3D modeling of HTS tape stacks in superconducting magnetic bearings with real thickness

Asef Ghabeli, Francesco Grilli and Jens Hänisch
Institute for Technical Physics
Karlsruhe Institute of Technology
Karlsruhe, Germany
asef.ghabeli@kit.edu
francesco.grilli@kit.edu
jens.haenisch@kit.edu

Günther Fuchs and Oliver de Haas
evico GmbH
Dresden, Germany
g.fuchs@evico.de
deHaas@evico.de

Pengbo Zhou
[1]*Institute for Technical Physics*
Karlsruhe Institute of Technology
Karlsruhe, Germany
[2]*Southwest Jiaotong University*
Chengdu, China
pengbo.zhou@kit.edu

***Abstract*—Superconducting magnetic bearings (SMB)s offer a passive and contactless technique for rotating machines and, as linear bearings, for superconducting maglev systems. Stacks of superconducting tapes have been recently used as an alternative to the bulk. Modeling has been employed as a cost-effective, fast and reliable tool for improving the performance of SMBs. 2D models have been extensively used in the past, due to offering much faster computations compared to 3D models. However, using the 3D models is sometimes inevitable, especially when the depth of the problem geometry is comparable to the width and height or when the magnet guideway or the passive component geometries are complicated or asymmetrical. In this study, we employ an energy minimization method called MEMEP 3D, developed in C++, for modeling the magnetization of the tape stacks in three dimensions in a reasonable time. This method is significantly faster and more efficient than the previously proposed 3D methods giving the opportunity to model tens of HTS tapes with their real thickness with consideration of $J_c(B,\theta)$ dependence.**

***Keywords*—Tape Stacks, Magnitization of tape stacks, Numerical modeling, Superconducting magnetic bearing, Lorentz force calculation**

I. Introduction

The passive superconducting levitation of superconducting magnetic bearings (SMB)s is very promising for the development of levitated trains [1]. The advantage is that the generated repulsive force between the magnet guideway and the superconducting part is mechanically stable without using any control system, unlike the repulsive force between two permanent magnets (PM).

Bulk superconductors have been mostly employed as the passive component in SMBs [2]–[5]. However, recently, stacks of superconductor tapes have been utilized as an alternative for the bulks offering better mechanical properties, better thermal conductivity and a simpler production process. [6]–[8].

Modeling is a cost-effective, fast and reliable tool to optimize or improve the performance of the SMBs. This issue has been investigated in several studies using numerical methods or a combination of analytical and numerical methods. For performing the optimization process, the problem should be solved in a reasonable time, which makes the 2D models a more popular option. However, using a 3D model is sometimes inevitable for the following reasons: when the depth of problem geometry is comparable to the width and height, the 2D model usually leads to a large errors. Moreover, when the magnet guideway or the passive component geometries are complicated or asymmetrical, the 2D model would be either incapable of simulating or subjected to a large error. A fast and efficient 3D model that can be solved in a reasonable time period can be the solution of the above mentioned issues.

There are several numerical models with the purpose of reproducing the performances of tape stacks or cables made of stacks such as 2D models in [9]–[16] and 3D models in [17]–[19]. The 2D models take advantage of several strategies to reduce the computational load such as homogenization, densification and multi-scaling. However, these strategies have been mostly implemented and verified on 2D models due to the very high aspect ratio of the HTS tape and enormous numbers of degrees of freedom in 3D models.

In this study, we employ an energy minimization method called minimum electromagnetic entropy production method in 3D (MEMEP 3D), implemented in C++, for solving the problem of magnetization of tape stacks in three dimensions. This method had been presented and verified by experiments and other methods in several works [18]–[22]. We develop this method to calculate the levitation force between magnet and tape stacks in field cooling (FC) and zero field cooling (ZFC) cases and compare the results with experimental data. We investigate the implementation of strategies such as homogenization and densification and study the possibility of implementing the real configuration of tape stacks including modeling of each individual HTS tape with its real thickness and $J_c(B,\theta)$ dependence of the HTS tape. The

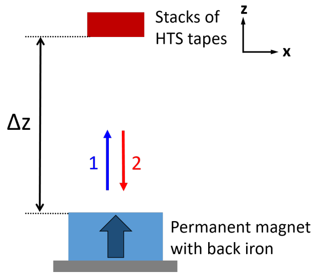

Fig. 1. Schematic of the problem

TABLE I
PROBLEM PARAMETERS INCLUDING PM GEOMETRY AND MOVEMENT, AND HTS STACKS OF TAPES CHARACTERISTICS

Permanent Magnet	Diameter	35 mm
	Height	20 mm
	Remanent flux density, B_r	1.22 T
Magnet displacement	2 mm $< \Delta z <$ 52 mm	
	Movement speed 1 mm/s	
2 Stacks of Tapes	Width	24 mm
	Depth	24 mm
	Height	10 mm
HTS Tape	Width	12 mm
	Thickness	76 µm
	Thickness of Superconducting layer	1 µm
	Tape Critical Current I_c	350 A
	Assumed n-value	25

non-superconducting layers in the stacks are modeled as a conducting material of very high resistivity.

II. Problem Description

Fig. 1 shows the schematic of the problem and Table I lists the parameters related to PM geometry and movement as well as characteristics of the stacks. The passive part of the SMB is comprised of two parallel stacks of SuperOx tapes, each one containing 132 pieces of tapes.

The first investigated case is ZFC in which the magnet traverses the distance from $\Delta z = 52$ mm, where the magnet is far enough from the stack so that the applied field is negligible, up to the distance of $\Delta z = 2$ mm and comes back to its initial position in a full cycle. The goal is to obtain the hysteresis force loop between stacks and PM. The force $\mathbf{F}$ is defined as the Lorentz force due to interaction between the PM magnetic field and the screening current generated in the HTS stacks of tapes:

$$\mathbf{F} = \int_v \mathbf{J} \times \mathbf{B}\, dv \tag{1}$$

where v is the volume of the HTS domain, $\mathbf{J}$ is the screening current in the HTS stacks, and $\mathbf{B}$ is the magnetic field of PM.

III. Modeling Results

As the first step, we use the homogenization process to obtain the force loop. Using homogenization, we transform the two parallel HTS tape stacks into a single homogeneous bulk. This is more convenient and faster in terms of computational speed. The calculation time is about one hour for one cycle.

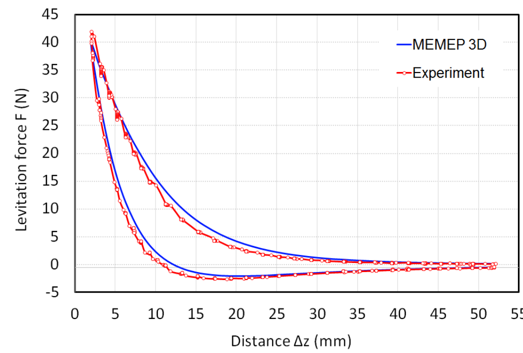

Fig. 2. MEMEP 3D bulk homogenization modeling results against experiment for the ZFC case

Due to unavailable $J_c(B,\theta)$ data of the SuperOx tape at the present time, we use the trial-and-error process to find the two parameters of isotropic Kim-Anderson model for describing the dependence of the critical current density of the HTS tape to the magnetic field [23]. Figure 2 shows the MEMEP 3D bulk homogenization modeling result against the experimental data in the ZFC case. Good agreement between modeling and experiment can be observed. We expect even better agreement when the measured $J_c(B,\theta)$ data of the tape is used instead of the Kim-Anderson model for defining the $J_c(B,\theta)$ dependence of the HTS tape to the magnetic field.

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