Performance Analysis of an HTS Magnetic Suspension and Propulsion System with a Double-Sided HTSLSM Driving

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Abstract — Electromagnetic design of a high temperature superconducting (HTS) magnetic suspension and propulsion system driven by a double-sided HTS linear synchronous motor (HTSLSM) is introduced firstly in this paper. The equivalent current sheet method is then used to analyze the flux density distribution of the permanent magnet guideway (PMG) for the HTS magnetic suspension sub-system. Moreover, finite element analysis (FEA) method is employed to study the performance of the HTSLSM. Theoretical investigations are finally verified by the measurements.

I. INTRODUCTION

HTS magnetic suspension systems have been paid more attention recently for the quick development of superconductivity technology [1]. It consists of HTS bulks on the moving cryogenic vessels and permanent magnet guideway (PMG) on the track. If driven by a linear motor, this system can be applied to Maglev and other suspension propulsion systems for it can provide stable levitation force and guidance force.

In this paper, an HTS magnetic suspension and propulsion system driven by a long-primary double-sided HTSLSM has been developed. The normal force of the HTSLSM is mostly cancelled for its symmetry structure and has no influence on the load capacity, which is beneficial to the stability of the HTS suspension propulsion system. Furthermore, a type of Halbach array PMG has been designed to optimize the flux density distribution in the interaction space so as to get optimal levitation and guidance forces. The performance characteristics of the HTSLSM are analyzed based on the finite element analysis (FEA) method with the results presented. Simulation on typical performance curves are verified by the experiments on the prototype.

II. MODEL OF HTS MAGNETIC SUSPENSION AND PROPULSION SYSTEM

The structure model of the HTS magnetic suspension propulsion system is composed of a double-sided HTSLSM and HTS bulks-PMG magnetic suspension sub-system as shown in Fig. 1. The primary stator mainly consists of three-phase copper windings and iron cores, while the secondary is made up of HTS bulk magnets.

The HTS magnetic suspension sub-system is located on the bottom of the HTSLSM, and the levitator containing HTS bulks is connected and fixed with the moving secondary, which ensures that the secondary mover with HTS levitator can run without any sliding friction force. The PMG is a type of Halbach magnet array with the schematic diagram as shown in Fig. 2, where the arrow direction is the magnetization direction of PM.

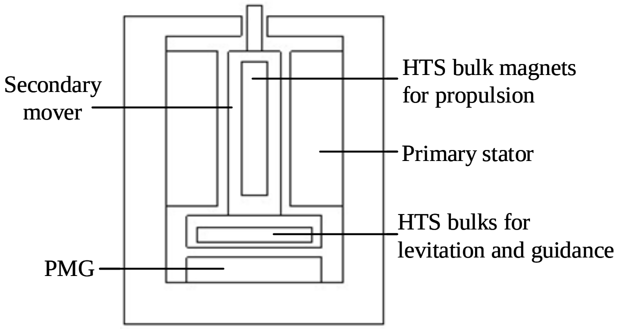


Fig. 1. Model of HTS magnetic suspension and propulsion system.

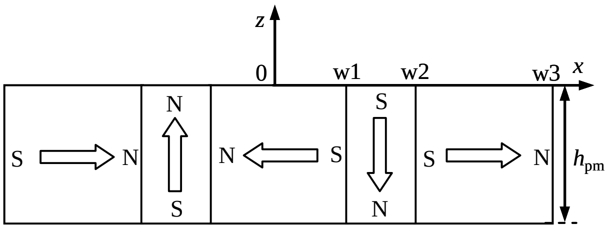


Fig. 2. Structure schematic diagram of the Halbach array PMG.

III. PMG NUMERICAL MODEL

Equivalent current sheet method is used to build up the Halbach PMG model, and the current directions are illustrated in Fig. 3. The flux density components B_z and B_x at point (x, z) for different heights h generated by all the current sheets are calculated and indicated in Fig. 4(a) and Fig. 4(b), respectively.

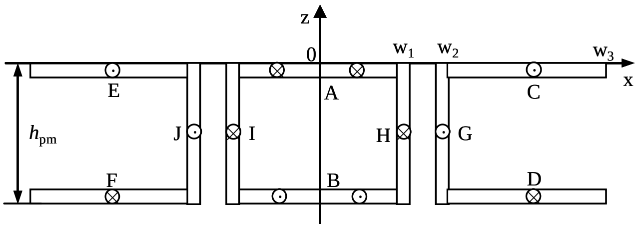
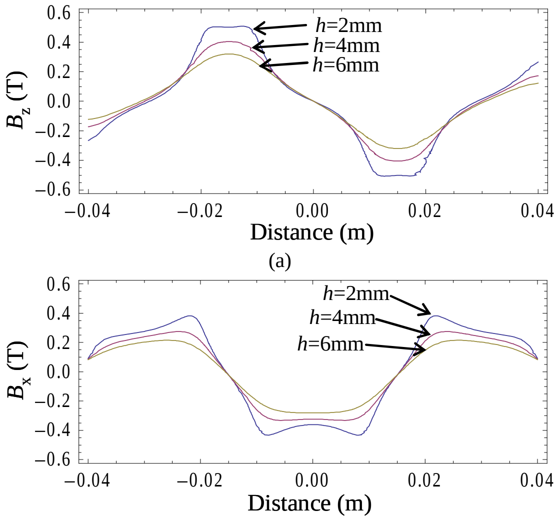


Fig. 3. Current sheet model of the Halbach array PMG.



(a)

(b)

Fig. 4. Transversal distributions of flux density component B_z and B_x.

IV. PERFORMANCE ANALYSIS BY FINITE ELEMENT METHOD

A. FE Model

According to the geometric parameters of the HTSLSM, a 2D FE model is built up as shown in Fig. 5. 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.

The time-stepping transient analysis method is applied in the resolution. Typical performance curves in different working conditions can be obtained.

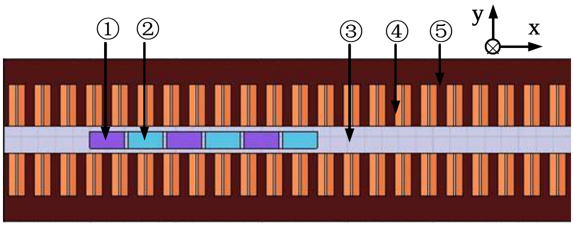


Fig. 5. FE model of the double-sided HTSLSM.

B. Thrust Characteristics

For the long-primary double-sided HTSLSM, the primary copper loss cannot be neglected. Hence its electromagnetic thrust can be derived as follows [2]

$$F_{em}=\frac{P_{em}}{v_s}=\frac{6pE_0\left[U\left(X_t\sin\theta+R_1\cos\theta\right)-E_0R_1\right]}{2\tau f\left(R_1^2+X_t^2\right)} \qquad (1)$$
$$=6pk_E\left[U\sqrt{R_1^2+X_t^2}\sin\left(\theta+\phi\right)-2\tau fk_ER_1\right]\Big/\left(R_1^2+X_t^2\right)$$

where P_{em} is the electromagnetic power, v_s the synchronous speed equal to $2\tau f$, τ the pole pitch, f the frequency, E_0 the root mean square value of the back electromotive force (EMF), k_E the back EMF constant equal to $\pi N_1 k_N \psi_{SC}/\sqrt{2}\tau$, N_1 the number of turns of one coil winding, k_N the winding factor, ψ_{sc} the magnetic flux linkage of one coil, p the number of pole pairs, R_1 the phase resistance, U the phase voltage, X_t the synchronous reactance; ϕ the load shaft angle equal to $\arctan R_1/X_t$. When load angle θ = 90°-ϕ, the maximum thrust F_{em_max} can be obtained.

Based on 2D FE transient analysis, the locked-mover thrust versus phase angle for different trapped magnetic field B_{trap} of HTS bulk magnet are simulated with the results as shown in Fig. 6. From the graph, the thrust reach a maximum value of F_{em_max} = 3.42 kN at B_{trap} = 3.0 T, θ = 36°, which are consistent with the numerical calculations.

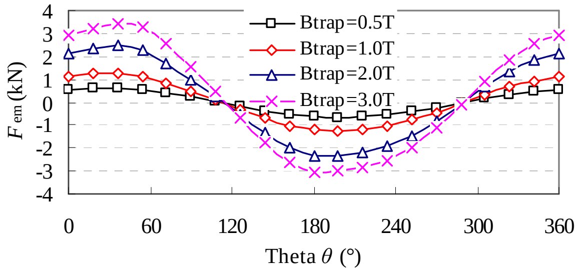


Fig. 6. Locked-rotor thrust characteristic.

V. TESTING RESULTS AND CONCLUSIONS

The HTS magnetic suspension and propulsion system driven by the double-sided HTSLSM has been verified by a prototype. The motor control system based on the SVPWM control strategy is developed and the PWM signals are produced by the LabVIEW software. So we can run the HTS suspension propulsion system through the LabVIEW control panel on the computer freely. The locked-mover thrust of the HTSLSM is measured under different frequencies for different air gap length L_{gap} when B_{trap} = 0.5 T with the results as shown in Fig. 7. As can be seen from the graph, F_{em_max} = 403 N at f = 11 Hz, L_{gap} = 12 mm, and F_{em_max} = 239 N at f = 12 Hz, L_{gap} = 17 mm, respectively.

A bigger thrust with less volume and weight for the HTSLSM can be readily realized by using HTS bulk magnets with higher trapped magnetic fields, which lead to the great prospect of using the HTS magnetic suspension propulsion system into Maglev and electromagnetic aircraft launch system (EMALS), etc.

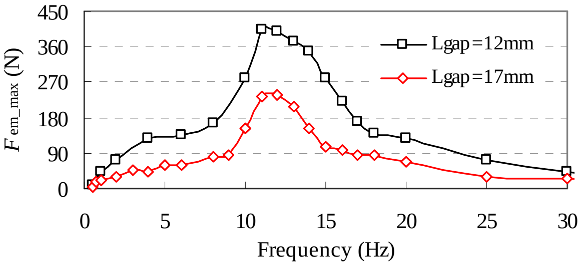


Fig. 7. Maximum locked-mover thrust versus different frequencies.

VI. REFERENCES

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