Emulation and experimental analysis of an axial superconductor magnetic bearing

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Abstract. Today the high-speed and high-performance systems are each more important for many areas like industry and transport system. The magnetic levitation system can be used to improve the performance. For super conducting levitation, it is important to know the behavior of levitation force. However, its behavior is not completely known and studies about it are necessary. This work presented a description of the test bench and a brief introduction to the new software developed to the magnetic levitation measurement system (SCML-02). The system tested is compound by a superconducting bulk and permanent magnet. This system makes data acquisitions using the load cells and the data processing is built by the new software developed in the LabVIEW. The results are verified and compared by simulations which were done in the software of finite elements and measurement data of the magnetic levitation done at Federal University of Rio de Janeiro - UFRJ. The measurements of the new system show compatible results with the simulations and the measurement data done at UFRJ. Therefore, with this new software, the users can easily to do magnetic levitation measurements through an interface easy to understand.

1. Introduction
High-speed and high-performance industries are developing ways to use the advanced in technology to improve its products, mainly in cost reduction, wear and efficiency. Magnetic levitation has been shown as an important tool, because it allows advantages in reducing losses, maintenance and reliability of the performance [1][2].

Magnetic levitation can be classified in Active Magnetic Levitation (AML), Passive Magnetic Levitation (PML) and Hybrid Magnetic Levitation (HML). These can be found into the industries of transport and the rotary machines. Each levitation technique has advantages and disadvantages and its use depends on the application.

PML is being of interest for not needing a loop control system for levitation. Technological advances and new materials have made these actions possible. Superconducting Magnetic Levitation (SML) and PML using a permanent magnet of Nd2Fe14B are a good examples. High temperature superconductors (HTSs) may be used in a wide variety of applications such as magnetic bearings, rotating machines and MagLev vehicle due to stability on all axes [3][4][5][6][7]. Permanent Magnet Passive Magnetic Levitation (PMPML) has limitations due to its instability, as shown by Earnshaw’s theorem. Nevertheless, this can be used for stability in an axis or the total stability, as in the case of the magnetic top consisting of a couple of the ring-shaped permanent magnets with relative velocity.
between them [8]. HML uses two or more levitation techniques, in which the technical characteristics each are integrated to reduce the losses and improve the performance [2][9][10].

It is necessary to have suitable tools to identify and study the technical characteristics of the magnetic suspension. These tools can be simulation or test bench. Simulation software is a widely used and reliable way to evaluate real phenomenon and design equipment without an excessive cost. Its results allow getting a good idea of the real product, but in some cases, it is necessary to check these results. Test benches are used to verify or evaluate the results obtained by simulation software [11].

In this context, the test bench at Applied Superconductivity Laboratory (ASCLab) of Southwest Jiaotong University (SWJTU) is under development and improvement aiming to simulate and verify the magnetic suspension prototypes developed. The first generation of magnetic levitation measurement system (SCML-01) was used by measuring the properties between YBCO bulk superconductors and a permanent magnet (PM) and PM guideway (PMG) [12]. An update of this equipment (SCML-02) was accomplished to improve the precision and allow to measure the magnetic properties of single and multi-HTS bulks when moved in three dimensions at one time [13]. These prototypes helped to build an HTS MagLev dynamic test system (SCML-03). SCML-03 is a dynamic test bench that can measure the levitation and guidance forces of a cryostat of the HTS MagLev vehicle when it is moving above of the PMG at 300 km/h [14].

With this in mind, this paper will focus on showing the software update being made on SCML-02. These improvements are looking to develop a test bench with high reliability and precision. More flexibility to programming and movement are also implemented. This new version of SCML-02 can be used to emulate some dynamic magnetic suspension movements. Experimental results showed the behavior of the movement and magnetic force were obtained by SCML-02. These results will be verified through the simulations and experimental results obtained in the Laboratory for Applied Superconductivity (LASUP) of Federal University of Rio de Janeiro (UFRJ).

2. Modeling of the HTS-PM system

There are many formulations that we can apply in the finite elements such as A-Ω, T-Ω, E-Formulation and H-formulation. When the simulations have a superconductor the relationship between electric field “E” and current density “J” is very nonlinear and its structure is also anisotropic. H-formulation works well with that behavior how we can see in [15][16], therefore we choose this formulation to work and this equation were implemented with COMSOL 5.1.

H-formulation can be written using the Faraday’s law, Ohm’s law and Ampere’s Law

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{H}}{\partial t} \]  
\[ \mathbf{E} = \rho \nabla \times \mathbf{H} \]  
(1)

Where \( \rho \) is the electrical conductivity and \( \mu \) is the magnetic permeability of material. Applying the equation (2) in (1) and organizing this equation, we have:

\[ \nabla \times (\rho \nabla \times \mathbf{H}) + \mu \frac{\partial \mathbf{H}}{\partial t} = 0 \]  
(3)

Comparing this equation with the equation General Form PDE in COMSOL, we can write

\[ e_a \frac{\partial^2 \mathbf{u}}{\partial t^2} + d_a \frac{\partial \mathbf{u}}{\partial t} + \nabla \cdot \mathbf{f} = 0 \]  
(4)

Where \( e_a \) and \( d_a \) are represent for tensors and \( \mathbf{f} = \begin{bmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \end{bmatrix} \). H-formulation can be writing how:

\[ \mathbf{u} = \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix}, \ e_a = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, d_a = \begin{bmatrix} \mu & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & \mu \end{bmatrix}, \ f = \begin{bmatrix} 0 \\ -E_z \\ E_y \end{bmatrix}, \ \Gamma = \begin{bmatrix} 0 & \rho & \rho \\ E_x & 0 & -E_z \\ -E_y & E_z & 0 \end{bmatrix}. \]
$E$ is the electric field vector $E = \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix}$ and it is calculated by Ohm’s law. Considering the $\rho$ constant for all axis $E = \begin{bmatrix} \rho J_x \\ \rho J_y \\ \rho J_z \end{bmatrix}$. The relationship of $E$ and $J$ in superconductors is given by $E = E_0 \left( \frac{\rho}{J_{c(B)}} \right)^n$ where $E_0$ critical electrical field and $J_c$ is critical current, therefore the electrical conductivity is $\rho = \frac{E_0}{J_{c(B)}} \left( \frac{\rho}{J_{c(B)}} \right)^{n-1}$ [15] and the relationship between $J$ and $B$ was modeled by Anderson-Kim: $J_c(B) = \frac{J_{co}}{1 + \frac{B}{B_0}}$ where $B_0$ and $J_{co}$ are constant. Figure 1 shows the division of domains used in the simulation.

3. Experimental

3.1. Magnetic levitation measurement system description
This system has three linear actuators, whose position is controlled by servo motors. The hardware of the magnetic levitation measurement system can be simplified, as showed in Fig. 2. This consists by a central processing, servo system used for each axis, the body frame of the SCML-02 and the load cells.
Central processing is developed in LabVIEW software, a graphical language of National Instrument (NI). This has two boards connected to the computer via PCI bus and may be synchronized via the real-time system integration (RTSI) bus. The NI 6036E board is used to acquire data of the load cells. Motion control 7344 board will be responsible for controlling movement of the servo motors.

The servo system configuration has the protection of the power supply line, noise filter, servopack of SGDM model and servo motor of SGMAH model. SGDM-04ADA servopack is used on each axis and its power supply is 200 V. Two servo motors are used, SGMAH-04AAA4 and SGMAH-04AAA4C. The difference between them is the use of the brake and it is used on the z-axis.

Body frame of the SCML-02 is shown in Fig. 3. The location of the servo motors of the x, y and z axes can be observed. Underneath the flat table is the counterweight to compensate the inertial force due to the moving parts. The base structure support for load cells shows the position of the load cells to measure the vertical force and the guidance force.

![Image of SCML-02](image)

**Figure 3.** Description of the SCML-02.

### 3.2. Description of the program and the HMI

The program used to update SCML-02 is developed in NI graphical language called LabVIEW and uses two boards to control the motors and to measure the force. Figure 4 shows the diagram blocks that describe the main program. This can be separated into two main parts. First part is for configuration and checking of the boards. The settings are by reading the file with the basic settings. After setup completed, it begins to check the work of each board. In the end of this stage, it is possible to look for problems with the boards before using the test bench. It can save time and wrong operation. Second part is a wait, where the program is waiting for the user to choose the action. This stage may be separated in four options, some modification of the setup, manual handling of the motors, programming and execution of the test, and exit of the program. HMI of the main program is showed in Fig. 5.

#### 3.2.1. A subsection

The modification of the setup is divided into two options. Changing the parameters of the drivers, such as the speed, acceleration and deceleration of the motor. The other option is to rewrite the file of the basic settings, as well as frequency of the acquisition, number of samples from average of the measure and parameters of linearization of the load cells.

#### 3.2.2. Manual handling of the motor

This subprogram is used to verify the correct movement of the motor and the measurement of the force. HMI of this subprogram is shown in Fig. 6. Two motion options are possible, linear or circular. In the linear motion, the user can control the distance and the axis of the movement. However, in the
circular motion just \( x \) and \( y \) axes can be moved, but the user chooses the radius and the circumference segment to move. This is used to aid for positioning of the target in the operating area for the test.

Load cells data are obtained from each channel and displayed in real time. These can be analyzed before the average or evaluate them with the average. If necessary, they can be saved for a future post-processing.

Information of the motors and position can be showed, as well as the user can remove the TARA before starting the test.

![Figure 4. Block diagram summarizing SCML-02 software.](image)

![Figure 5. HMI of the main program.](image)

3.2.3. Programming and execution of the test

Figure 7 shows the HMI used for programming and execution of the test. This HMI offers options for motion programming, save the test data, remove the TARA, choose which data to be displayed and position information for each motor. The motion programming button opens a new window with
options for building the motion path for each axis and the repetition number of the entire motion, as shown in Fig. 8.

Figure 6. Handling movement HMI.

Figure 7. HMI of the programming and execution of the test

Figure 8. HMI to motion programming.

3.3. Results

In order to validate the results obtained from the tests performed in SCML-02, the test bench of the Laboratory for Applied Superconductivity (LASUP) of Federal University of Rio de Janeiro (UFRJ) was used. For this test, the HTS bulk and the permanent magnet block will be used, where the permanent magnets and superconductors have similar characteristics in each laboratories. Both permanent magnets are the Nd-Fe-B N35 with approximately 0.3 T of magnetic flux density at 10 mm from the face. Dimensions are 47x49x95 mm$^3$ and 60x50x99 mm$^3$ for ASCLab-SWJTU and LASUP-UFRJ, respectively. The superconductors used are Y$_1$Ba$_2$Cu$_3$O$_{7-\delta}$ (YBCO) bulks with three seeds and dimension of 64x32x13 mm. Figure 9 presents the test benches assembled in each laboratory.

The test bench was programming to apply discrete displacements of 1 mm along the z axis between desired limits. Average magnetic levitation force is measured after this movement is completed.

In these experiments, the HTS is cooled with liquid nitrogen and obtained the maximum levitation force. For this, the zero field cooling (ZFC) is performed. This procedure requires the HTS is cooled in a position without any external magnetic flux. Therefore, the cooling air gap between HTS and permanent magnet is 90 mm. Figure 10 shows the comparison of the levitation force measured during the ZFC of both test benches and simulations.
Figure 9. Experimental test bench used to measure force. Details of the permanent magnet and YBCO bulk of the (a) ASCLab / SWJTU and (b) LASUP / UFRJ.

Figure 10. Comparative of the levitation force between the test benches of the (a) ASCLab / SWJTU and (b) LASUP / UFRJ.

4. Conclusion
This work presented a description of the test bench and a brief introduction of the new software developed to magnetic levitation measurement system (SCML-02). This software is a tool for students with an easy to use and update option for a wide possibility of testing.

Basic structure of the HTS and PM are used to verify the proper operation of SCML-02. The results obtained showed the correct work of the software and hardware. This is confirmed by comparing the results obtained on both test benches. For comparing these results, they were done with basically the same structure. Where the movement of the tests benches were done with the equal distance and the PMs that were used in the tests at UFRJ and SWJTU have the same magnetic density. Besides, those tests were done many times to verify if the results were kept the same. Then with it, the experimental results stay more reliable. After that, the results were compared with the finite element simulations, where it was used H-formulation to represent the behavior of the superconductor.

Moreover this work presented 3D model simulations used to represent the problem. These results showed that simulations represent an approximation the real behavior and good operation of the SCML-02 test bench. The differences between of the experimental results can be variations of the superconducting bulks or problems in the distribution of magnetic flux density. For this work, magnetic flux density was measured in eight points on the PM surface. The magnetic flux density on the surface of the PM will be checked more carefully.

However, more care should be careful consideration of treatment in the simulation to get better results. New experimental tests will be performed to verify the behavior of the SCML-02. For example, the test bench may be tested to obtain the guiding force. For this, the superconductor may be
cooled at different height and moved on the X-axis. These tests will help identify the scope what SCML-02 can achieve.

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