Numerical Modeling for the Dynamic Characteristics of HTS Magnetic Levitation System

Wenjiao Yang[1], Tianyong Gong[1], Manuel Perez[1,2,3] , Changing Ye[1],
Loïc Quéval[4], Gang Li[1], and Guangtong Ma[1]*

1. Applied Superconductivity Laboratory, Southwest Jiaotong University, Chengdu, China
2. Escuela Técnica Superior de Ingeniería, Universidad de Sevilla, Spain
3. École Centrale de Lyon, France
4. Group of electrical engineering - Paris (GeePs), CNRS UMR 8507, CentraleSupélec, France

2018. 06. 26
Universidade Nova de Lisboa, Portugal

Contents

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

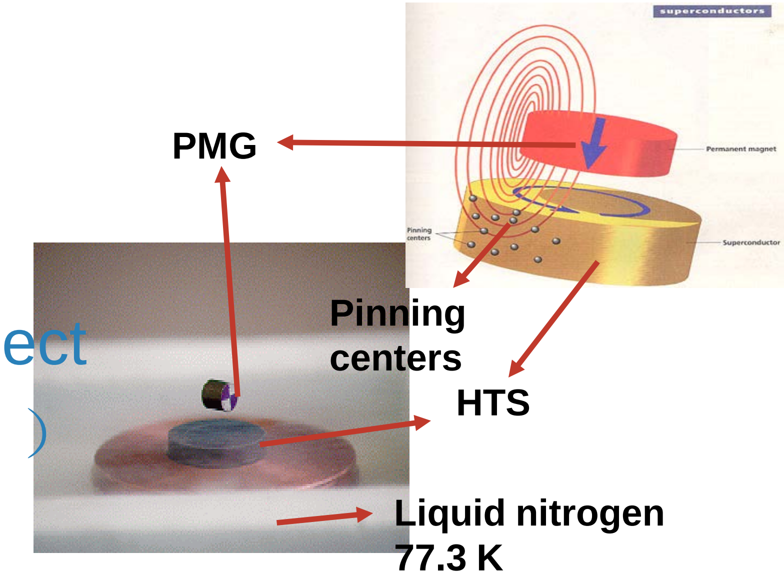
Southwest Jiaotong University
Chengdu, China

Contents

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

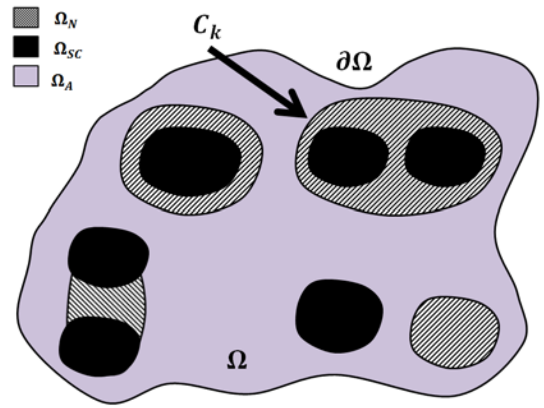
Electromagnetic Model

H-formulation

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

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

$$J_c(\mathbf{B}) = \frac{J_{c0} \cdot B_0}{1 + |\boldsymbol{B}|}$$

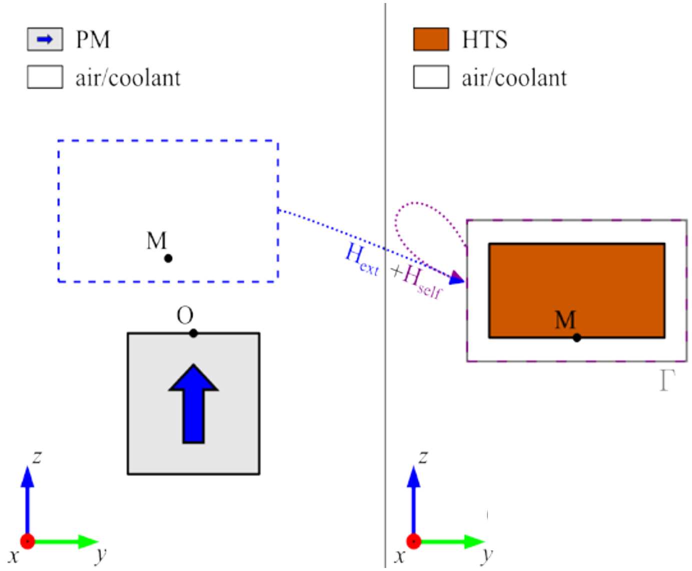


Boundary conditions

$\boldsymbol{H} = \boldsymbol{H}_{self}(x, y, z) + \boldsymbol{H}_{ext}(x, y, z)$ **in** $\partial\Omega$

$z = z(t)$

- $\boldsymbol{H}_{self}$: Biot-Savart's law
- $\boldsymbol{H}_{ext}$: magnetic filed of PMG
  - Numerical magnetic-field (FEM, Comsol)
  - Analytical magnetic-field

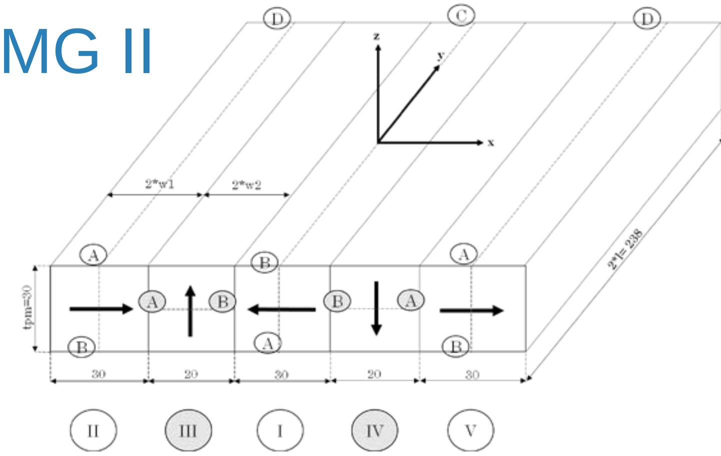


indirect coupling of HTS and magnetic field

Electromagnetic Model

☐ Analytical magnetic-field

- Biot-Savart's law: e.g. for AB in PMG II



$$dB = \frac{\mu_0}{4\pi} \frac{I d\boldsymbol{l} \times \boldsymbol{r}}{r^2}$$

$$\boldsymbol{M} = M\boldsymbol{x}$$

$$\boldsymbol{J} = \boldsymbol{M} \times \boldsymbol{n} = M\boldsymbol{z}$$

$$I = M dx$$

$$\overrightarrow{dl} = \overrightarrow{dz'}\,, |r|^2 = (x - x')^2 + (y + l)^2 + (z - z')^2$$

$$dBx_1 = \frac{\mu_0 \cdot M}{4 \cdot \pi} \cdot dx' \cdot \int_0^{-tpm} -\frac{y+l}{|r|^{\frac{3}{2}}} \cdot dz'\,; \qquad Bx_1 = \int_{-(3*w1+2*w2)}^{-(w1+2*w2)} dBx_1 \cdot dx$$

$$dBy_1 = \frac{\mu_0 \cdot M}{4 \cdot \pi} \cdot dx' \cdot \int_0^{-tpm} \frac{x-x\prime}{|r|^{\frac{3}{2}}} \cdot dz'\,; \qquad By_1 = \int_{-(3*w1+2*w2)}^{-(w1+2*w2)} dBy_1 \cdot dx$$

$$dBz_1 = 0$$

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:

$$Bx_2 = \int_{-(3*w1+2*w2)}^{-(w1+2*w2)} dBx_2 \cdot dx$$

$$Bz_2 = \int_{-(3*w1+2*w2)}^{-(w1+2*w2)} dBz_2 \cdot dx$$

CD:

$$Bx_3 = \int_{-(3*w1+2*w2)}^{-(w1+2*w2)} dBx_3 \cdot dx$$

$$By_3 = \int_{-(3*w1+2*w2)}^{-(w1+2*w2)} dBy_3 \cdot dx$$

DA:

$$Bx_4 = \int_{-(3*w1+2*w2)}^{-(w1+2*w2)} dBx_4 \cdot dx$$

$$Bz_4 = \int_{-(3*w1+2*w2)}^{-(w1+2*w2)} dBz_4 \cdot dx$$

$$B_{IIx} = \sum_{i=1}^{4} B_{xi}$$

$$B_{IIy} = \sum_{i=1}^{4} B_{yi}$$

$$B_{IIz} = \sum_{i=1}^{4} B_{zi}$$

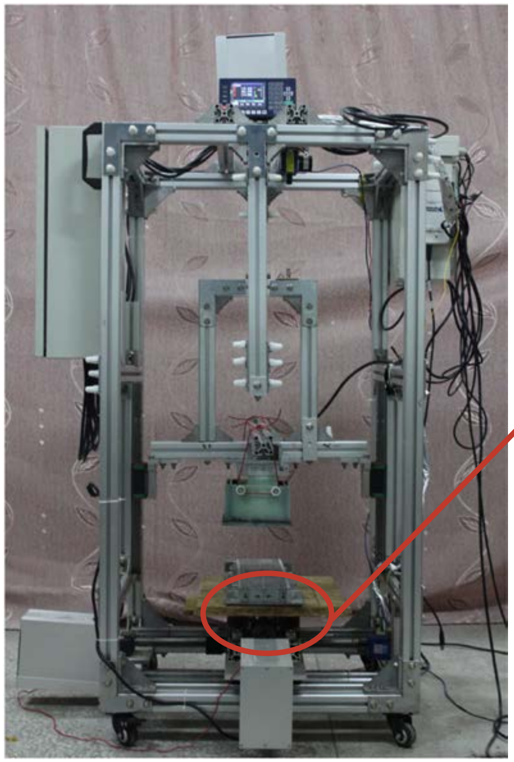
$$\boldsymbol{B}_{II} = B_{IIx} \cdot \boldsymbol{x} + B_{IIy} \cdot \boldsymbol{y} + B_{IIz} \cdot \boldsymbol{z}$$

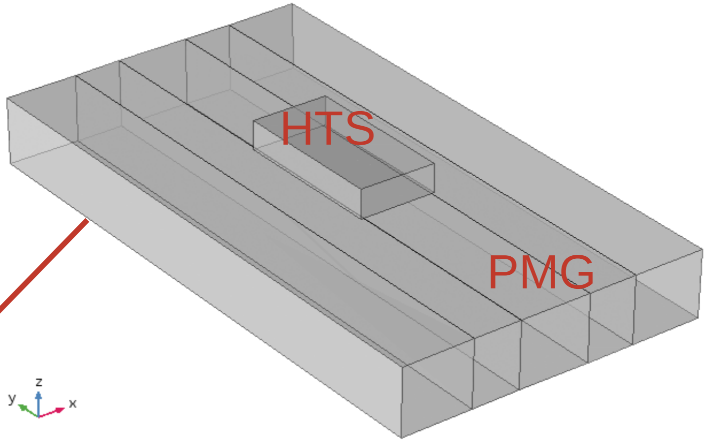
And so on for other PMGS:

$$\boldsymbol{B}_{total} = \boldsymbol{B}_{I} + \boldsymbol{B}_{II} + \boldsymbol{B}_{III} + \boldsymbol{B}_{IV} + \boldsymbol{B}_{V}$$

Electromagnetic Model

Experimental system





QUANTITY	VALUE
Height of HTS bulk (z direction)	13[mm]
Width of HTS bulk (x direction)	32[mm]
Depth of HTS bulk (y direction)	64[mm]
Deepth of PMG (y direction)	238[mm]

Thermal Model

H-formulation with thermal effect

$$\nabla \times (\rho \nabla \times \boldsymbol{H}) = -\mu \frac{\partial \boldsymbol{H}}{\partial t}$$

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

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

Thermal transient equation:

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

Connective boundary condition:

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

Symbol	QUANTITY	VALUE
k	Thermal conductivity [W/(m*K)]	(7.90506*1E-6*(T[K^-1])^3-2.17*1E-3*(T[K^-1])^2+0.17407*(T[K^-1])-0.21246) [W/m/K]
c	Heat capacity [J/(m^3*K)]	(73.75*(T[K^-1])^2+5599.78*(T[K^-1])+87669.311)[J/m^3/K]
h	Connective heat transfer coefficient [W/(m2*K)]	400 [W/(m2*K)]
T_c	Critical temperature [K]	92 [K]
T_0	Initial temperature [K]	77 [K]
Q	Joule heat [W/m^3]	/

Dynamic Model

Dynamic equations

$$F = \iiint_{SC} J \cdot B$$

$$F_z = \iiint_{SC} \left(J_x \cdot B_y - J_y \cdot B_x\right) d_x d_y d_z$$

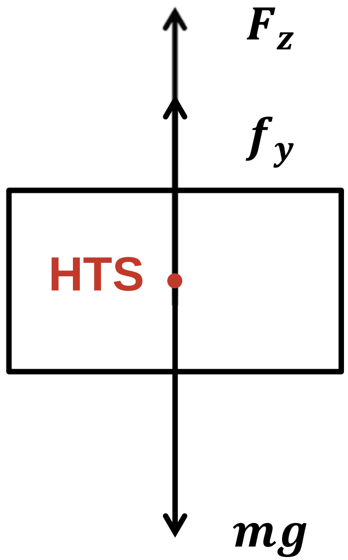
$$m\ddot{z} + F_z - mg = f_y$$

f_y: exciting force

z: vertical displacement (s_vibtarion [m])

$v = \dot{z}$, vibration speed [m/s]

$a = \ddot{z}$, acceleration [m/s^2]



Boundary condition

$$H = H_{self}(x, y, z) + H_{ext}(x, y, z)$$

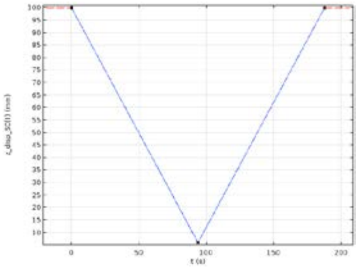
$$H = H_{self} + H_{ext}(x, y, z + s\_vibration)$$

Contents

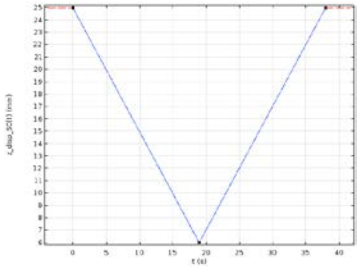
Validation of Electromagnetic Model

☐ 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: 1mm/s
- mf: (x,y,z)=((-90,0,6),(90,0,6))



ZFC z (t)



FC z(t)

Symbol	QUANTITY	VALUE
M	PM Magnetization	7.8*10^5 A/m
E_c	Critical current criterion	1·10^{-4} V/m
n	HTS parameter	21
J_{c0}	HTS parameter	1.8·10^8 A/m^2
B_0	HTS parameter	0.2 T
ρ_{air}	Air resistivity	1 Ω·m [Lahtinen2012]
μ_0	Air/HTS permeability	4π ·10^{-7} H/m

Validation of Electromagnetic Model

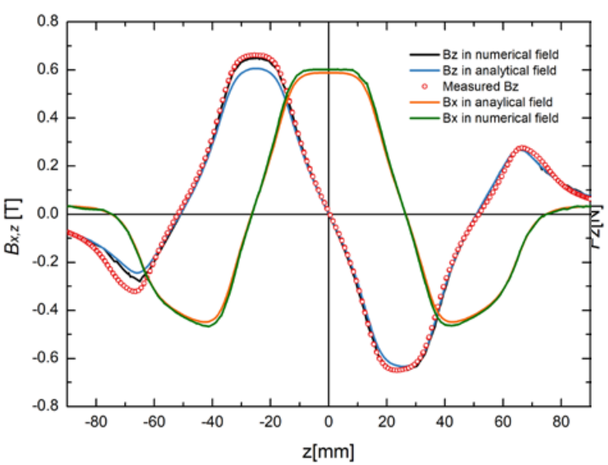
Results

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

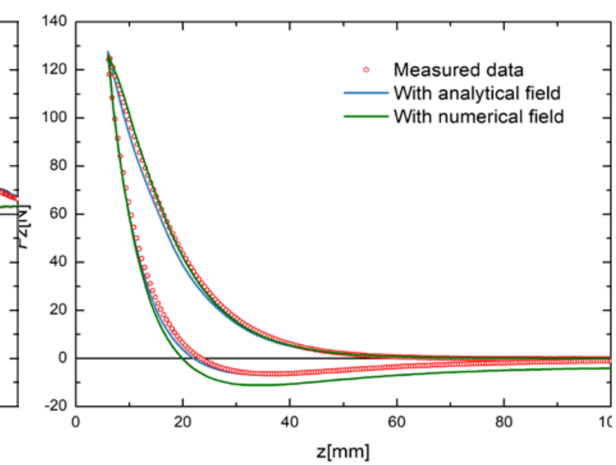
with analytical field: 18h

with numerical field: 20h

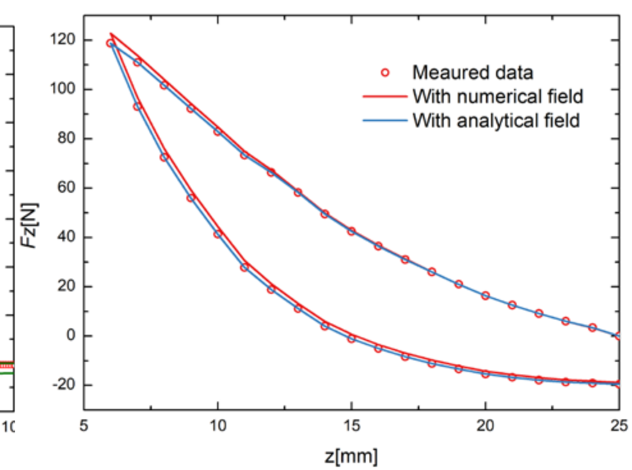
Model	Advantages	Disadvantages
with analytical field	1.Easy to build gap 2.Easy to extend halbach PMG in y direction	Long programming time and poor extendability
with numerical field	Fast implementation	1.Lots of meshes and extremely fine mesh in the gap 2. Long modeling time to extend PMG



Magnetic Field



Fz during ZFC



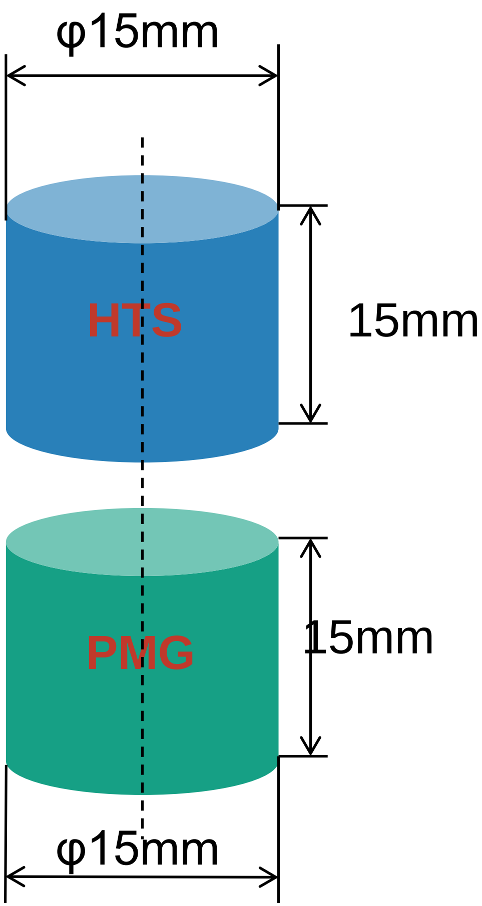
Fz during FC

Reference model

Reference model

- to reduce computing time
- Same parameters with electro-magnetic model ($m = 1kg$)
- Studied case: free vibration after field cooling

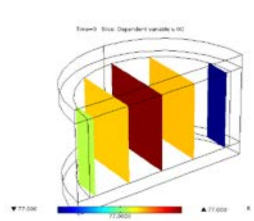
FC:(x,y,z)=((0,0,30), (0,0,10))



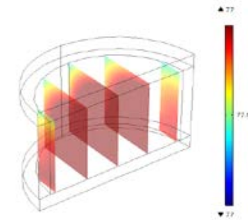
Thermal effect

Results

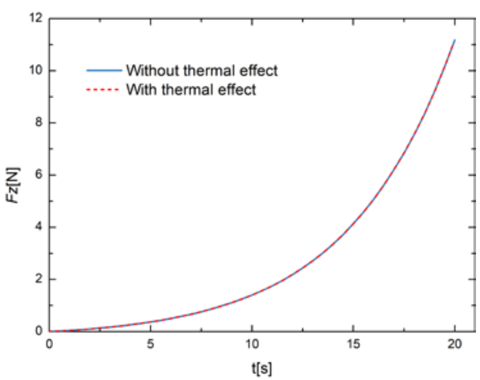
- Same levitation force during field cooling;
- Same trend during vibration, but different amplitude;
- Enormous difference in computing time: 6days for model without thermal effect; 11days for the model including it



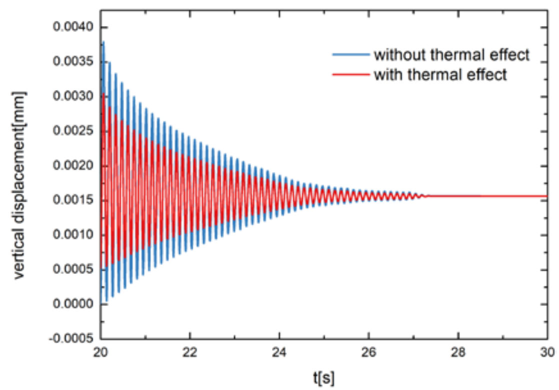
FC



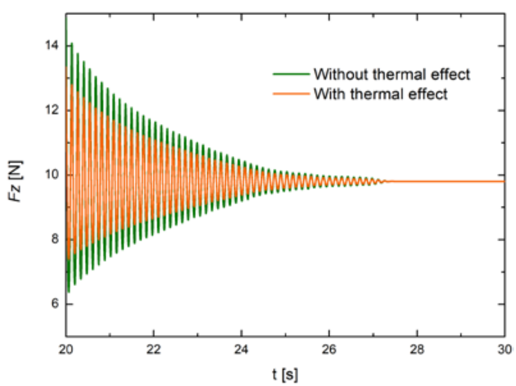
Vibration



Fz during FC



Vertical displacement during vibration

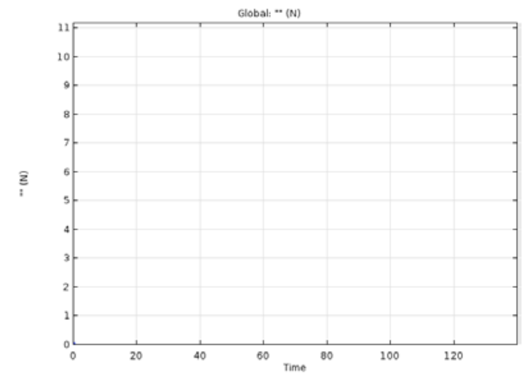


Fz during vibration

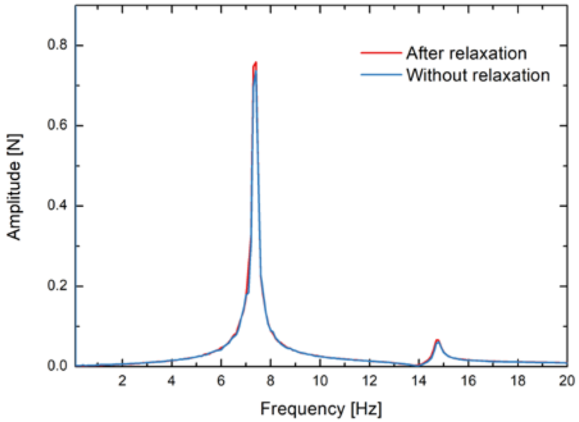
Relaxation

Results

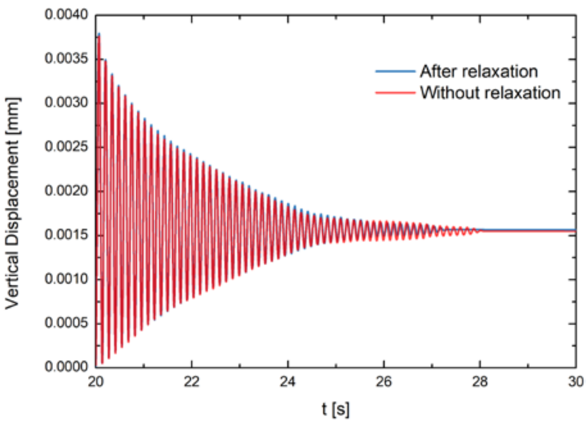
- Figure of model after 120s relaxation is moved forward parallel to t-axis
- Fz decay during relaxation;
- Little changes to nature frequency
- Almost same amplitude during vibration;
- Less time to get back to the stable regime



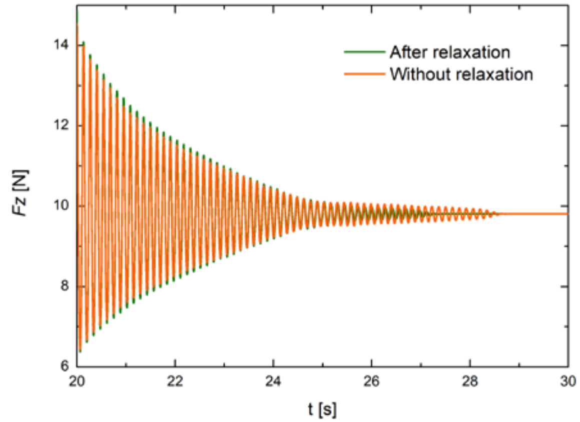
Fz during relaxation



A-F figure after FFT



Vertical displacement during vibration



Fz during vibration

Content

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**

Acknowledgments

Main collaborators:

Tianyong Gong (Master)

Manuel Perez (Master)

Changing Ye (Post Doctor)

Loïc Quéval (Assistant professor)

Guangtong Ma (Professor)

Foundations:

This work was supported in part by the National Natural Science Foundation of China, in part by the Sichuan Youth Science and Technology Foundation, in part by the State Key Laboratory of Traction Power, and in part by the Fundamental Research Funds for the Central Universities.

THANKS FOR YOUR ATTENTION

motor_yang@163.com