Optimization of two-dimensional permanent magnet arrays for diamagnetic levitation

Roland Moser, François Barrot, Jan Sandtner, Hannes Bleuler

Laboratory of Robotic Systems
Swiss Federal Institute of Technology, Lausanne (EPFL)
1015 Lausanne, Switzerland
Tel.: ++41-21-693-5927 / Fax: ++41-21-693-3866 / hannes.bleuler@epfl.ch

Keywords

Contact-less levitation, Diamagnetism, Magnetic bearings, Permanent magnets, Pyrolytic graphite

Abstract

This paper presents new results in the field of passive diamagnetic levitation of macroscopic objects. Two dimensional permanent magnet arrays have been analyzed and optimized in order to obtain high thrust force and stiffness for fully passive magnetic levitation at room temperature in all 6 degrees of freedom. Experimental results with strongly diamagnetic materials like pyrolytic graphite indicate that diamagnetic levitation can be an interesting alternative to active magnetic bearings. Possible applications are pointed out and functional experimental prototypes are presented.

1 Introduction

Novel results for the optimization of fully contact-free passive suspension of objects at room temperature are presented. Earnshaws' theorem [1] discards the possibility of passive static magnetic levitation, but by taking advantage of the diamagnetic effect, passive magnetic systems can be stabilized. A diamagnetic material for levitation purposes was already proposed [2], the pyrolytic graphite, and full suspension and asynchronous propulsion of small disc shaped rotors was presented in [3]. Also, one-dimensional magnet arrangements have been investigated and optimized by finite element simulation [4]. In the present report we show that, by optimizing a 2 D permanent magnet array in two dimensions, the obtainable thrust force can be significantly increased, allowing the passive static levitation without weight compensation of objects weighting up to several grams.

2 Passive Diamagnetic Levitation

2.1 Principle

In diamagnetic materials, the presence of an external field induces a slight net magnetic moment, an effect akin to electronic polarization in dielectric materials. This induced magnetic moment translates into a slightly negative magnetic susceptibility and therefore into a relative permeability slightly less than unity. If such a diamagnetic substance is placed in a non-uniform magnetic field, it is attracted to the regions where the field is weak. In other words, a diamagnetic substance is "repelled" by a non-uniform magnetic field. The amplitude of the repelling force is proportional to the cross product of the gradient and amplitude of the applied magnetic field. The highest diamagnetic effect can be observed at room temperature using NeFeB permanent magnets and highly orientated graphite (HOPG – highly orientated pyrolytic graphite).

For magnetic levitation, we propose the use of the less orientated, less pure and much cheaper pyrolithic graphite (PG).

2.2 Studied case of diamagnetic levitation

Figure 1 depicts the studied case of passive diamagnetic levitation:

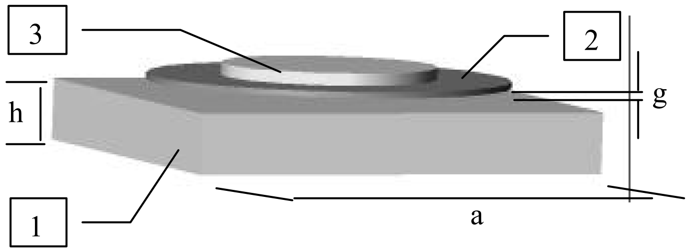

Fig. 1. Loaded pyrolytic graphite plate levitating with an air-gap g over a permanent magnet array of dimensions $a \times a \times h$.

A permanent magnet array **1** of square dimension a and height h lifts a plate of pyrolytic graphite **2** on which the payload **3** is located. This is a variant of diamagnetic levitation, the only known form of 'real' levitation at room temperature (without any energy input).

2.3 Variants of permanent magnet arrays

The magnet array of figure 1 can be decomposed into sub-magnets of different magnetization directions. Figure 2 shows the investigated arrangements and their nomenclature:

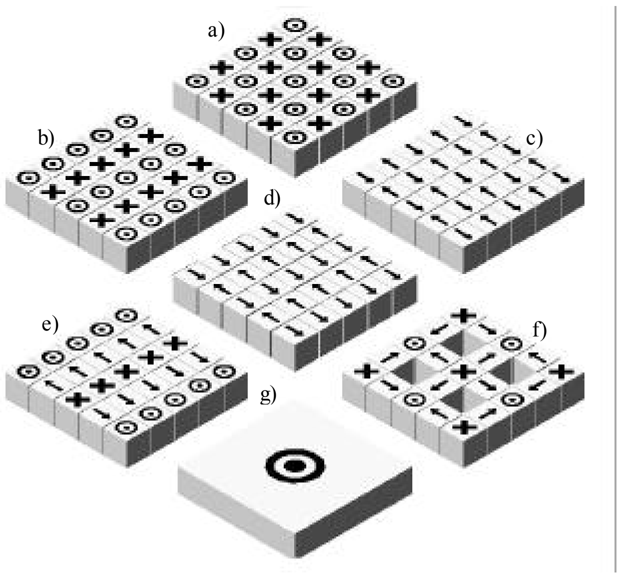

Fig. 2. Possible magnet arrays for diamagnetic levitation. a) Opposite 2D, b) Opposite 1D, c) Repulsive 2D, d) Repulsive 1D, e) Halbach 1D, f) Halbach 2D, g) Reference

The different arrangements are compared with a monolithic magnet (position 'g' in figure 2). By subdividing the available magnet volume into submagnets of different magnetization direction, the total magnetic flux and its gradient can be varied. Since the diamagnetic repulsion force is proportional to the flux' amplitude and gradient, the force should have a different allure in function of the air gap g for the various magnet arrangements.

3 Experimental Results

Figure 3 plots the thrust force densities versus the air-gap g for the mentioned magnet arrangements:

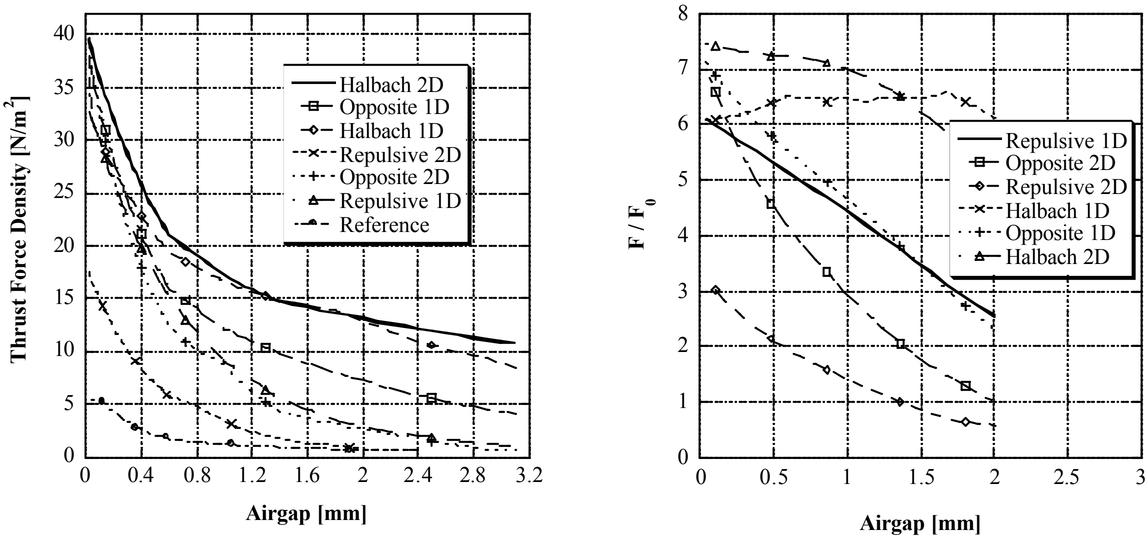

Fig. 3. a) Thrust force density for various NeFeB magnet arrangements for h = 5mm. b) Array performance F, compared to a monolithic reference F_0. The pyrolytic graphite specimen has a thickness of 1 mm.

It can be seen (figure 3a) that for a 5mm thick magnet array, using a Halbach 2D arrangement, up to 40 N/m^2 force density can be obtained (if the rotor has a 1mm thick pyrolytic graphite layer). This force density allows already the passive suspension of objects weighing several grams. Using the Halbach 2D arrangement, the performance can be increased up to a factor eight with respect to the monolithic permanent magnet block. The other interesting magnet arrangements are the Halbach 1D, the Opposite 1D and 2D and Repulsive 1D. The Halbach 2D arrangements features by far the highest force density per submagnet (see figure 2). The Opposite 2D is the only magnet array that can be assembled without additional glue, which can be a decisive advantage.

4 Prototypes

4.1 Non-weight compensated levitation

Figure 3 suggests the possibility to levitate objects weighting several grams without weight compensation. Figure 4 shows the experimental verification, using a rotor weighting 3 grams.

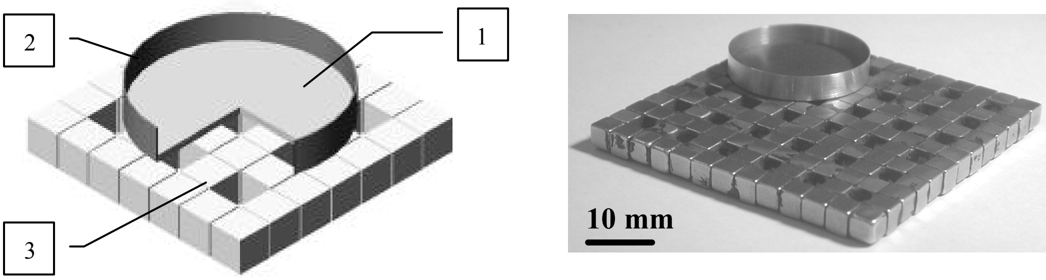

Fig. 4. Non-weight compensated diamagnetic levitation. a) Principle b) Photo of experimental verification

A disc shaped plate made out of pyrolytic graphite **1** and loaded with an aluminum ring **2** is levitating over a Halbach 2D array **3** (see figure 2f). The air-gap between rotor and magnet array is about 200µm. Obviously for stable levitation in the vertical axis, it would be enough if the magnet array has just the same dimensions as the rotor. We observed, using the experimental setup shown in figure 3, that for a certain ratio between rotor diameter and sub-magnet side length (the sub-magnets which form the magnet array are of cubic shape), passive stable levitation in five degrees of freedom is possible. Figure 5 sketches this situation:

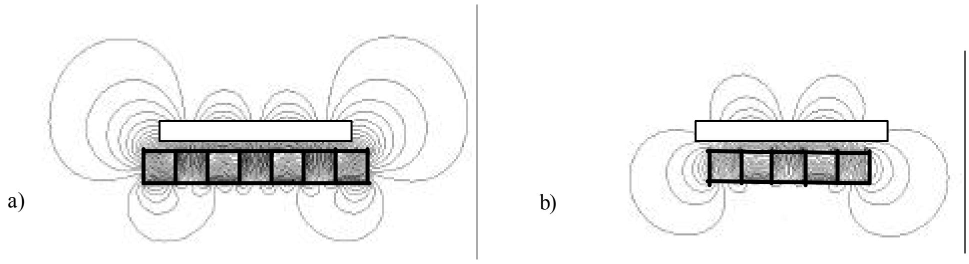

Fig. 5. a) Five degree of freedom levitation b) three degree of freedom levitation (unstable for horizontal translations). Flux-lines are simulated using the finite element method.

It can be seen that for miniaturized systems where the payload is in the order of some grams and contact-less levitation is required, diamagnetic actuators can be an interesting solution. Based on the measurements (figure 3), the following arrangements are proposed for various concrete applications:

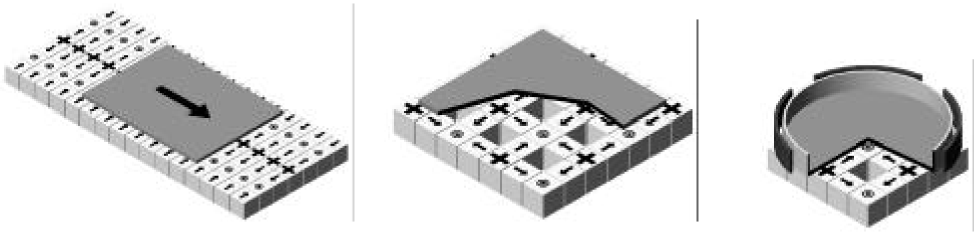

Fig. 6. a) Linear guide b) 6 DOF suspension c) Unstable contact-less suspension with active electrostatic actuators (acceleration sensing)

4.2 Weight compensated levitation

This diamagnetic levitation principle [4] is shown in figure 7:

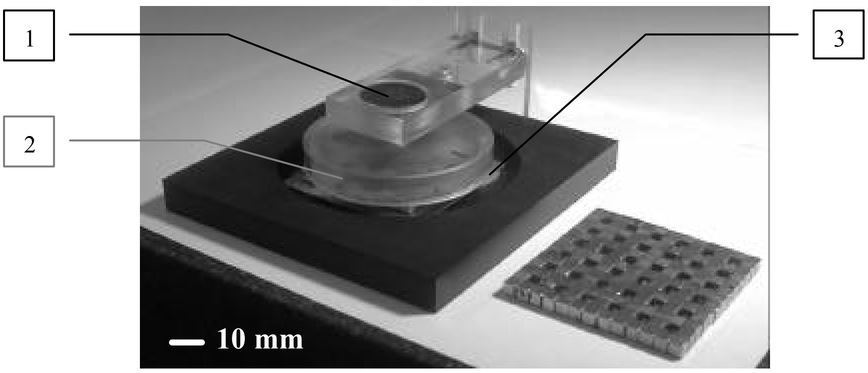

Fig. 7. Weight compensated diamagnetic levitation. Photo of experimental verification. Rotor weights 70 grams.

By adding a magnetic or ferromagnetic element on the rotor **2**, the weight of the rotor is almost compensated using a permanent magnet **1**. The remaining weight is compensated by the interaction between the pyrolytic graphite and the magnet array. Using a Halbach 2D array, a 5 mm thick magnet array was able to levitate a disc shaped rotor weighting 70 grams (10 mm thickness, 70 mm diameter). This compact passive and remarkably stable levitation device could find applications in the field of precise rotary positioning of optical devices [4].

5 Conclusion

Strong diamagnetic materials such as pyrolytic graphite are repelled by magnetic fields and therefore develop forces opposed to a magnet. Using strong rare earth magnets such as NeFeB, stable passive levitation of macroscopic objects at room temperature can be obtained. We determined the optimal permanent magnet pattern that supports a diamagnetic disc with respect to a maximization of the thrust force density. Using a Halbach array in two dimensions of 5 mm thickness, a 3 cm diameter disc weighting 3 grams could be stabilized 200µm above the magnet array. The trust force of such a Halbach array was shown to be 8 times higher than the thrust force of a monolithic magnet of same dimension.
Different applications were pointed out, such as a linear guide, a 6 degree of freedom suspension for rectangular plates, as well as a potential acceleration sensor, where the unstable horizontal degrees of freedom are controlled by active electrostatic actuators.
The compactness and simplicity of the presented levitation system (no active control, no sensors, no amplifiers and no control computer, no air compressors for air film, no low temperatures for superconductivity) without any kind of losses makes it an interesting solution for the levitation, positioning and guidance of objects weighting up to several grams.

6 Acknowledgments

The generous support by the Gebert Rüf foundation (Gebert Rüf Stiftung), Switzerland, has made this research possible.

7 References

1. Earnshaw S. *On the nature of the molecular forces which regulate the constitution of the lumiferous ether*, Trans. Camb. Phil. Soc, 1842, vol. 7, pp. 97-112.
2. Moser R., Bleuler H. *Precise Positioning Using Electrostatic Glass Motor with Diamagnetically Suspended Rotor,* IEEE Transactions on applied superconductivity, IN PRESS
3. Moser R., Sandtner J., Bleuler H. *Diamagnetic suspension system for small rotors,* Journal of Micromechatronics, VSB, Vol.1, No. 2, (2001), pp. 131-137.
4. Moser R., Sandtner J., Bleuler H., *Diamagnetic suspension assisted by active electrostatic actuators*, 6th International Symposium on Magnetic Suspension Technology, Turin 2001, pp. 241-246
5. Geim A.K., Simon M. D. *Magnet levitation at your fingertips*, Nature 400 (1999), pp. 323-324