Numerical Modeling for the Dynamic Characteristics of HTS Magnetic Levitation System

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1. Self-introduction
2. Dynamic Electromagnetic-thermal Model
3. Results and Discussion
4. Conclusion
Self-introduction

Education

- **Southwest Jiaotong University, Chengdu, China** 2017-now
  State-Key laboratory of Traction Power, Department of vehicle Operation Engineering;
  Degree: PhD student
  supervisor: Guangtong Ma

- **Southwest Jiaotong University, Chengdu, China** 2016-2017
  State-Key Laboratory of Traction Power, Department of vehicle Operation Engineering;
  Degree: Master
  supervisor: Guangtong Ma

- **Southwest Jiaotong University, Chengdu, China** 2012-2016
  School of Mechanical Engineering, Department of vehicle engineering
  Degree: Bachelor
  School of Foreign Language, Department of English
  Degree: Bachelor

Main Awards

- Second Prize of 14th "Challenge Cup" National College Students' Academic Science And Technology Competition Works Competition (Province level, Design of Sterile mixer based on HTS maglev)

- Third Prize of 8th National College Students' energy conservation and emission reduction social practice and technology competition (State level)
Self-introduction

WELCOME TO CHENGDU

Universidade Nova de Lisboa
Lisbon, Portugal

Southwest Jiaotong University
Chengdu, China
Contents

1. Self-introduction
2. Dynamic Electromagnetic-thermal Model
3. Results and Discussion
4. Conclusion
Vibration of HTS Maglev

- **HTS Maglev System**
  - Merit of self-stability
  - Potential for high-speed application (i.e. Chinese project for 600km/h HTS maglev train)

- **Vibration of HTS maglev system**
  - Inevitably caused by external impulse
    - Changes of weight
    - Track irregularity
    - ...

- Safety
  - Levitation performance
Motivation

Dynamic Electromagnetic-thermal Model

1. Electromagnetic Model
2. Thermal Model
3. Dynamic Model
Electromagnetic Model


- **H-formulation**

  \[ \nabla \times (\rho \nabla \times H) = -\mu \frac{\partial H}{\partial t} \text{ in } \Omega \]

  \[ \rho_{sc}(|J|, B) = \frac{E_c}{J_c(B)} \left| \frac{J}{J_c(B)} \right|^{n-1} \]

  \[ J_c(B) = \frac{J_{co} \cdot B_0}{1 + |B|} \]

- **Boundary conditions**

  \[ H = H_{self}(x, y, z) + H_{ext}(x, y, z) \text{ in } \partial \Omega \]

  \[ z = z(t) \]

  - **H_{self}:** Biot-Savart’s law
    - **H_{ext}:** magnetic field of PMG
      - Numerical magnetic-field (FEM, Comsol)
      - Analytical magnetic-field

  indirect coupling of HTS and magnetic field
Electromagnetic Model

- **Analytical magnetic-field**
  - Biot-Savart’s law: e.g. for AB in PMG II

\[
\begin{align*}
\mathbf{dB} &= \frac{\mu_0}{4\pi} \frac{I d\mathbf{l} \times \mathbf{r}}{r^2} \\
\mathbf{M} &= M \mathbf{x} \\
\mathbf{J} &= M \times \mathbf{n} = M \mathbf{z} \\
I &= M dx \\
\mathbf{d}\mathbf{l} &= d\mathbf{z}', |r|^2 = (x - x')^2 + (y + l)^2 + (z - z')^2
\end{align*}
\]

\[
\begin{align*}
\mathbf{dB}_x_1 &= \frac{\mu_0 M}{4\pi} \cdot dx' \cdot \int_0^{-tpm} -\frac{y+l}{3} \cdot dz' ; \\
\mathbf{B}_x_1 &= \int_{-(w1+2*w2)}^{-(w1+2*w2)} dB_x_1 \cdot dx \\
\mathbf{dB}_y_1 &= \frac{\mu_0 M}{4\pi} \cdot dx' \cdot \int_0^{-tpm} \frac{x-x'}{3} \cdot dz' ; \\
\mathbf{B}_y_1 &= \int_{-(3*w1+2*w2)}^{-(3*w1+2*w2)} dB_y_1 \cdot dx \\
\mathbf{dB}_z_1 &= 0
\end{align*}
\]
Electromagnetic Model

Magnetic field in BC, CD, DA can be evaluated by same method, and \( B \) of PMG II is the sum of \( B \) of AB, BC, CD, and DA.

BC:
\[
B_{x2} = \int_{-(w1+2*\text{w2})}^{-(w1+2*\text{w2})} dB_{x2} \cdot dx
\]
\[
B_{z2} = \int_{-(3*w1+2*\text{w2})}^{-(w1+2*\text{w2})} dB_{z2} \cdot dx
\]

CD:
\[
B_{x3} = \int_{-(w1+2*\text{w2})}^{-(3*w1+2*\text{w2})} dB_{x3} \cdot dx
\]
\[
B_{y3} = \int_{-(3*w1+2*\text{w2})}^{-(w1+2*\text{w2})} dB_{y3} \cdot dx
\]

DA:
\[
B_{x4} = \int_{-(w1+2*\text{w2})}^{-(3*w1+2*\text{w2})} dB_{x4} \cdot dx
\]
\[
B_{z4} = \int_{-(3*w1+2*\text{w2})}^{-(w1+2*\text{w2})} dB_{z4} \cdot dx
\]

\[
B_{\text{IIx}} = \sum_{i=1}^{4} B_{xi}
\]
\[
B_{\text{IIy}} = \sum_{i=1}^{4} B_{yi}
\]
\[
B_{\text{IIz}} = \sum_{i=1}^{4} B_{zi}
\]
\[
B_{\text{II}} = B_{\text{IIx}} \cdot x + B_{\text{IIy}} \cdot y + B_{\text{IIz}} \cdot z
\]

And so on for other PMGS:
\[
B_{\text{total}} = B_{I} + B_{\text{II}} + B_{\text{III}} + B_{IV} + B_{V}
\]
Electromagnetic Model

- Experimental system

<table>
<thead>
<tr>
<th>QUANTITY</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of HTS bulk (z direction)</td>
<td>13[mm]</td>
</tr>
<tr>
<td>Width of HTS bulk (x direction)</td>
<td>32[mm]</td>
</tr>
<tr>
<td>Depth of HTS bulk (y direction)</td>
<td>64[mm]</td>
</tr>
<tr>
<td>Depth of PMG (y direction)</td>
<td>238[mm]</td>
</tr>
</tbody>
</table>
H-formulation with thermal effect

\[ \nabla \times (\rho \nabla \times \mathbf{H}) = -\mu \frac{\partial \mathbf{H}}{\partial t} \]

\[ \rho_{sc}(|\mathbf{J}|, \mathbf{B}) = \frac{E_c}{J_c(\mathbf{B}, T)} \left| \frac{\mathbf{J}}{J_c(\mathbf{B}, T)} \right|^{n-1} \]

\[ J_{c0}(T) = J_{c0} \times \frac{T_c - T}{T_c - T_0} \]

Thermal transient equation:

\[ k \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) - c \cdot \left( \frac{\partial T}{\partial t} \right) = -Q \]

Connective boundary condition:

\[ k \cdot \left( \frac{\partial T}{\partial n} \right) + h \cdot (T - T_0) = 0 \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>QUANTITY</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>k</td>
<td>Thermal conductivity [W/(m*K)]</td>
<td>(7.90506<em>1E-6</em>(T[K^-1])^3-2.17<em>1E-3</em>(T[K^-1])^2+0.17407*(T[K^-1])-0.21246) [W/m/K]</td>
</tr>
<tr>
<td>c</td>
<td>Heat capacity [J/(m^3*K)]</td>
<td>(73.75*(T[K^-1])^2+5599.78*(T[K^-1])-0.21246) [J/m^3/K]</td>
</tr>
<tr>
<td>h</td>
<td>Connective heat transfer coefficient [W/(m^2*K)]</td>
<td>400 [W/(m^2*K)]</td>
</tr>
<tr>
<td>T_c</td>
<td>Critical temperature [K]</td>
<td>92 [K]</td>
</tr>
<tr>
<td>T_0</td>
<td>Initial temperature [K]</td>
<td>77 [K]</td>
</tr>
<tr>
<td>Q</td>
<td>Joule heat [W/m^3]</td>
<td>/</td>
</tr>
</tbody>
</table>
Dynamic Model

- **Dynamic equations**

\[
F = \iiint_{SC} J \cdot B \\
F_z = \iiint_{SC} (J_x \cdot B_y - J_y \cdot B_x) \, dx \, dy \, dz \\
m\ddot{z} + F_z - mg = f_y \\
f_y: \text{exciting force} \\
z: \text{vertical displacement (s_vibration [m])} \\
v = \dot{z}, \text{vibration speed [m/s]} \\
a = \ddot{z}, \text{acceleration [m/s}^2]\]

- **Boundary condition**

\[
H = H_{self}(x, y, z) + H_{ext}(x, y, z) \\
H = H_{self} + H_{ext}(x, y, z + s\_vibration)
\]
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Validation of Electromagnetic Model

Sequences

- FC: \((x, y, z) = ((0, 0, 25), (0, 0, 6), (0, 0, 25))\)
- ZFC: \((x, y, z) = ((0, 0, 100), (0, 0, 6), (0, 0, 100))\)
- Velocity: 1 mm/s
- mf: \((x, y, z) = ((-90, 0, 6), (90, 0, 6))\)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(M)</td>
<td>PM Magnetization</td>
<td>(7.8 \times 10^5) A/m</td>
</tr>
<tr>
<td>(E_c)</td>
<td>Critical current criterion</td>
<td>(1 \times 10^{-4}) V/m</td>
</tr>
<tr>
<td>(n)</td>
<td>HTS parameter</td>
<td>21</td>
</tr>
<tr>
<td>(J_{c0})</td>
<td>HTS parameter</td>
<td>(1.8 \times 10^8) A/m²</td>
</tr>
<tr>
<td>(B_0)</td>
<td>HTS parameter</td>
<td>0.2 T</td>
</tr>
<tr>
<td>(\rho_{air})</td>
<td>Air resistivity</td>
<td>(1\ \Omega\cdot m) [Lahtinen2012]</td>
</tr>
<tr>
<td>(\mu_0)</td>
<td>Air/HTS permeability</td>
<td>(4\pi \times 10^{-7}) H/m</td>
</tr>
</tbody>
</table>
Validation of Electromagnetic Model

- **Results**
  - Good agreements;
  - Similar computing time

  *with analytical field: 18h*
  *with numerical field: 20h*

<table>
<thead>
<tr>
<th>Model</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| with analytical field | 1. Easy to build gap  
2. Easy to extend halbach PMG in y direction | Long programming time and poor extendability        |
| with numerical field | Fast implementation                     | 1. Lots of meshes and extremely fine mesh in the gap  
2. Long modeling time to extend PMG                   |

- **Magnetic Field**
- **Fz during ZFC**
- **Fz during FC**
Reference model

- to reduce computing time
- Same parameters with electromagnetic model \( m = 1\, kg \)
- Studied case: free vibration after field cooling

\[ \text{FC: } (x, y, z) = ((0, 0, 30), (0, 0, 10)) \]
Thermal effect

Results

- Same levitation force during field cooling;
- Same trend during vibration, but different amplitude;
- Enormous difference in computing time: 6 days for model without thermal effect; 11 days for the model including it.
Results

- Figure of model after 120s relaxation is moved forward parallel to t-axis
- Fz decay during relaxation;
- Little changes to nature frequency
- Almost same amplitude during vibration;
- Less time to get back to the stable regime
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Conclusion

- Electromagnetic model with numerical / analytical field
  - Good agreement, similar computing time
  - Analytical field is more suitable for modeling of long Halbach guideway- avoid large amount of meshes and extremely fine mesh in the gap

- Dynamic model with thermal effect
  - Extendable for further research
  - Safe to study dynamic characteristic with dynamic model without thermal effect
  - Relaxation will be helpful for dynamic stability of HTS maglev system
  - Challenge: long computation time
Main collaborators:
Tianyong Gong (Master)
Manuel Perez (Master)
Changing Ye (Post Doctor)
Loïc Quéval (Assistant professor)
Guangtong Ma (Professor)

Foundations:
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THANKS FOR YOUR ATTENTION

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