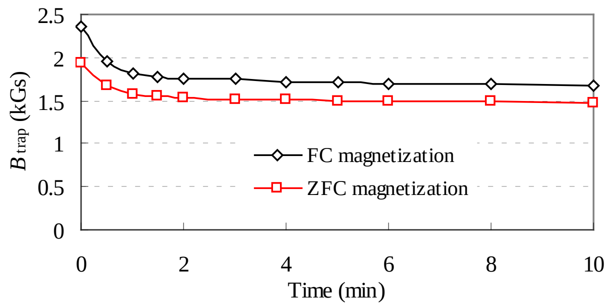

FIG. 3. The B_{trap} of HTS bulk magnet attenuates with time.

IV. Thrust Model and Characteristics of the Double-sided HTSLSM

Neglecting the magnetic reluctance of primary iron-core and secondary back-iron, the magnetic flux linkage of one coil generated by one pole-pair HTS bulk magnets can be obtained approximately as

$$\psi_{\text{SC}} = \frac{\mathscr{F}}{R_{\text{tot}}} = \frac{2H_c \cdot h_s}{\dfrac{2h_s}{3\mu_r\mu_0 l_s w_s} + \dfrac{4g}{\mu_0\cdot(l_s+l_t)/2\cdot(3w_s+w_t)/2}} = \frac{3\mu_0\mu_r H_c h_s l_s w_s\cdot(l_s+l_t)\cdot(3w_s+w_t)}{h_s\cdot(l_s+l_t)\cdot(3w_s+w_t)+24g\mu_r l_s w_s} \quad (1)$$

where $\mathscr{F}$ is the magnetomotive force of magnetic circuit, R_{tot} the total magnetic reluctance, H_c the magnetic field intensity of HTS bulk magnet, μ_0 the permeability of vacuum; μ_r is the relative permeability of HTS bulk magnet, and the value is set to be 0.4 according to the empirical value; l_s, w_s, and h_s are the length, width and height of HTS bulk magnet respectively; l_t, w_t are the length and width of stator-tooth respectively. When the motor parameters shown in Table I are substituted in (1), ψ_{sc} can be calculated out with the value of 1.869 mWb.

The back electromotive force (EMF) is determined with an rms value as

$$E_0 = \frac{1}{\sqrt{2}}\frac{\pi}{\tau}N_1 k_N \psi_{\text{SC}} v_s = k_E v_s \quad (2)$$

where $k_E = \frac{1}{\sqrt{2}}\frac{\pi}{\tau}N_1 k_N \psi_{\text{SC}}$ is the back EMF constant, τ the pole pitch, N_1 the number of turns of winding, and k_N the winding factor.

For the long-primary HTSLSM, the stator copper loss cannot be neglected [5], so the electromagnetic power can be derived as follows

$$P_{\text{em}} = \frac{6E_0}{R_1^2+X_t^2}\left[U\left(X_t\sin\theta + R_1\cos\theta\right) - E_0 R_1\right] \quad (3)$$

The thrust for p pole pairs secondary is

$$F_{\text{em}} = \frac{P_{\text{em}}}{v_s} = \frac{6pE_0\left[U\left(X_t\sin\theta+R_1\cos\theta\right)-E_0R_1\right]}{2\tau f\left(R_1^2+X_t^2\right)} = \frac{6pk_E\left[U\sqrt{R_1^2+X_t^2}\sin(\theta+\phi)-2\tau fk_ER_1\right]}{\left(R_1^2+X_t^2\right)} \quad (4)$$

where R_1 is the phase resistance, U the phase voltage, v_s the synchronous velocity, and $v_s = 2\tau f$, f the frequency; X_t is the synchronous reactance, and $X_t = 2\pi fL_1$, $L_1 = N_1^2/R_{\text{tot}}$; ϕ is the load shift angle, and $\phi = \arctan R_1/X_t$. When load angle θ = 90°-ϕ, the maximum thrust force $F_{\text{em\_max}}$ can be obtained.

According to the geometric parameters of the HTSLSM, a 2D FE model is built up as shown in Fig. 4.

The materials in model are numbered as: ① HTS bulk magnet North (with the magnetization direction along the negative y-axis direction); ② HTS bulk magnet South (with the magnetization direction along the positive y-axis direction); ③ Band; ④ Copper stranded coils; and ⑤ Stator iron core.

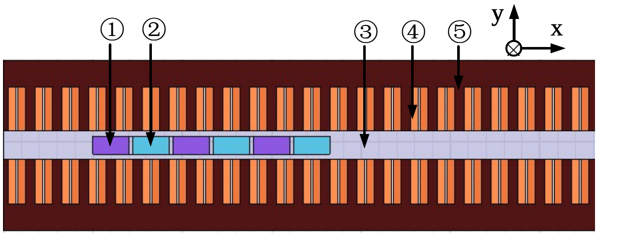

FIG. 4. FE model of the double-sided HTSLSM.

The time-stepping transient analysis method is applied in the resolution. Typical performance curves in different working conditions can be obtained. Based on 2D FE transient analysis, the locked-mover thrust versus phase angle for different B_{trap} are simulated with the results as shown in Fig. 5. The amplitude of the locked-mover thrust is the peak thrust force F_{em_max}. From the graph, the thrust reach a maximum value of F_{em_max} = 3.42 kN at B_{trap} = 3.0 T, θ = 36°.

When the B_{trap} = 0.5 T, f = 5 Hz, the F_{em_max} is calculated versus working current I by using both the magnetic circuit calculation and FEA method, and compared with the measurements, as shown in Fig. 6. It can be found from the graph, the values obtained by magnetic circuit method are slightly bigger than FE simulated and measurements, which is allowed within the scope of the error.

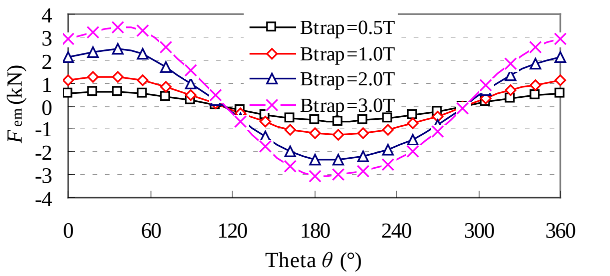

FIG. 5. Locked-rotor thrust characteristic.

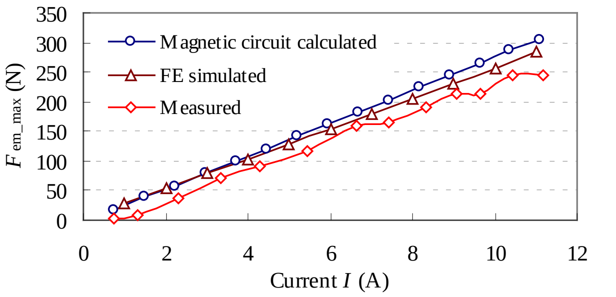

FIG. 6. Comparison F_{em_max} calculated by magnetic circuit method and FEA method with the measurements.

V. TESTING RESULTS AND ANALYSIS

The double-sided HTSLSM with HTS bulk magnet secondary, which is levitated by HTS magnetic suspension system, has been verified and tested with a practical prototype. The motor control system based on the SVPWM control strategy is developed and the PWM signals are produced by the LabVIEW software. So it can run the HTSLSM through the LabVIEW control panel on the computer easily.

The F_{em_max} of HTSLSM has been measured versus running frequencies for different air gap length L_{gap}, and the results are shown in Fig. 7. As can be seen from the graph, the F_{em_max} increases with decreasing the L_{gap}, and reach a peak value at about f = 11 Hz. So it is perfect to run the HTSLSM in best frequency nearby with a smaller L_{gap}. Fig. 8 shows that F_{em_max} increases with I linearly, and increases with frequency when f < 11 Hz, which is consistent with that indicated in Fig. 7.

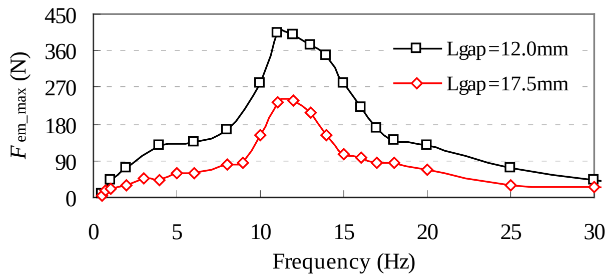

FIG. 7. F_{em_max} versus different frequencies.

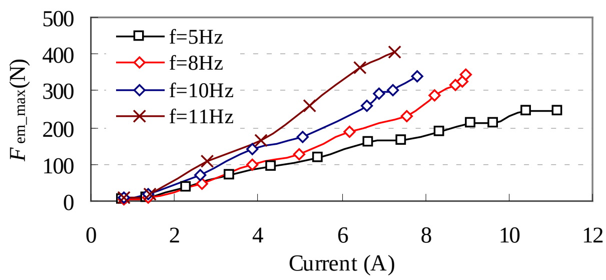

FIG. 8. F_{em_max} versus I for different frequencies under L_{gap} = 12 mm.

VI. CONCLUSION

The thrust characteristics have been comprehensive studied by magnetic circuit and FEA method, and verified by measurements. The results show that the thrust increase with current linearly, and increases with frequency when the f smaller than 11 Hz. Using the smaller air gap length can enlarge the thrust obviously. When the HTS bulk magnets with higher trapped magnetic field are used, the bigger thrust will be obtained than conventional linear motors with smaller volume and litter weight.

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