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Design and analysis of a non-hysteretic passive magnetic linear bearing for cryogenic environments

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Abstract

In this study, the mechanical design and analysis of a magnetic levitating linear bearing suitable for working in the non-hysteretic range of forces is presented. The semi-cylindrical design of the superconductor provides stable equilibrium positioning and restoring forces in all degrees of freedom except for two with a cylindrical magnet floating along the axis of revolution/displacement. Using finite element analysis, it has been proven that the magnet can float stably and passively in a complete non-hysteretic Meissner state. This non-hysteretic passive linear bearing could be suitable for long-stroke precision positioning. The high translational symmetry of the magnetic field seen by the superconductor assures a usable long stroke of around ± 90 mm with full performance and ± 150 mm with reduced performance. This linear bearing in combination with an actuating system for only one degree of freedom could be used for accurate precision positioning systems for cryogenic environments with zero hysteresis in the movement.

Keywords

Contactless mechanism, frictionless linear bearing, cryogenic mechanism; superconducting magnetic levitation, self-stability

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Introduction

The space and aerospace industry, optical communication, and bio-medical precision industries are increasingly demanding precise mechanisms that are able to work in cryogenic environments ($T < 100$ K).[1] The signal/noise ratio in any sensor usually increases as the temperature decreases, hence cryogenic environments are quite desirable for accurate and precise measurements such as those required for far infrared interferometer spectroscopy.[2,3]

At very low temperatures, conventional mechanisms present tribological problems in bearings and joints like backlash, cold spots, fatigue, and wear.[4,5] Only solid lubricants such as PFTE or MoS2 can be a solution at low temperatures.[6,7] However, for long life-time operation solid lubricants turn out not to be a reliable solution.

Frictionless levitation bearings have been proposed as a tribological solution to wear and fatigue.[8–10] There are several kinds of bearings that use levitation in order to avoid contact between rotatory parts like air bearings, magnetic bearings or superconducting magnetic bearings. Nevertheless, not all kinds are suitable for cryogenic environments. For instance, it is not possible to use hydrodynamic or air bearings for low temperature applications because the fluids freeze in these conditions.[11] Active magnetic bearings (linear or rotatory) require active generation of the magnetic forces applied by coils.[12–14] The currents circulating in these coils produce a heat flux into the systems, which is something undesirable in cryogenic environments. Passive magnetic bearings based on magnetic parts are mainly unstable in at least one direction, so they always need a conventional bearing to hold against this instability; thus typical low temperature tribological problems again appear,[15,16] except in some special cases.[8,17]

Devices based on superconducting magnetic levitation (SML) seem to be a suitable option for actuators and positioners in cryogenic environments. SML provides self-stable levitation of a permanent magnet

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(PM) over a high temperature superconductor (HTS).[18,19] At cryogenic temperatures, HTS are naturally in the superconducting state and no cooling power is required. However, only little attention has been paid to positioners based on this technology. Some kinds of conveyors have shown reasonable results with strokes of not more than a few mm and resolutions in the micrometer range.[20,21] Recently, a linear bearing based on SML is being investigated, where the authors claim to achieve a maximum stroke of 18 mm in one direction with very high resolution.[22,23] The main limitation of precise non-contact linear sliders is that the stroke is limited to several millimeters.

Nevertheless, so far most of the experimental mechanical devices based on SML have kept superconductors not in the Meissner but in the mixed state. In this case, the magnetization of the superconductors provides the desired contactless stability region but together with undesired hysteresis when moving away from the stable position.[24]

On the contrary, the magnetization of a superconductor in the Meissner state is non-hysteretic and, consequently, so too are the levitation forces. A pure Meissner state does not produce friction at all. How to design stable levitating mechanisms while keeping the superconductor in the Meissner state is an open challenge, with multiple potential uses such as in precision positioning or magnetic confinement.[25]

In the present work, the mechanical design of a magnetic levitating linear bearing suitable for working in the non-hysteretic range of forces is presented. A drawing of the geometrical configuration of the device is given in Figure 1. The semi-cylindrical design of the superconductor provides stable equilibrium positioning and restoring forces in all degrees of freedom (DOF) except for two (rotation and displacement along *X*) with a cylindrical magnet floating along the axis of revolution/displacement.

An analysis of forces and pressures based on finite elements for each direction has been developed, demonstrating the equilibrium as a stable position of the linear bearing. The radial and axial stiffness of the bearing have been calculated.

Figure 1. Drawing of the linear bearing: Magnet over a superconductor in the Meissner state.

Moreover, the calculation of the maximum pressures and thus the magnetic field applied for each position of the displacement proves that it can operate at 100 K or below depending on the superconductor material used. With an appropriate selection, it can be assured that a complete Meissner state occurs; hence the displacement will be completely non-hysteretic. This linear bearing could hold the magnet floating over and it would allow a non-hysterical movement of the magnet.

Even if the vertical load capability of the slider is reduced, having a front surface of the magnet of 12.56 mm^2 could be enough for a laser beam such as those used in precision positioning measurements. This makes this system an attractive configuration for nano and micro-load positioners and interferometric devices

This non-hysteretic passive linear bearing could be suitable for long-stroke precision positioning because the length of the motion range can be easily modified by simply increasing the length of the semi-cylindrical superconducting guideline. This linear bearing in combination with an actuating system for only one DOF could be used for accurate precision positioning systems for cryogenic environments with zero hysteresis in the movement.

Mechanical behavior of a magnet-superconductor mechanism in the Meissner state

The mechanical behavior of a magnet-superconductor mechanism in the Meissner state is very different from the behavior of the same permanent magnet levitating over a superconductor in the mixed state, as can be seen in Figure 2.

When a magnet approaches a superconductor, a purely repulsion force starts to arise. Up to a certain point, defined as the lower critical field, the path followed by the magnet is completely reversible, i.e. no hysteresis in the mechanical behavior appears because the superconductor behaves as a perfect diamagnetic material. However, if the magnet goes beyond this point, into the mixed state, the higher magnetic field starts to magnetize the superconductor bulk and so an attractive force also appears. This magnetization of the bulk generates a hysteretic behavior in the displacement of the magnet. In fact, thanks to this property it is simple to obtain stable levitation points. Also the load capacity is higher in the mixed state. Nevertheless, the hysteretic mechanical behavior of the mixed state is a problem when designing this kind of mechanism and its control. Thus, designing a passive stable mechanism operating in a complete Meissner state can offer an advantage for precision mechanisms.

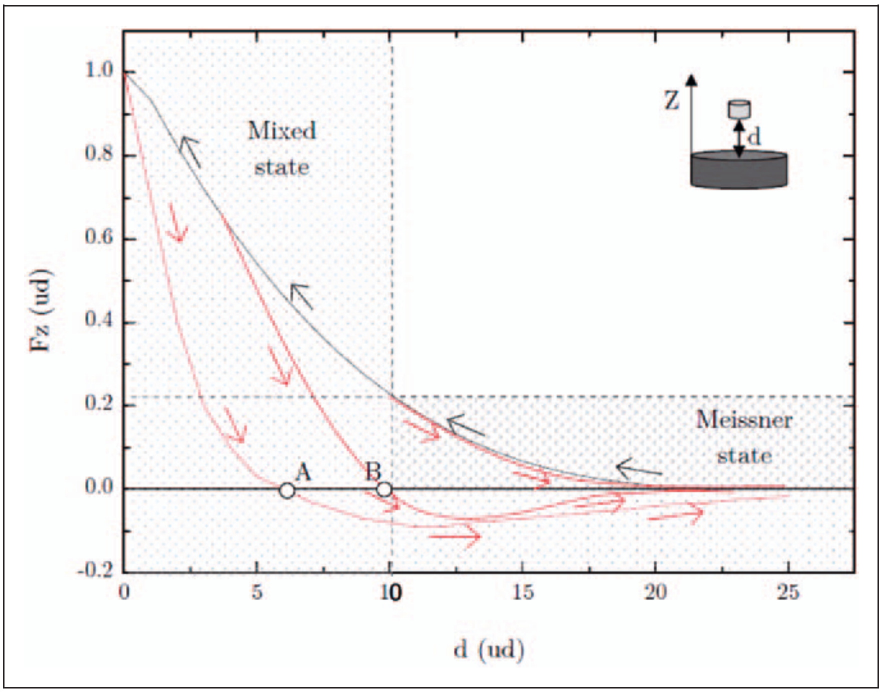

Figure 2. Mechanical behavior of a magnet over a superconductor.

It is also possible to obtain equilibrium levitation positions and direction working in a complete Meissner state. In order to achieve a stable and passive displacement direction, it is necessary to summarize some design rules for a magnet-superconductor mechanism in the Meissner state obtained from various literatures:[26–31]

- A magnetic dipole is always repelled by a superconducting surface.
- A magnetic dipole tends always to be oriented parallel to a superconducting surface.
- A magnetic dipole tends always to be oriented tangential to a curve superconducting surface.
- The force decays to the power of four with distance.
- The sum of the magnet-superconducting surface forces can generate stable or unstable levitation positions.
- A stable levitation position can be obtained by adequate design of the superconducting surfaces such as in a torus.

This set of rules provides the mechanical engineer with some tips and fast considerations for the design of this kind of mechanism. However, there is still a need for quantitative evaluation using analytical or numerical tools.

Mechanical design and analysis of the linear bearing

The design of a levitating mechanism for a linear displacement must consider greater stiffness or restoring forces in all DOF except the displacement one. Considering that, and considering the first tip for the mechanical design (always repulsive forces), it seems logical to think about a superconducting surface with a "U-shape" in order to have lateral boundaries for guiding the displacement and a lower boundary to provide the levitation load. Considering also that a magnetic dipole always tends to align itself parallel to any superconducting surface, it is reasonable to select a magnetic dipole orientation perpendicular to the "U shape" plane, i.e. parallel to *X* direction. In this way, the dipole will tend always to be perpendicular to this plane.

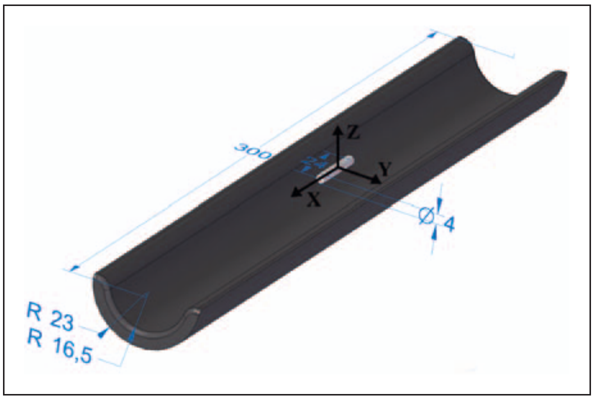

Figure 3. Geometrical definition and coordinate system. Magnet polarization direction parallel to *X* direction.

The exact definition of the mechanical design is presented in Figure 3.

The length of the superconductor (300 mm) was set to have a large displacement range far from the border where the lift force and restoring forces are supposed to be reduced.

A numerical analysis using finite element software was developed in order to calculate the exact equilibrium position, to characterize the expected stiffness and to check the linear bearing behavior. The superconductor was simulated considering the bulk as a perfect diamagnetic material and the magnet as a hard magnetic material with high remanence and coercivity. The magnetic material chosen for the magnet was NdFeB with 1.25 T remanence.

Results and discussion

The analysis started by setting the center of coordinates at the center of the semi-cylindrical circumference and in the middle of the total length. From this initial position, the magnet was displaced and the magneto-mechanical analysis was done.

As the superconducting guide is much longer than the magnet, for the first analysis the border effects and thus forces and displacements in X direction were disregarded. A second stage of analysis studied this part in detail afterwards.

Equilibrium levitation position

The lift force (force in Z direction) was calculated for different positions of the magnet from the centre ($Z = 0$ mm) and above in order to set the height at which the lift force can compensate the weight of the magnet. The results are displayed in Figure 4.

It can be determined that at 2.3 mm height from the center, the levitation force is enough to compensate the weight of the magnet. At this height, the maximum tangential magnetic field calculated is 6775.85 A/m. This maximum magnetic field is far from the lower critical field (Meissner state limit) for superconductors like YBaCuO (9223.2 A/m) or Ti2223 (8234.45 A/m) at relatively low temperatures (100–50 K),[32–36] so it is assured that a complete Meissner state can occur. The lower critical field is higher when the temperature decreases. Other conventional superconductors like lead or aluminium have critical fields that are also larger than the calculated values.

This linear bearing could hold the magnet floating over and it would allow a non-hysteretic movement of the magnet.

Passive stable position

From the previous equilibrium position ($Z = 2.3$ mm, $X = 0$ mm) the magnet was displaced along Y direction in order to determine the value and direction of the lift and lateral forces (Fz and Fy). Both the results are presented in Figure 5.

As expected, the lateral force is negative, which means that a restoring force appears towards the initial equilibrium point. Therefore a passive and stable levitation position occurs. It is also noticeable that the lift force is even higher for Y displacement so the levitation is assured for lateral run out positions.

The maximum magnetic field was also analyzed for this displacement (Figure 6).

Depending on the superconductor selected, the results of Figure 6 provide the maximum admissible lateral run out to assure a complete Meissner state and so a non-hysteretic passive magnetic linear bearing. For example, an YBaCuO at 50 K could hold up to 9223.2 A/m without overpassing the Meissner state.

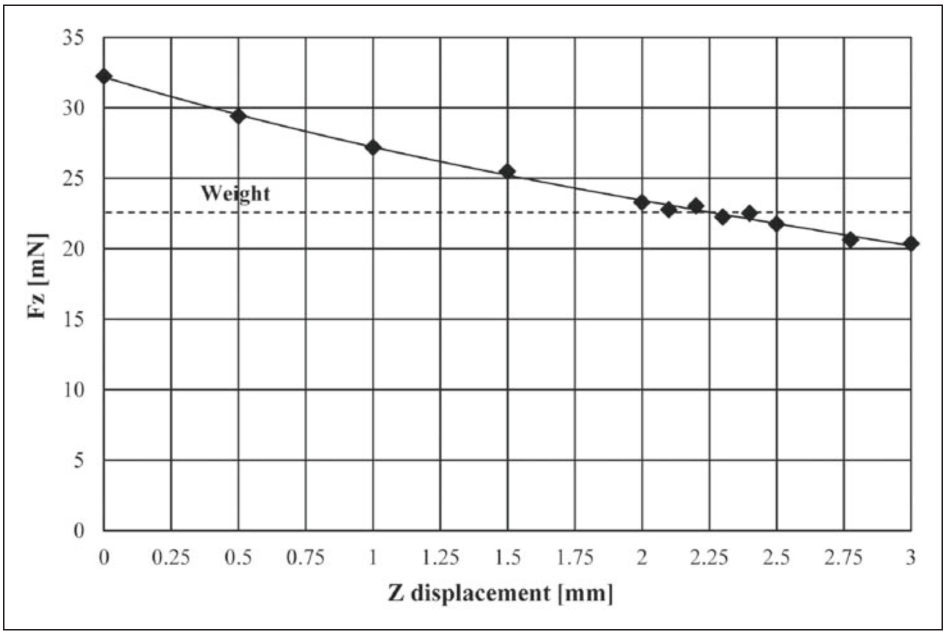

Figure 4. Lift force (Fz) versus Z displacement for $X = 0$ mm and $Y = 0$ mm.

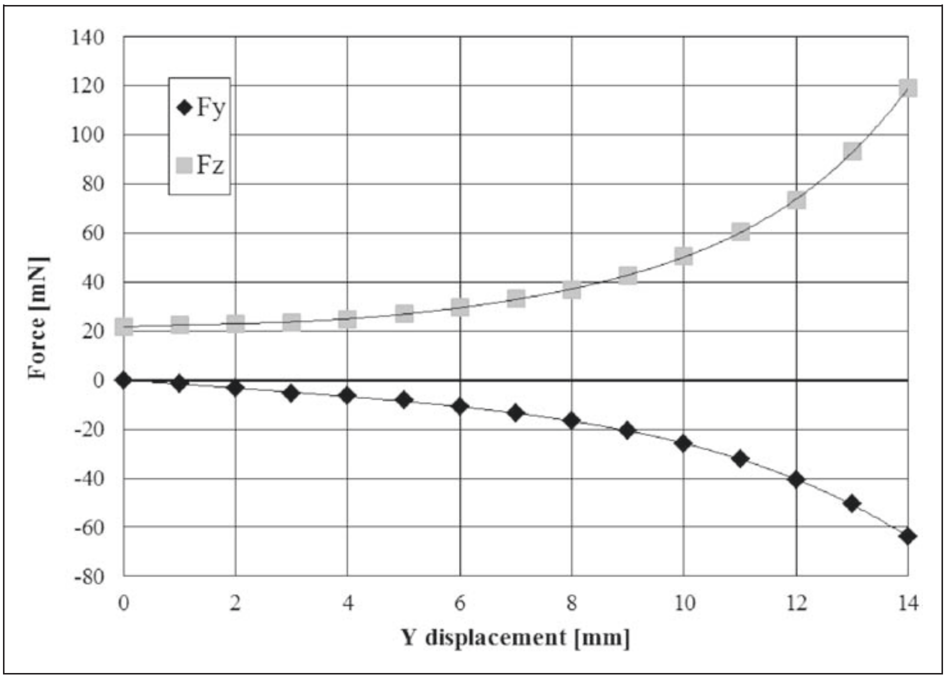

Figure 5. Lift force (*Fz*) and lateral force (*Fy*) versus *Y* displacement for $X = 0$ mm and $Z = 2.3$ mm.

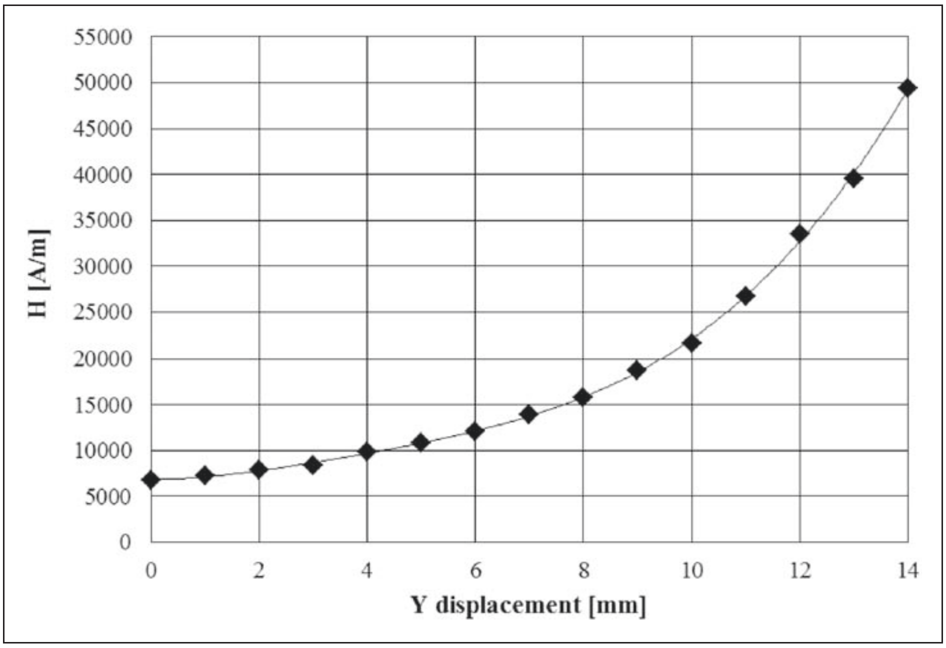

Figure 6. Maximum magnetic field versus *Y* displacement for $X = 0$ mm and $Z = 2.3$ mm.

For the linear bearing to be useful the permanent magnet needs to be stable against rotational torques, both along y (pitch) and z (yaw) directions. The rotational stiffness calculated around the centered equilibrium position were $RSy = -8 \times 10^{-5}$ Nm/rad and $RSz = -4 \times 10^{-5}$ Nm/rad. Both the stiffnesses are negative, which means that if small rotations around Y and Z occur, there will be a self-alignment torque in the horizontal position.

As the magnetic polarization is parallel to X direction, the rotation around this direction generates no counter torque because of the symmetry.

Border effect

Due to the high translational symmetry of the magnetic field seen by the superconductor for any X positions of the magnet, the superconductor and the magnet form a kinematic pair such that a "sliding path" is established in X direction. However, this only happens when the magnet is far from the borders

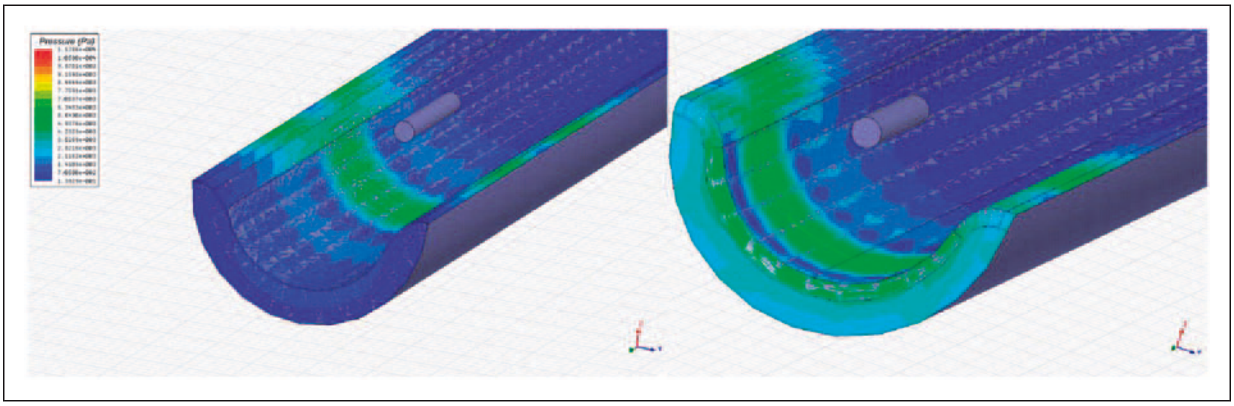

Figure 7. Pressure of the magnet over the superconductor for a usable stroke position (left) and close to end of stroke position (right).

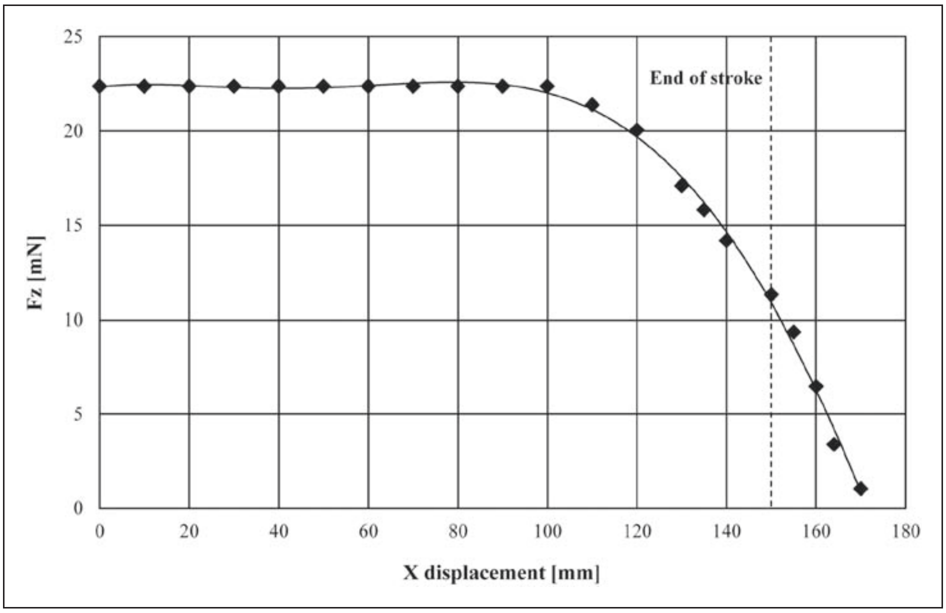

Figure 8. Lift force (Fz) versus X displacement for $Z = 2.3$ mm and $Y = 0$ mm.

or end of stroke. In Figure 7, the pressure exerted over the superconductor by the magnet is shown.

As the magnet gets closer to the end of stroke, the translational symmetry of the field (and consequently the forces) is lost and a different behavior is expected. The contribution of the end of the stroke surfaces is the main contributor to this change in behavior.

Therefore it becomes necessary to better understand the effect that borders cause in the linear bearing.

Firstly, the lift force (Fz) versus X displacement was analyzed, as shown in Figure 8.

Although the end of the stroke physically is at $X = 150$ mm, the results show that from a displacement of around 100 mm the lift force starts to decay and at the end of the stroke there only remains around a half of the initial lift force. This decay of the force would imply a drop of the levitation height. From this first calculation, we can set the usable stroke from -100 mm to $+100$ mm.

However, the axial force must also be analyzed. It is essential to know the value and direction for dimensioning an eventual actuating system. The results of this analysis are presented in Figure 9.

As for the lift force, there is no appreciable axial force until a certain point, exactly at $X = 90$ mm. Then an axial force towards the border appears and it is a maximum 10 mm beyond the end of the stroke. The positive sense indicates that it is not a restoring force. Therefore, the useable stroke is reduced from ± 100 mm to ± 90 mm.

In section "Mechanical behavior of a magnet-superconductor mechanism in the Meissner state", it was stated that "A magnetic dipole tends always to be oriented tangential to a curve superconducting surface". Because the mechanical design and magnet selection is

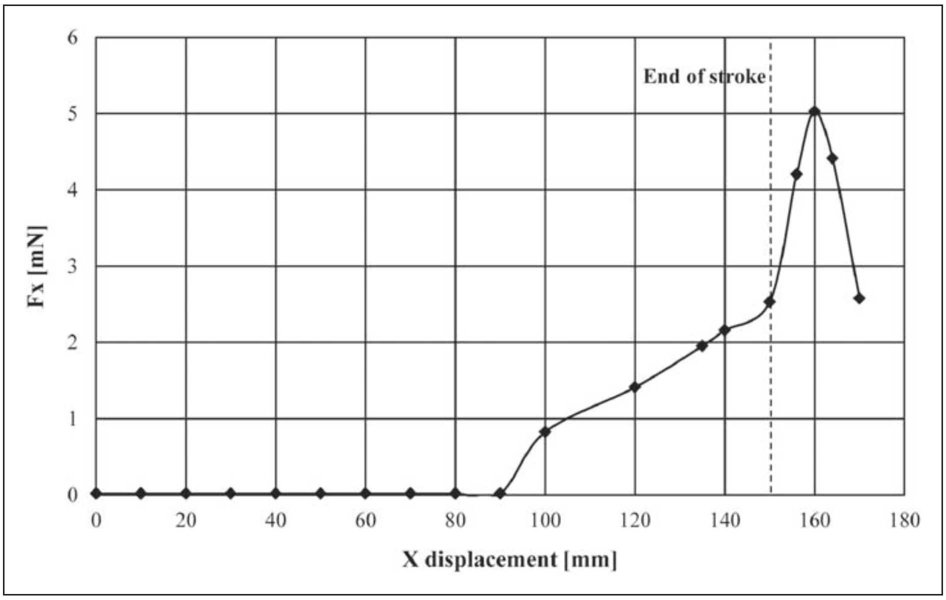

Figure 9. Axial force (*Fx*) versus *X* displacement for $Z = 2.3$ mm and $Y = 0$ mm.

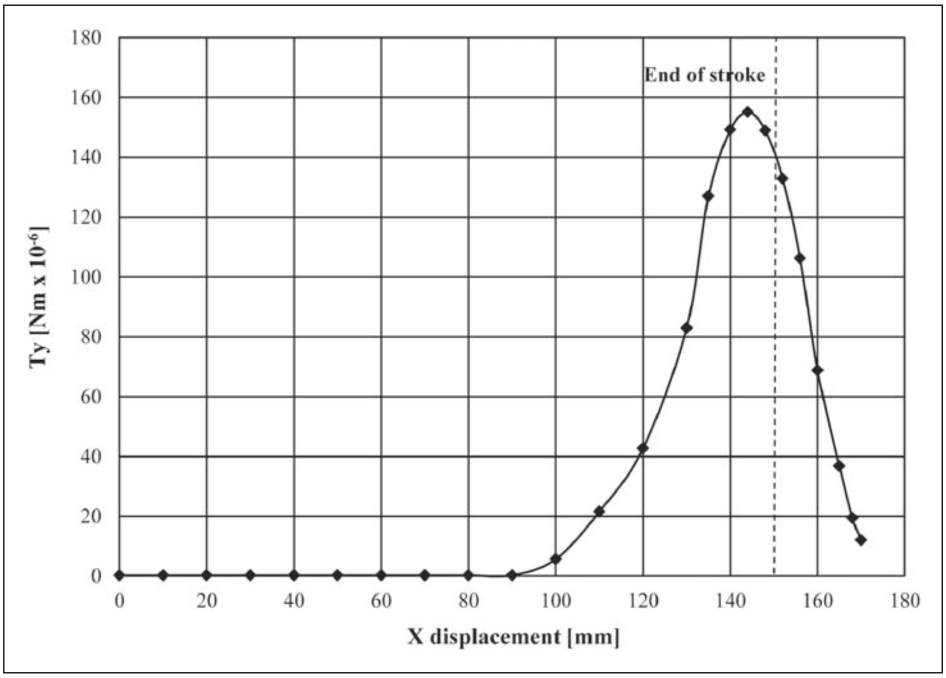

Figure 10. Pitch torque (*Ty*) versus *X* displacement for $Z = 2.3$ mm and $Y = 0$ mm.

close to the center positions, this effect contributes in favor of the stability. However, for positions closer to the end of the stroke, an alignment effect or torque of the dipole magnetic direction with the border surface is expected. The calculation of the pitch torque around Y direction is displayed in Figure 10.

As for the previous border effect results, the pitch torque value is negligible close to the center. On the contrary, the torque increases when the magnet is near to the end of the stroke, having the maximum just before the end of the stroke. Like for the axial force, the pitch torque is zero until the magnet reaches $X = 90$ mm, so we maintain the usable stroke in ± 90 mm.

The last parameter to consider is the maximum magnetic field in order to assure whether or not the complete Meissner state is achieved. These results are given in Figure 11.

As expected the maximum magnetic field in the usable stroke (up to $X = 90$ mm) remains in the same values. However, at the end of the stroke the maximum magnetic field increases.

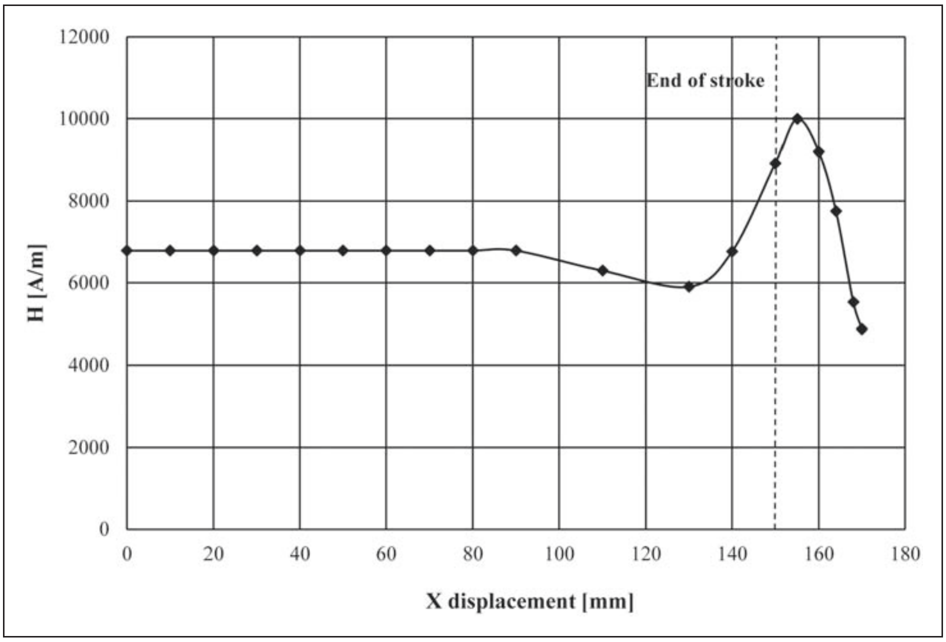

Figure 11. Maximum magnetic field versus X displacement for $Z = 2.3$ mm and $Y = 0$ mm.

From the border effect analysis it can be concluded that there is a "usable stroke" of around 90 mm in which the borders do not affect the sliding kinematic pair of the linear bearing. Beyond the "usable stroke", the total stroke could also be used, but with reduced performance of the stiffness and stable levitation.

Conclusions

A non-hysteretic passive magnetic linear bearing for cryogenic environments was designed and numerically analyzed.

The "U-shape" of the guideline made from a superconducting material and the magnet dipole selection provide a stable levitation point. The restoring force for a lateral run out (so the stiffness) was calculated.

The calculation of the maximum magnetic field in the equilibrium position and the comparison with the critical fields for different superconductors demonstrates the viability of a passive linear magnetic bearing with no hysteresis in the displacement. For example, a YBaCuO at 50 K could hold up to 9223.2 A/m without overpassing the Meissner state, much more than the maximum magnetic field applied, so a full Meissner state is proven.

Even if the vertical load capability of the slider is reduced, having a front surface of the magnet of 12.56 mm^2 could be enough for a laser beam such as those used in precision positioning measurements. This makes this system an attractive configuration for nano and microload positioners and interferometrical devices.

The high translational symmetry of the magnetic field seen by the superconductor assures a usable long stroke of around ±90 mm with full performance and ±150 mm with reduced performance. The main advantage of the system is that the usable long stroke can be extended as long as required with the same cross section of the superconductor and the same magnet. The larger the superconducting guide is, the smaller, in stroke percentage, the border effects are.

A border effect characterization provides a complete understanding of the expected behavior of the whole stroke.

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Conflict of interest

None declared.

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