Electromagnetic Investigation of a High Temperature Superconducting Linear Synchronous Motor for High-Speed Railway

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1. Background

Challenges of Higher Speed Railway

※ Difficulty of high-speed current collection by pantograph

※ Large weight and size of the rotate motor

※ The higher speed is, the worse climbing capacity it gets

※ The complex transmission mechanism
Advantages of using HTS LSM for traction system

- Higher magnetic field by HTS magnets (>3T) is possible and then it could increase the mechanical gap of traction system
- The better climbing ability than the conventional traction that relays on the adhesion
- Reducing the weight and volume of train Significantly
- Non-contacting electromagnetic propulsion
- Non-contacting current collection
- ......

HTS linear synchronous motor (LSM): a promising option to the future traction of high-speed railway
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2-D Modeling and simulation

Geometrical layout of the motor model

Magnets model extracted from the motor model above
2. HTS LSM with iron-core stator

**2-D Modeling and simulation**

- **Step 1**: A-formulation and kinematical equations

\[
\nabla \times \left( \mu^{-1} \nabla \times \overrightarrow{A} \right) = -\sigma \overrightarrow{A} + J_e
\]

\[
\frac{ds(t)}{dt} = \mathbf{v}(t) \quad \frac{d\mathbf{v}(t)}{dt} = \frac{f_x(t) + F}{m}
\]

- **Step 2**: H-formulation and heat diffusion equation

\[
\nabla \times \left( \rho \nabla \times \overrightarrow{H} \right) = -\mu_0 \overrightarrow{H}
\]

\[
\rho(T, \mathbf{B}) = \frac{E_c |J|^{(n-1)} \left(1 + \sqrt{B_\perp^2 + (kB_\parallel)^2} / B_0 \right)^{bn}}{J_{c0}^n} \left( \frac{T_c - T_0}{T_c - T} \right)^n
\]

\[
\rho(T, \mathbf{B}) \quad Q = \iint_{\Omega} \mathbf{EJ}ds
\]

\[
\left( k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} \right) - C \left( \frac{\partial T}{\partial t} \right) = -Q
\]

\[
k_x = 1 / \sum \frac{w_i}{k_i \cdot w_i} \quad k_y = \sum k_i \cdot w_i / w \quad C = \sum c_i \cdot w_i / w
\]
2. HTS LSM with iron-core stator

Maximum temperature increment

<table>
<thead>
<tr>
<th>k value</th>
<th>K [mK/s]</th>
<th>k1</th>
<th>k2</th>
<th>k3</th>
<th>k3/k1</th>
</tr>
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<tbody>
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<td>g[mm]</td>
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<td></td>
<td></td>
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<td>30</td>
<td>4.25</td>
<td>32.57</td>
<td>7.69</td>
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</tbody>
</table>

k2 > k3 > k1, the temperature of HTS magnets increases quickly when subjected to a travelling magnetic field.
Joint of coated superconductor tapes

2. HTS LSM with iron-core stator

The manually lapped joints device, Phase I

The automatically lapped joints device, Phase II

Schematic view of the electrical joint configuration

Lapped joint

Bridged joint

Butted joint
2. HTS LSM with iron-core stator

Joint of coated superconductor tapes

Micrograph of the transverse cross-section of jointed sample scanned by either (a) the SEM and (b) the metallographic microscope.

6.3 nΩ (14-cm joint length, less than 10-μm solder thickness) was achieved.
2. HTS LSM with iron-core stator

Force-measuring equipment

HTS coils

Force-measuring system

Conventional flat stator
2. HTS LSM with iron-core stator

An example of the testing result

Measured thrust, normal force and transverse force

The transverse force slightly oscillates near zero may due to that the four coils installed onto epoxy board were no fully symmetric.

Comparison of electromagnetic forces as a function of the time phase between the experiment and simulation

The distortion is due to the presence of induced transport current in coils.
2. HTS LSM with iron-core stator

Laboratory prototype of HTS LSM

Running Scenario

Dynamic simulation
Although a stator with iron core indeed can increase the air-gap magnetic field thus improve the force properties of motor, the iron core is easy to be saturated under the strong enough field generated by HTS magnets.

Some advantages of air-core stator includes:

- Increasing the load capacity and dynamic response;
- Avoiding the iron loss and saturation;
- Reducing the cost of stator;
- Decreasing the high-order harmonic and noise;
- ……
3. HTS LSM with air-core stator

Geometrical layout

Three-dimensional geometry of HTS linear synchronous motor with air-core stator

Copper windings

Superconducting coils

Non-metallic materials

Geometrical layout of the electromagnetically modeled HTS LSM
### Voltage equation

\[ \hat{U} = \hat{E}_0 + \hat{i}R_a + j\hat{i}X_s \]

\[ X_d = X_q = X_s = 2\pi fL \]

### Power equation

\[ P_e = \frac{mE_0U}{\sqrt{R_a^2 + X_s^2}} \sin(\theta + \alpha) - \frac{mE_0^2 R_a}{R_a^2 + X_s^2} \]

\[ \alpha = \arctan\left(\frac{R_a}{X_s}\right) \]

\[ P_1 = P_{Cu} + P_\Omega + P_0 \]

The power equation has an invariably negative component due to the stator copper loss.

**Phasor diagram**

**Electric circuit**
3. HTS LSM with air-core stator

Mathematical Foundations

- **Biot-Savart law**

\[ B(x, y, z) = \frac{\mu_0}{4\pi} \iiint_{V'} \frac{J(x', y', z') \times e_R}{R^2} dV' \]

- **Maxwell stress tensor**

\[ F = \iiint_{\Omega} -\frac{1}{2} (H \cdot B) \vec{n} + (n \cdot H) B^T \] \[ ds \]

\[ F_x = \iiint_{\Omega} -\frac{1}{2} (H_x B_x + H_y B_y + H_z B_z) n_x + (n_x H_x + n_y H_y + n_z H_z) B_x \] \[ ds \]

\[ F_y = \iiint_{\Omega} -\frac{1}{2} (H_x B_x + H_y B_y + H_z B_z) n_y + (n_x H_x + n_y H_y + n_z H_z) B_y \] \[ ds \]

\[ F_z = \iiint_{\Omega} -\frac{1}{2} (H_x B_x + H_y B_y + H_z B_z) n_z + (n_x H_x + n_y H_y + n_z H_z) B_z \] \[ ds \]
3. HTS LSM with air-core stator

Air-gap field distribution at 3 mm and 7 mm, the high-order harmonic components are too small to be ignored.

The time-evolution of magnetic fields when HTS magnets moving over a flat stator.
Determination of the engineering current

Three typical tapes in a race-track superconducting coil who may undergo the biggest self-field and are most likely to quench.

Maximal engineering current vs. transport current for the three typical tapes, a minimal value of 93 A is found and regarded as the critical current of superconducting coil.
3. HTS LSM with air-core stator

Force characteristics of HTS LSM

The average normal force is positive and accounts for 11% of the maximal normal force, which means the normal force becomes lift force of the HTS LSM (the electromagnetic gap is 20 mm.)

Stable thrust (a) and normal force (b) per magnet
Air-core and iron-core stator with a pole pitch of 150-mm were made. Once the corresponding HTS magnets are fabricated, its electromagnetic properties will be tested and compared with that of an iron-core stator.

Two identical stators were made, one is iron-core and the other is air-core.
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4 Conclusions
1. A 2-D thermo-electromagnetic model and force-measuring equipment was developed, allowing to simulate the thermal behavior inside HTS magnets and to measure the three-dimension electromagnetic forces of HTS LSM;

2. A simple and effective process was proposed to join coated superconductor tape at a low resistance, and a laboratory prototype of HTS LSM was fabricated and run successfully;

3. It was analytically proven that the normal force of a coreless-typed HTS LSM can provide stable lift force for a rail transit or Maglev vehicle if the load angle could be properly controlled in the rang of $0^0 \sim 90^0$. 

4. Conclusion
Acknowledgments

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State Key Laboratory of Traction Power
Positions for Postdoc, Assistant Professor, Associate Professor and Full Professor in our State Key Laboratory is open for people who are skilled in the applied superconductivity, cryogenic technology and electrical machine system.

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Thanks for your attentions!