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Contactless suspension for cryogenic applications

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Abstract

Traditional cryogenic vibration isolators require elements in contact to isolate the suspended mass. Potential creep, plasticity or permanent elongation issues limit the number of times that these systems can be rebooted thermally. In addition, conducted heat coming from ground compromises the performance of suspended optic and electronic devices.

To provide passive vibration isolation and to eliminate heat conducted between the external interface and the suspended mass, a Superconducting Magnetic Suspension (SMS) has been developed by a consortium led by MAG SOAR. The lack of contact makes conduction of heat to be zero. An additional advantage of the SMS is that the energy is dissipated on ground and consequently does not influence the suspended mass.

Individual test results have shown that the technology is a promising candidate to future cryogenic space instruments [1]. Based on the lessons learn during the component design, four components have been designed and manufactured at MAG SOAR facilities to support a 12 kg Focal Plane Array (FPA) in cryogenic space-based instruments. An example of a mission utilizing a cryogenic FPA would be the planned X-ray observatory ATHENA. The vibration isolator and thermal disconnect can be scale up and re-design depending of the desired suspended mass.

Introduction

The use of High Temperature Superconductors (HTS) has been continuously growing in recent years. The application range is very wide, it includes high technology devices (some kinds of particle accelerators, as Spallation Neutron Source [2], and Nuclear Magnetic Resonance and Magnetic Resonance Imaging machines [3]) and simple applications like positioning mechanism [4] and journal and linear non-contact bearings [5-6].

In this paper, a Superconducting Magnetic Suspension (SMS) is presented. To better understand the concept proposed, in the figure below it is shown the main parts that form the SMS.

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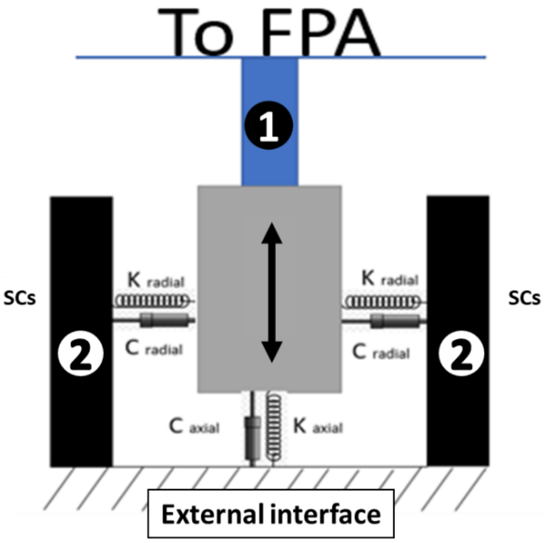

Figure 1: SMS schematic representation

The first part (1) is a shaft composed of SmCo permanent magnets which is connected to the suspended mass. The other part (2) is fixed to the external interface and contains an array of polycrystalline melt textured YBa2Cu3O7 rings manufactured by CAN SUPERCONDUCTORS (https://www.can-superconductors.com/). The SMS is activated when the superconductors are below their critical temperature. A Hold Down Release Mechanism is required to maintain the suspended mass when the superconductors (SCs) are above its critical temperature.

Magnetic devices for space and cryogenic applications are an attractive solution due to the following characteristics:

- Lack of contact and zero thermal conductivity.
- Lubrication is not needed.
- No debris is generated.
- The damping power is dissipated in the outer part.
- Inherent overload protection among others [7-9].

In this particular device, the capacity to prevent power dissipation in the core and the turnability of the damping coefficient are also very valuable. In this paper, the results of the test campaign in an environment similar to the working conditions (high vacuum and cryogenic temperatures) are presented. These results demonstrate the compliance with the requirements specifications for vibration isolation and thermal disconnect.

Objective of LEVISOLATOR project

The objective of this project is to develop a vibration isolator system to minimize the sensitivity to external vibrations of a 12kg Focal Plane Array (FPA). This vibration isolator system is formed by an array of 4 SMS.

Two main features of the technology are:

1. Vibration isolation. The four SMS together have to isolate vibrations by a factor of 10 at 30 Hz (project requirement defined by the Statement Of Work). In Figure 2 it is presented the expected transmissibility curve on radial direction for the 6 degrees of freedom (DOF) system (black line) and the transmissibility curve (green line) for one component by considering a 3% damping ratio. In 6 DOF curve there are three peaks which corresponds with the different modes of the suspended mass in that excitation direction.

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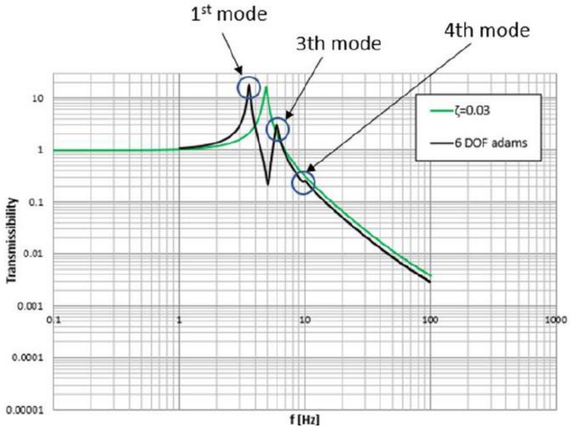

Figure 2: 12 kg FPA transmissivity from 0 to 100 Hz

2. Zero thermal conductivity. The technology eliminates thermal conductivity between the external interface and the suspended equipment (i.e. the FPA). This requirement makes the SMS the most adequate solution when heat is a limitation for the correct operation of some equipment (for example, electronics or optical devices). In the next figure, the superconductors (orange line) are cooled down to 10.78 K, while the PMs shaft (blue line) is at room temperature during all the test.

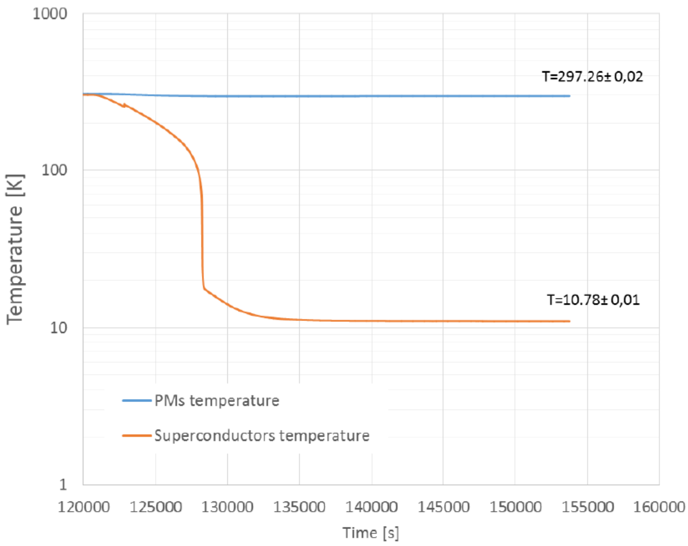

Figure 3: Thermal disconnect feature (null thermal conductivity)

The SMS is design to work in two different scenarios:

1. Orbit scenario: FPA is located in its orbit position (Z_{min}=0 mm).
2. Ground scenario: The FPA can move a maximum of 3.5 mm in axial direction (Z_{max} = 3.5 mm) due to gravity.

With these two working situations, it can be defined an equivalent stiffness (K_{eq}) of each component as (equation 1):

$$K_{eq} = -\frac{F_{max} - F_{min}}{Z_{max} - Z_{min}} \tag{1}$$

Where F_{max} is the force which correspond to Z_{max} and F_{min} is the force in corresponding with Z_{min}.

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Once finished the component test campaign, the next step within LEVISOLATOR project is to isolate vibrations in the 12 kg FPA as well as guarantee thermal isolation. Axial and radial directions will be evaluated by inducing a harmonic micro-vibration from 0 to 100 Hz by means of a piezoelectric actuator model APA 120ML-PP. The set up for this step is shown in the next figure (Fig. 4):

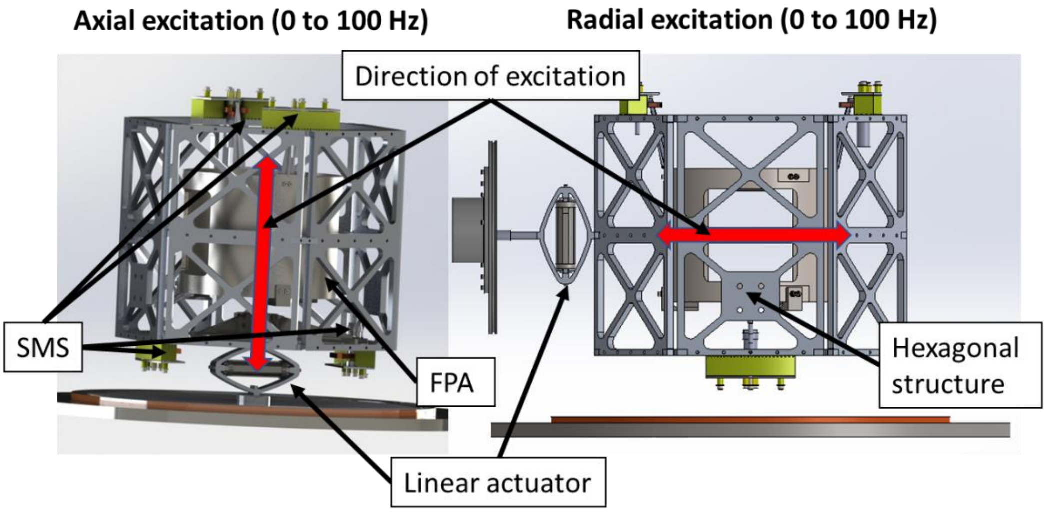

Figure 4: Axial and Radial test bench for FPA characterization

Transmissibility will be characterized by relating the acceleration of the input excitation (hexagonal structure of Figure 4) and the acceleration of the suspended FPA. Two triaxial accelerometers will be placed on the FPA and in the input structure in order to address the 6 DoF of each body. Hence, the transmissibility of the two bodies can be related by the following equations:

$$Input \longrightarrow \|\ddot{U}_{hex.structure}\| = \bar{X} \cdot 4\pi^2 f^2 \tag{2}$$

$$Output \longrightarrow \|\ddot{U}_{FPA}\| = T(f) \cdot \bar{X} \cdot 4\pi^2 f^2 \tag{3}$$

$$Transmissibility = \frac{\|\ddot{U}_{hex.structure}\|}{\|\ddot{U}_{FPA}\|} = \frac{T(f) \cdot \bar{X}}{\bar{X}} \tag{4}$$

Experimental set-up

For the design of each SMS, the first test to perform is at LN2 temperature. The objective of this test is to characterize the load capability of each component as well as stiffness (among other properties). The test bench shown below allows axial and radial component characterization at LN2 temperature (Fig. 5).

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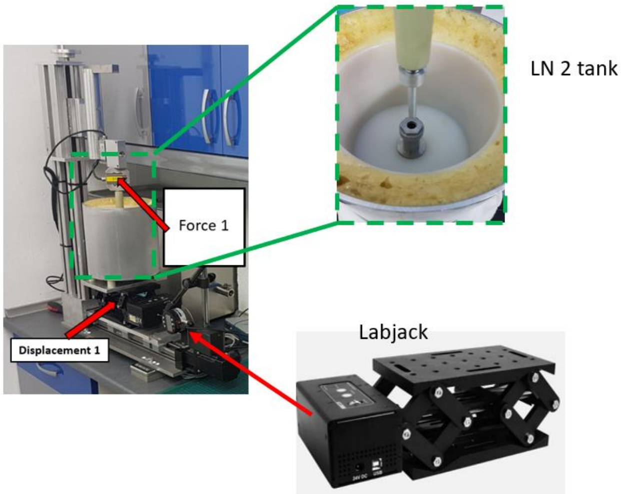

Figure 5: The LN2 test bench for component characterization

For LN2 characterization, the SMS is rigidly linked to a LN2 tank and centred with respect the PM shaft. The Labjack depicted in the figure above moves vertically the LN2 tank. The PMs shaft is keep it stationary and are linked rigidly to a load cell. For accurate positioning, initially contact is reached by carefully moving the Labjack till a peak of force is observed. This point is kept it as reference (taking into thermal contractions). LN2 is added to the LN2 tank to activate the magnetic properties of the component.

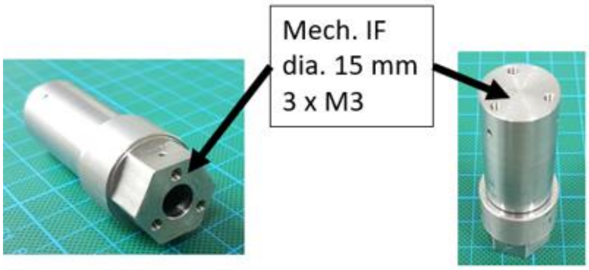

Figure 6: SMS manufactured by MAG SOAR.

The next step is to test each SMS at 15 K and high vacuum (1e-7 mbar) conditions. To reach these conditions, the cryostat property of MAG SOAR has been used (Fig. 7). The cryostat is formed by:

- A thermal vacuum chamber
- A Cold Head model SRDK-4082D2-F50H
- A scroll pump model nXDS12i from Edwards
- A turbomolecular pump model TurboVAc 450i from Leybold

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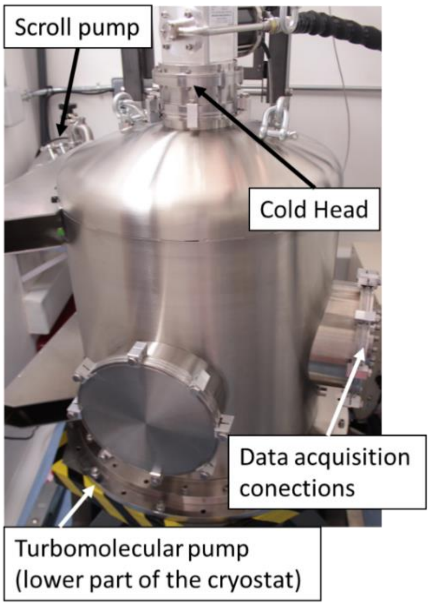

Figure 7: Vacuum chamber with 4K Cold Head

Inside the chamber, a Voice Coil actuator model VCS06-500-CR-01-MC from H2W technologies is installed. The actuator will be used for component characterization inside the vacuum chamber. The Voice Coil is provided with a linear magnetic encoder from Renishaw to position the PMs shaft. The actuator has a stroke of 16 mm and a resolution of 1 micron. A magnetic shield has been designed and installed inside the chamber to minimize the magnetic contamination of Voice Coil in the components during the tests.

Axial and radial forces are measured using a traction-compression load cell. The cell is connected to the SmCo shaft and to the Voice Coil actuator. The measuring range of the load cell is 50 N and the linearity error is 0.1%. The temperature is recorded using a PT100 sensor in the shaft and a silicon diode model DT-760 from Lakeshore in the superconductors. In the next figure (Fig. 8) it is presented the main parts of the test bench used for component test characterization.

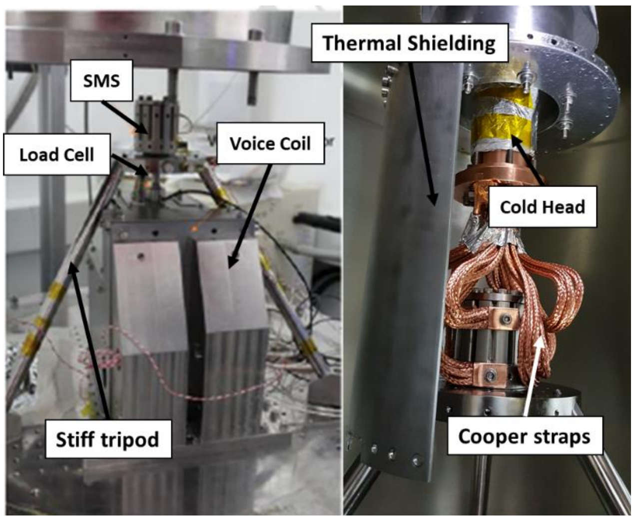

Figure 8: Axial characterization test bench

The experimental characterization campaign is based on the quasi-static motion of the SmCo permanent magnets in axial and radial direction of the SMS keeping the superconductors fixed to the external interface.

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Results

In the following figure, the characteristic curves for each of the four SMS developed for FPA vibration isolation are presented. The average stiffness of each SMS is calculated as -9198 N/m and the standard deviation is 156.7 N/m. The total load capability of the four SMS is 120 N in order to have a static deflection lower than 3.5 mm (project requirement).

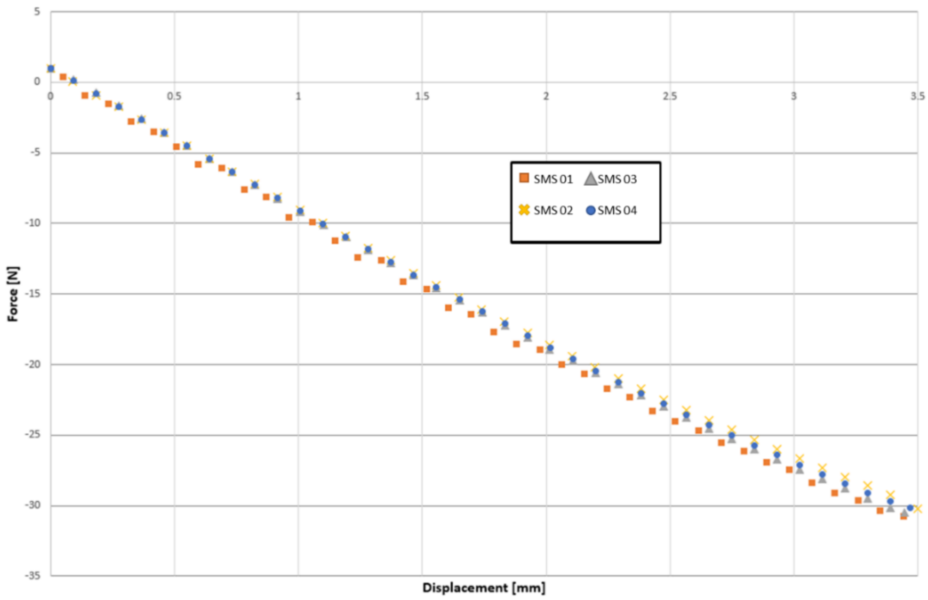

Figure 9: Characteristic curve for each SMS.

Damping test

To characterize the damping ratio of the SMSs, it has been designed and manufacture a specific set up that allows free oscillation test. This set up is presented in the figure below (Fig. 10).

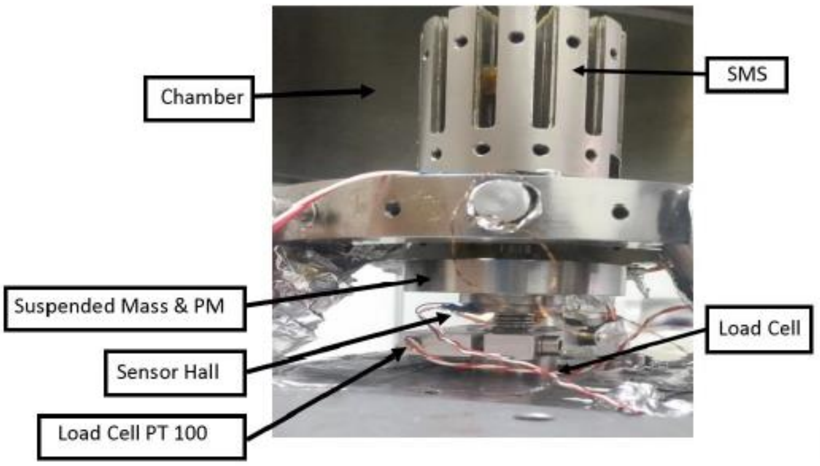

Figure 10:Free oscillation test-bench

First of all, the suspended mass attached to the shaft of permanent magnets is positioned using the Voice Coil actuator and all the system is cooled down until 15 K are reached. In that point, the actuator is switched off and the suspended mass is free to move up and down until the equilibrium position is reached. In the figure below it is presented the free oscillation of the suspended mass versus time from the time. It is observed that after a sudden event, the SMS reached its equilibrium position.

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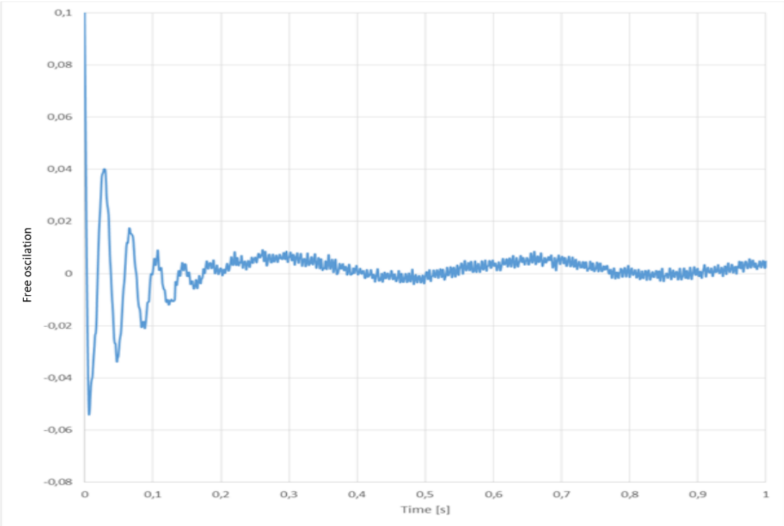

Figure 11: Free oscillation vs. time

Two different frequencies are identified in the signal. A main frequency contribution at f= 25±1 Hz, corresponding to the axial damped first mode and an additional frequency contribution at 2.5±0.2 Hz which might be an harmonic of the first eigenfrequency.

Frequency [Hz]	Damping ratio (in terms of the suspended mass)	Damping coefficient [Ns/m]
25	0.11±0.04	11±4
2,5	0.04±0.01	4±1*

*Assuming that all the suspended mass is participating in this mode and a stiffness of 8000 N/m

Note that the dissipated energy in the system can be estimated as:

$$W = C \cdot V^2 \tag{5}$$

where C is the damping coefficient and V is the velocity of the harmonic excitation. It can also be expressed as:

$$W = C \cdot \mathrm{A} \cdot (2\pi f)^2 \tag{6}$$

Where A is the amplitude of the oscillation and f the frequency of the excitation. Assuming that both oscillations present a similar order of magnitude on the oscillation, the power dissipation ratio between both modes is:

$$r = \frac{W_{25Hz}}{W_{2,5Hz}} \approx 300 \tag{7}$$

Therefore, dissipation in the secondary mode (2,5Hz) can be neglected with respect to the main one. In conclusion, the total damping ratio was 0.04

Conclusions

In this paper, a new contactless Superconducting Magnetic Suspension (SMS) for cryogenic space mission has been presented. The lack of contact between parts makes this product to have zero thermal conductivity between ground

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and the suspended equipment. The SMSs presents constant load and stiffness capabilities below 30 K. Damping can be customized and mechanical vibration power is dissipated exclusively in outer part– preventing heating of the suspended equipment.

MAG SOAR know-how and previous heritage allow to design a device capable of isolate vibration by a factor of 10 at 30 Hz and to eliminate thermal conductivity between ground and the suspended equipment such as FPA. The vibration isolator and thermal disconnect can be scale up and re-design depending of the desired suspended mass.

Acknowledgements

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