11th International Symposium on Magnetic Bearings
August 26-29, Nara, Japan

APPLICATION OF DIAMAGNETIC LEVITATION IN MECHATRONIC SYSTEMS

François Barrot*[1,2]
*1 Swiss Federal Laboratories for Materials Testing and Research (EMPA),
CH-8600 Dübendorf, Switzerland.
francois.barrot@epfl.ch

Hannes Bleuler*[2]
*2 Ecole Polytechnique Fédérale de Lausanne (EPFL), Laboratory of Robotic systems
CH-1015 Lausanne, Switzerland.
Hannes.bleuler@epfl.ch

ABSTRACT

Diamagnetic levitation is the only passive levitation technique working at room temperature.
Using planar arrangements of permanent magnets, it is indeed possible to levitate diamagnetic materials at room temperature
Such a principle is particularly interesting to use for the design of mechatronic systems, especially in applications where friction between mechanical parts should be avoided such as, for instance, high precision inertial sensors or actuators for clean-room applications.
In this article the authors show with some examples extracted from their research on the subject, that diamagnetic levitation is a promising technique that can be of great interest for the design of small scale mechatronic systems.

INTRODUCTION

Diamagnetic forces have always been described in Physics textbooks as being of very small intensity and, consequently, the engineering community hardly ever considers using this magnetic effect for designing new products.
However, with the advances of strong rare earth permanent magnets, it is now possible to use the diamagnetic effect at the macroscopic scale, using conventional materials.
In particular, the Engineering community can now use this unique and fascinating characteristic phenomenon of diamagnetism: the possibility of achieving stable levitation at room temperature using simple permanent magnets without any other energy input.

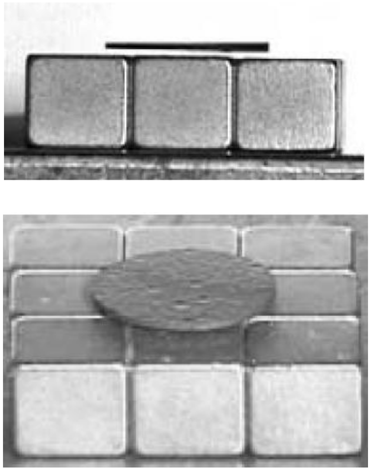

Figure 1: Diamagnetic levitation of a pyrolitic graphite pellet

THE DIAMAGNETIC FORCE - OPTIMIZATION FOR LEVITATION AT THE MACROSCOPIC SCALE

Diamagnetic levitation is the only stable levitation at room temperature using magnetostatic fields [1]; indeed, when the external magnetic field is conveniently shaped, it is possible to levitate, in a stable equilibrium, a diamagnetic material over an array of permanent magnets (Fig.1).

$$\vec{F} = \frac{\chi_m}{2\mu_0}\left(\vec{B}.\overrightarrow{grad}\right)\left(\vec{B}\right) \text{ ….. (Eq. 1)}$$

The diamagnetic force (Eq.1) being proportional to the magnetic field intensity and to its gradient, it is therefore important, for the maximization of the diamagnetic force intensity, to use strong permanent magnets and to assemble them judiciously so as to create both a strong magnetic field and a strong magnetic gradient.

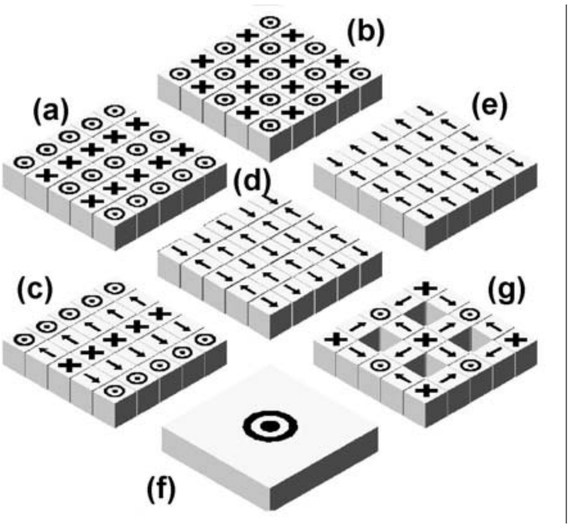

Figure 2: 2D arrangement of cubic permanent magnets for diamagnetic levitation

All 2D-configurations of permanent magnets that can be used to obtain a stable diamagnetic levitation (Fig. 2), have been tested experimentally in one of our previous work [2]. Based on these experiments, it can be concluded that some arrangements are much more efficient than others (Fig. 3).

A particularly interesting configuration is the one where neighbouring magnets have opposite polarities: it is auto-stable and produces a strong diamagnetic levitation effect at the macroscopic scale.

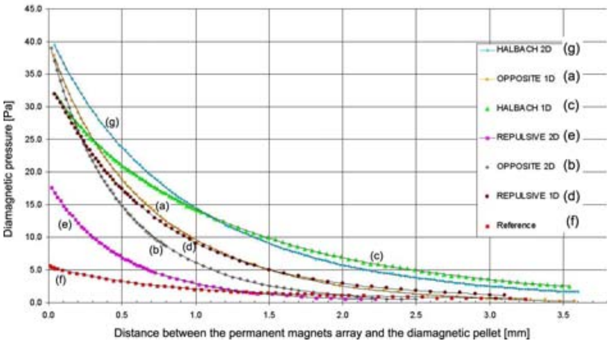

Figure 3: Diamagnetic levitation pressure on a 1mm thick diamagnetic pellet depending on the structure of permanent magnet array

The arrangement of permanent magnet leading to the largest levitation force is the one that we untitled ‘‘Halbach 2D’’ (Fig. 2g). It also corresponds to the most efficient arrangement since it uses less magnets than other arrangements; however it is not easy to assemble since it is not auto-stable and requires very strong binding of neighbouring magnets.

Using a permanent magnet biasing technique (Fig. 4) to compensate for the weight of the levitated object and using the diamagnetic force only to stabilize the levitation, it is even possible to levitate relatively heavy objects which, otherwise, could not be levitated by the diamagnetic force alone [3].

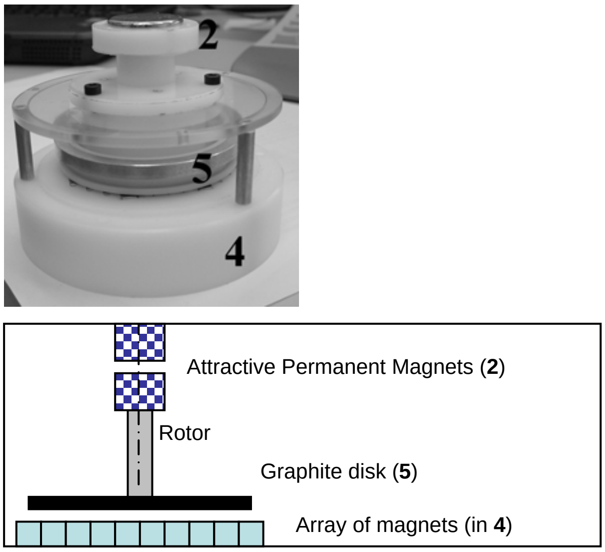

Figure 4: Weight compensation technique with a biasing permanent magnet to enable diamagnetic levitation of heavy elements.

MECHATRONIC SYSTEMS BASED ON DIAMAGNETIC LEVITATION

Many small size mechatronic systems suffer from a recurrent problem: the influence of friction between moving pieces which is a limiting factor at small scale. Indeed friction generates dust, causes wear and limits the precision of the displacement between moving pieces.

Based on these observations and given the potential use of diamagnetic levitation for eliminating friction without additional energy consumption, we propose some example of sensors and actuators that can greatly benefit from diamagnetic levitation.

Actuators

In applications where particle contamination should be avoided, such as in clean-room micro-factories, it is essential to avoid contact between moving pieces.

A linear conveyor for micro-factory applications typically benefits from diamagnetic levitation combined with contactless actuation. We have reported such an implementation for 1D linear movements in [4][5] and a planar 2D implementation is proposed here (Fig. 7).

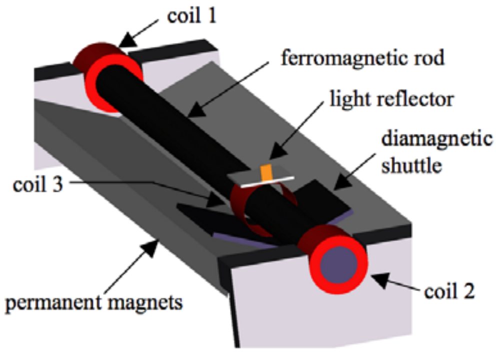

Figure 5: Contactless linear actuator based on diamagnetic levitation

1D linear actuator, The contactless 1D-linear actuator based on diamagnetic levitation (Fig. 5) relies on the jumping ring effect: a coil shorted on itself is fixed to diamagnetically levitated shuttle and a ferromagnetic rod, passing through the conveyor coil, guides the magnetic field created by two coils fixed at each of the rod extremity. When, for instance, a current is fed in the fixed coil 1, the shuttle coil is repelled by the magnetic field created by coil 1 and the shuttle slides away from coil 1 in the direction of coil 2.

This implementation has been successfully tested on a 15cm stroke. However, based on such a jumping ring implementation, it is not possible to design a 2D planar actuator with an X-Y stroke larger than a few millimetres.

2D planar actuator, To design a contactless long stroke 2D planar actuator based on diamagnetic levitation, it is necessary to investigate another contactless driving mean.

The diamagnetic force is affected by the shape of the magnetic potential created by the permanent magnet arrangements (Fig. 6). Therefore, if we modify the shape of the magnetic potential we can, in particular, modify the intensity and direction of the horizontal component of the diamagnetic force.

In Fig. 7, the proposed contactless bidirectional X-Y actuator based on diamagnetic levitation, relies on the modification of the magnetic potential shape. Some coils are inserted in the holes left in a Halbach 2D array of magnets; By varying accordingly the currents fed in the coils surrounding two opposite borders of the diamagnetically levitated plate, the magnetic potential pics surrounding these borders can be shifted orthogonally (let’s say in the X direction) to these borders, resulting in the lateral displacement of the diamagnetic plate (e.g in the X direction). To move in the orthogonal direction (e.g in the Y direction), the same procedure is applied to the two other opposite borders of the diamagnetic plate. Superposing these two effects, results in contactless long range X-Y displacement of the diamagnetic plate.

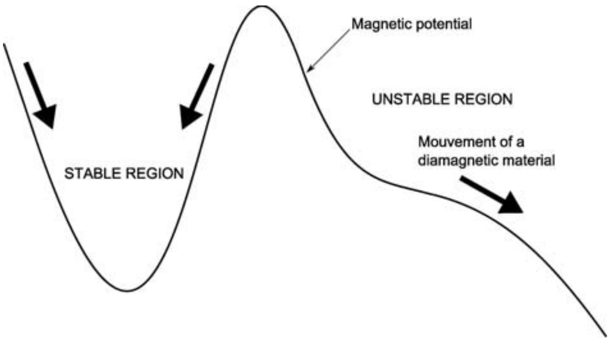

Figure 6: Stability of the diamagnetic levitation and shape of the magnetic potential

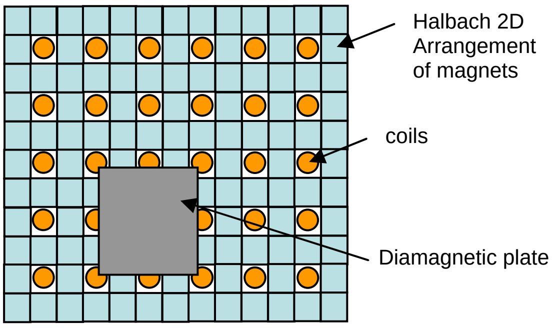

Figure 7: Contactless bidirectional X-Y actuator based on diamagnetic levitation

Sensors

Most inclination sensors are based on the relative displacement between an inertial mass and the base of the instrument; Their performance is mainly limited by the existence of a material link between these two elements. This material link is indeed the source of uncontrollable distortions due to friction, stiffness changes and thermal differential dilations which irremediably limit the precision of the measurements. Hence, all contacts between the inertial mass and the base of the instrument should be avoided.

We propose here an example of the application of diamagnetic levitation to realize a contact-free levitation of the inertial mass of an inclination sensor. In conjunction with electrostatic actuation; this principle leads to an entirely new family of potentially low cost high precision inclination sensors.

The proposed concept can be further implemented for 3D-accelerometers design [6] as well as for gyroscopes if a contactless rotation motor based, for instance, on the electrostatic glass motor [7] or on a comb-shaped electrostatic actuator is added to the aluminium ring of Fig. 8.

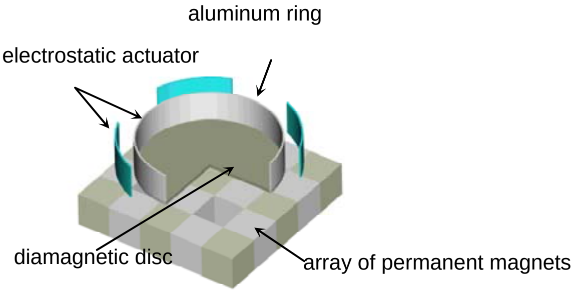

Figure 8: Principle of a 2D-inclination sensor based on diamagnetic levitation

The idea is to use diamagnetic levitation to lift the seismic mass and to maintain it at a specific position with a feedback loop using electrostatic actuators. Then, the amount of voltage fed into the electrodes to compensate for the external inclination is directly related to the external angle. In practice a common electrode made of an aluminum crown is fixed to a circular diamagnetic seismic mass and surrounded two differential pairs of copper electrodes.

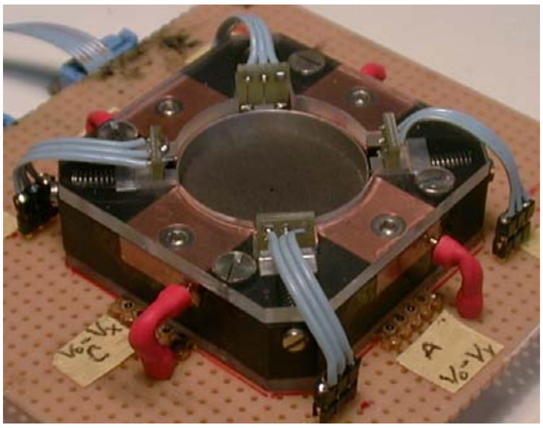

Figure 9: Prototype of a 2D-inclination sensor based on diamagnetic levitation

Based on such a principle, angles as small as a few arcseconds have been measured over a ±1° measurement range.

CONCLUSION

Diamagnetic levitation offers great potentials for small size mechatronic systems where friction is a limiting factor. Examples of actuators, such as conveyors used for clean room applications, as well as sensors, such as inertial sensors, have been designed on diamagnetic levitation and successfully implemented and tested, auguring future potential applications in small size mechatronic products.

ACKNOWLEDGEMENTS

This research was supported by the Gebert Rüf Stiftung, the EMPA Dubendorf and the Ecole Polytechnique Fédérale de Lausanne.

References

1. S. Earnshaw: On the nature of the molecular forces which regulate the constitution of the luminferous ether, Trans. Camb. Phil. Soc., 7, pp 97-112 (1842)
2. R. Moser, F. Barrot, H. Bleuler, “Optimization of Two-dimensionnal Permanent Magnet Arrays for Diamagnetic Levitation, MAGLEV, September 9th 2002, Switzerland.
3. H. Bleuler, J. Sandtner, Y.-.J. Regamey, and F. Barrot, “Passive Magnetic Bearings for Flywheels”, 8th International Symposium on Magnetic Suspension Technology, Dresden, Germany, Sept. 26 - 28, 2005.
4. F. Barrot, D. Chapuis, T. Bosgiraud, B. Loehr, L. Sache, R. Moser and H. Bleuler, “Preliminary Investigations on a Diamagnetically Levitated Linear Conveyor”, IEEJ Trans. on Industrial Applications, Vol. 126-A, N°10, p.1341, 2006
5. F. Barrot, B. Burns, D. Chapuis, T. Bosgiraud and H. Bleuler, “Position controlled diamagnetic linear conveyor”, ISMB10, August 21st -23rd 2006, Switzerland.
6. F. Barrot, J. Sandtner, H. Bleuler, “Acceleration sensor based on diamagnetic levitation”, IUTAM Symposium on Vibration Control of Nonlinear Mechanism and Structures, pp 81-90, Springer.
7. R. Moser, J. Sandtner and H. Bleuler, “Precise Positionning Using Electrostatic Glass Motor and Diamagnetically Suspended Rotor”, IEEE Trans. Appl. Superconductivity, vol 12 No 1 pp 937-39 (march 2002)