A Linear Motor Driver with HTS Levitation Techniques

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Abstract High temperature superconductor (HTS) high levitation force density with passive and self-stabilizing features allows a number of special applications to be developed. Linear motor driving systems are commonly required for those applications such as levitated transport systems. In this work a prototype linear motor driving system with HTS technology is analyzed with calculation details including its magnetic fields and driving forces presented in the paper.
Keywords: High temperature superconductor, levitation; linear motor, magnetic field, permanent magnet.

Introduction

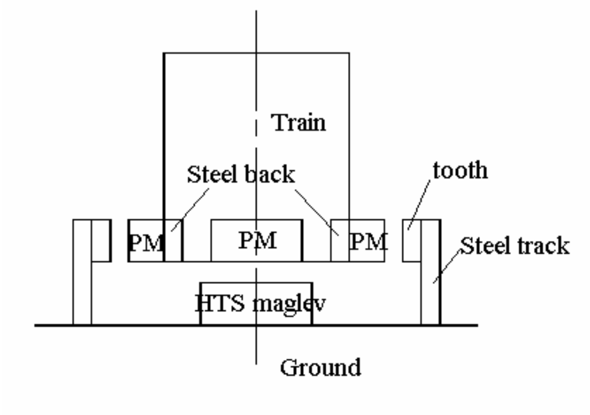
High temperature superconductor (HTS) having levitation force with passive and self-stabilizing features allows a number of special applications to be developed such as frictionless bearings for energy storage flywheels, gyroscopes, momentum wheels, high-speed machine tools, Mag-Lev trains and other levitated transport systems [1-3]. Linear motor driving systems are commonly required for those applications such as levitated transport systems. In this paper a prototype linear motor driving system using HTS technology is analyzed which has a long active track having three phase windings placed in the side of the track and with the HTS in the middle used for the levitation. The phase windings are controlled by an inverter/controller with a single-phase ac supply source. The driving control method is a brushless dc model. Permanent magnets (PM) are employed in the system for the levitation. Analysis and calculation details of magnetic fields and driving forces about the prototype device will be presented in the paper.

Principle Configuration

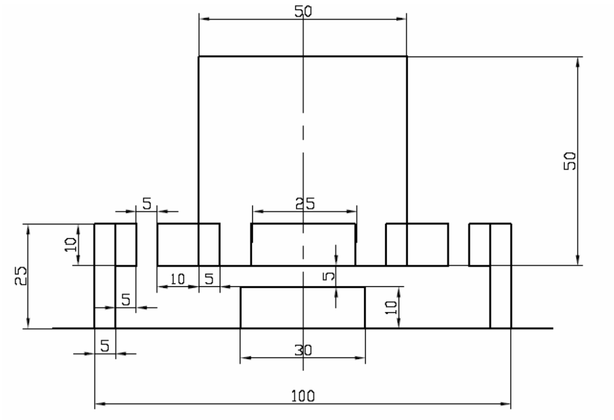
As shown in Fig.1, a combined HTS driving prototype is designed with long active tracks and 3-phase windings placed in the tracks. Standard 3-phase converters are used with brushless DC control. PMs are mounted on the sides of the moving object. Since the attraction force between the stator and PMs is very large, the motor tracks are beside the mover instead of below the mover. The attraction forces by two sidetracks can be cancelled. The inverter circuit contains the active windings only, facing to the train at a moment, instead of all the windings in the long track.

The design details are as follows: (i) Middle track-HTS/ PM blocks having width = 3 cm, height = 1 cm, and air gap = 0.5 cm; (ii) Main controlled moving body of 20 × 5 × 5 cm; (iii) PMs for levitation on the mover bottom having 20 × 2.5 × 1 cm; (iv) PMs of 1 × 1 × 1 cm for driving on sides of the body, 9 in each side; (v) The dimensions of the stator tooth is 1 × 1 × 0.5 cm (horizontal length); and (vi) The dimensions of a stator slot is 1 × 1 × 0.5 cm (horizontal length).

The dimension of the HTS unit block is 2.5 cm in diameter and 1 cm in height having a levitation force density up to 12 N/cm^2 when the gap is 0.1 cm [4].



(a) Schematic diagram



(b) Dimensions (unit: mm)

Fig. 1. Schematic diagram of the prototype.

HTS Levitation Technology

HTS materials can provide applicable magnetic levitation properties. Fig. 2 shows a practical demonstration example of a free spin PM levitated by a YBaCuO HTS disk. The HTS disk unit has ϕ - 25 mm, h - 10 mm, and its levitation force density loop is presented in Fig. 3 which is a practical measurement result of a NdFeB PM with 0.5 T surface magnetic fields levitated by the YBaCuO HTS disk.

Numerical analysis of the HTS levitation to PMs mainly can be based on basic electromagnetic principles: (i) Lorentz force equation, and (ii) Maxwell equations. HTS theoretical models are available such as Bean model, Kim model, Power law model, and Yin model. Algorithm tools include such as Matlab and Maxwell softwares using finite element analysis.

Calculation of levitation force F_{Lev} between a PM and a HTS based on Ampere's force f is related to current density J as

$$\vec{f} = \vec{J} \times \vec{B} \qquad (1)$$

The HTS-PM levitation force is given by

$$\begin{aligned} \vec{F}_{Lev} &= \iiint_{V_{SC}} \vec{f}\, dV = \iiint_{V_{SC}} dV\left(\vec{J}_{SC} \times \vec{B}\right) \\ &= \iiint_{V_{SC}} dV\left(\vec{J}_{SC} \times \vec{B}_{PM}\right) + \iiint_{V_{SC}} dV\left(\vec{J}_{SC} \times \vec{B}_{SC}\right) \end{aligned} \qquad (2)$$

$$\because \iiint_{V_{SC}} dV\left(\vec{J}_{SC} \times \vec{B}_{SC}\right) = 0$$

$$\therefore \vec{F}_{Lev} = \iiint_{V_{SC}} dV(\vec{J}_{SC} \times \vec{B}_{PM}) \qquad (3)$$

where V is volume, V_{SC} is HTS volume, J_{SC} is supercurrent density distribution, B is magnetic flux density, B_{PM} is PM magnetic flux density, and B_{SC} is for HTS. Obtaining the applied field B_{PM} and the current distribution J_{SC} is necessary in order to solve the above equation.

Fig. 2. Levitation of a free spin PM on a HTS disk.

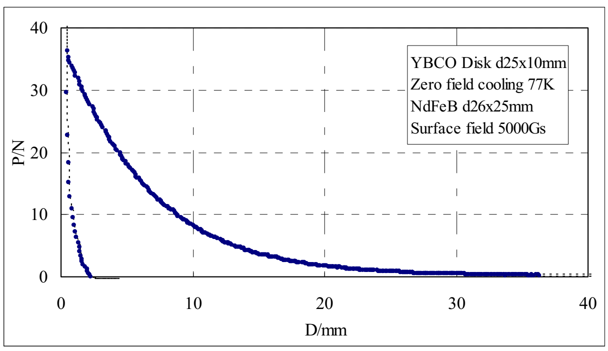


Fig. 3. Practical measurement result of a HTS applied with a PM.

Performance and Analysis

The controlled object moving speed v is

$$v = m\tau f \tag{2}$$

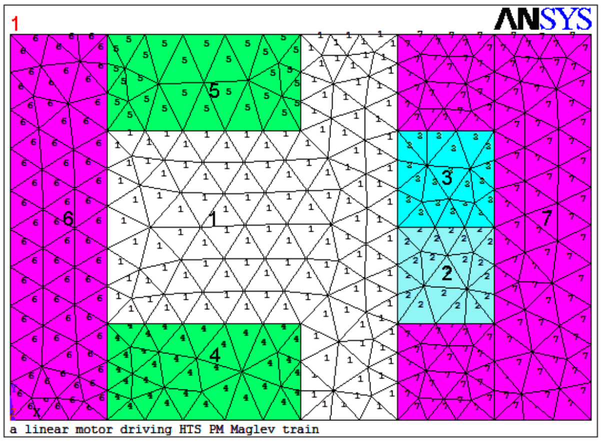
where m is the phase number, τ is the pole distance.
Electromagnetic thrust force F_{em}, when at each moment two phases (a and b) are excited (i.e. i_a=-i_b, i_c=0, E_a=-E_b), is

$$F_{em} = \frac{E_a i_a + E_b i_b + E_c i_c}{v} \tag{3}$$

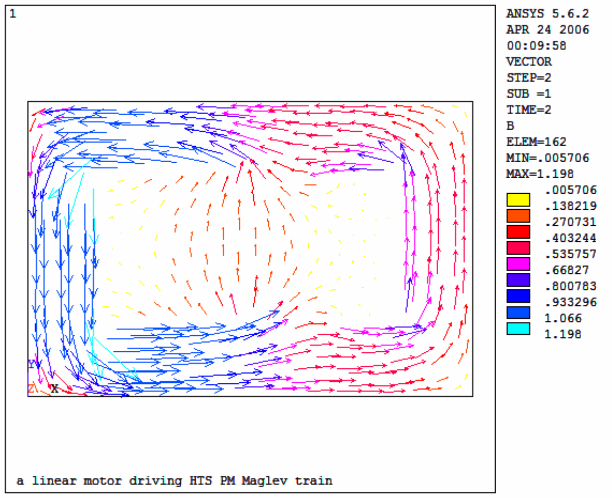
Motion equation is given by

$$\frac{dv}{dt} = \frac{F_{em} - F_L - \delta_0 v}{m} \tag{4}$$

where F_L is the load, δ_0 the friction coefficient, and m the total mass of the moving parts.
2D magnetic field finite element analysis is performed to solve the magnetic field distribution and the maximum PM flux linked to a coil [5]. Considering the structural symmetry, only one pole pitch is required for the field solution. Fig. 4(a) shows the meshes and material codes, where (1) stands for air, (2) and (3) stator coils, (4) and (5) driving PMs, (6) back iron of PMs, and (7) side track iron. Fig. 4(b) illustrates the vector plots of magnetic flux generated by the driving PMs, where the PMs face the stator teeth so that the PM flux in the coil is maximum. Fig. 5 shows the magnetic field distribution along the middle line of the air gap in the Fig. 4(a), and the result is obtained from the magnetic field finite element analysis.
From Fig. 4, the maximum flux passing through the coil (the tooth) can be found to be 0.0515 mWb which can also be calculated from $\phi_{coil} = F_m/(R_m+R_g)$. The NdFeB PM used has H_c = 950 kA/m. When the mover moves, an electromotive force (emf) is induced in the stator windings. Three phase windings, and at any moment, 9 coils (each side) face to the movers. The number of active coils for each phase is 6. For this case, $E_1 = 4.44fN_1\phi_{coil}$ =53.2 $\times 10^{-3}$ V, v = 3 m/s, F_{em} = 3.55 N, and a = 3.55 m/s^2 for 1 kg mass.

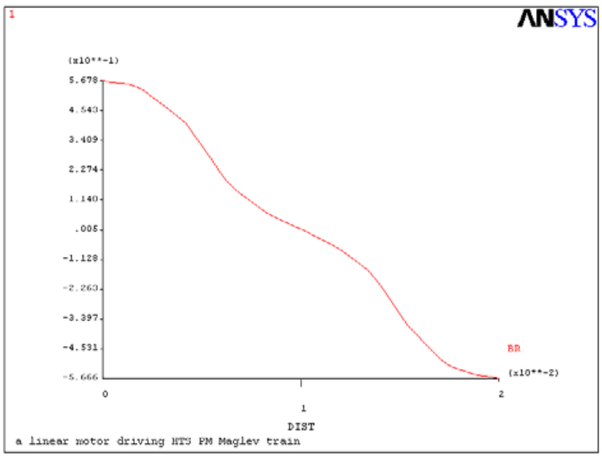


(a) 2D magnetic field FEA mesh and material code



(b) Plots of flux density vectors (Max. 0.6 T)

Fig. 4. Magnetic field finite element analysis.



(X-cm; Y-10^{-1}T)

Fig. 5. Magnetic field distribution along the air gap in the Fig. 4(a).

Conclusion

Linear motor driving systems have advantages built with HTSs. A prototype linear permanent magnet synchronous motor driving system with HTS levitators is analyzed with principle calculations and software simulations. This small scale experimental prototype and its analysis provides a base for the further development of this HTS linear driving technology.

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