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PASSIVE DIAMAGNETIC LEVITATION FOR FLYWHEELS

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ABSTRACT

This report resumes a feasibility study on passive magnetic bearings requiring zero energy input, designed to stabilize disc shaped rotors of about 10 cm diameter at high rotation. One potential application coud be inertial energy storage (flywheels). The proposed device combines diamagnetic levitation with an electro-dynamic bearing and allows stable passive static levitation at room temperature. It is shown that it is feasible to levitate disc shaped rotors of technically interesting weight. The possibilities and limits of the proposed concept are analyzed and discussed.

INTRODUCTION

Inertial energy storage (Flywheel) is an attractive alternative to batteries or super-capacitors. The main challenge is to minimize the losses. In case of contact-free bearings, the energy used for levitation of the rotor has to be minimized. Security is of prime concern since in conventional flywheels masses of several kilograms are spinning close to the critical surface velocity, and rupture due to centrifugal forces can be fatal.

The authors would like to examine a novel approach to flywheels, based on two new concepts: First, the rotor is levitated using a diamagnetic suspension system that allows the contact-less suspension of objects weighting several hundred grams. It is well known that this kind of magnetic suspension allows the only 'real' levitation at room temperature, without outer energy input. And second, the subdivision of a conventional flywheel rotor into many small rotors, each of them having a radius under 10 cm and weighing around 100 grams. The energy of many of these little flywheels is equivalent to one large device, as long as rotational speed increases with decreasing wheel diameter. Doing so, the destructive potential of a bursting rotor is significantly reduced.

In order to provide additional stiffness and damping, the feasibility of a dynamic bearing based on eddy currents generating a recentering force will be evaluated.

In the nominal center position, this system is not consuming any energy.

DIAMAGNETIC LEVITATION

Principle

Earnshaw discovered [1] in 1842 that it is impossible to obtain a stable levitation equilibrium when an object is governed by inverse square law forces. Most of the known forces, such as gravity, electrostatic and magnetic forces are proportional to $1/r^2$. Ferromagnetic substances are always attracted towards the maximum of the field. Since this maximum is always at the source (magnets), it is impossible to passively levitate this kind of material.

Diamagnetic materials are repelled by magnetic fields and pushed towards the regions where the flux density is minimal. Since it is possible to create a local flux minimum, diamagnetic substances can be passively levitated. For diamagnetic materials, the presence of an external field induces a slight net magnetic moment, an effect akin to electronic polarization in dielectric materials. The induced magnetic moments translate into a slightly negative magnetic susceptibility and therefore into a relative permeability slightly less than unity. The force acting on a volume V of diamagnetic material immerged in an inhomogeneous field H can be written as:

$$\vec{F} = \mu_0 \chi_m \int_V \nabla \vec{H} \cdot \vec{H} dV \qquad (1)$$

with the magnetic susceptibility χ_m defined by:

$$\mu = \mu_0 (1 + \chi_m) \qquad (2)$$

Diamagnetic materials have negative susceptibility. According to (1), a diamagnetic object is pushed to regions where the field is weak. Table 1 gives the susceptibility of some diamagnetic materials:

TABLE 1: Diamagnetic materials

Material	χ_m
Bismuth	$-1.5 \cdot 10^{-4}$
Graphite	$-1.6 \cdot 10^{-4}$
Pyrolytic graphite (anisotrope)	$-4.5 \cdot 10^{-4}$
Superconductor	-1

In other words, a diamagnetic substance is "repelled" by a non-uniform magnetic field. The amplitude of the repelling force is proportional to the product of the gradient and amplitude of the applied magnetic field.

Concept of weight compensated diamagnetic levitation

Consider the following experimental setup:

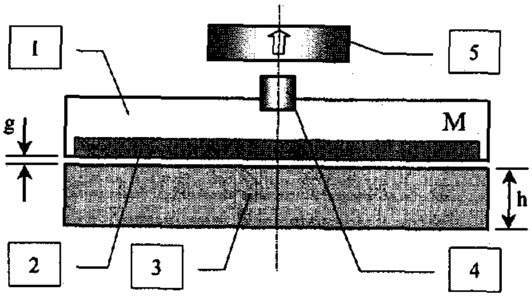

FIGURE 1: Weight compensated diamagnetic levitation

A disc shaped rotor of mass M, **1**, has at its lower side a layer of diamagnetic material **2**. This diamagnetic layer interacts with a permanent magnet array **3** with thickness *h*. At the rotors upper center is a magnetic object (ferromagnetic metal or permanent magnet) **4**, in interaction with a permanent magnet **5**. The weight of the rotor is almost compensated. The remaining weight is compensated by the interaction between the diamagnetic material and the magnet array, allowing levitation with an air-gap *g* above the magnet array **3**.

Optimization of the magnet array

The magnet array can be composed out of sub-magnets of different magnetization directions, as sketched in figure 2.

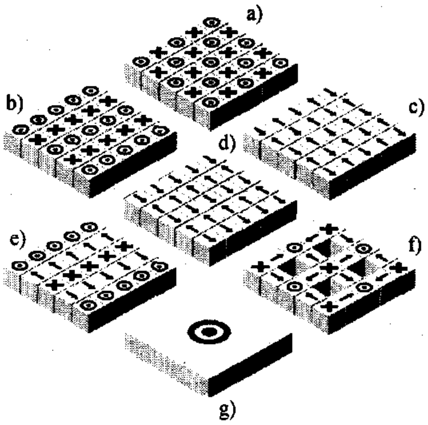

FIGURE 2: Possible magnet arrays for diamagnetic levitation. a) Opposite 2D, b) Opposite 1D, c) Repulsive 2D, d) Repulsive 1D, e) Halbach 1D, f) Halbach 2D, g) Reference

The differences between the various magnet arrays with respect to the obtainable force density and the force density gradient are quite important.

The different arrangements are compared with a monolithic magnet (position 'g' in figure 2). By subdividing the available magnet volume into sub-magnets 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, as shown in figure 3:

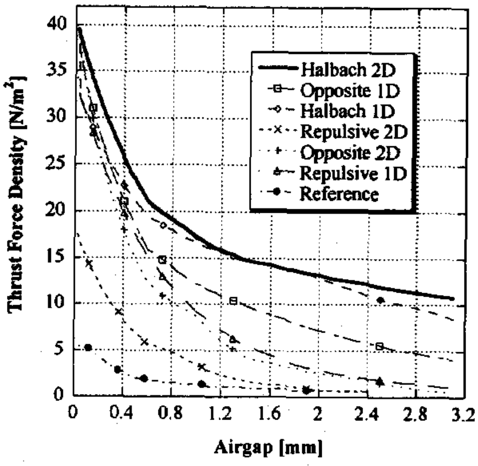

FIGURE 3: Thrust force density for various NeFeB magnet arrangements for h = 5mm. The pyrolytic graphite specimen has a thickness of 1 mm

It can be seen that the Halbach 2D array develops the highest force, but this in not the only relevant parameter for levitation. Table 2 indicates the stiffness of the tested magnet arrays at two different air-gaps *g* (slope of figure3):

TABLE 2: Magnet array stiffness (Pa/mm)

Array type	g=0.3mm	g=0.6mm
Opposite 2D	43.8	20.8
Hallbach 2D	33.3	21.9
Opposite 1D	41.1	18.6
Hallbach 1D	19.4	13.5
Repulsive 1D	29.1	16.7
Repulsive 2D	16.8	11
Reference	3.3	1.8

From this point of view, the "opposite 2D" array is optimal. It has also another appreciable advantage over its counterparts: It is inherently stable. Strong mutual repulsion forces imply tricky assembly and gluing techniques for the other magnet arrangements.

These results were obtained using a single layered array of 5x5x5 mm NeFeB magnet cubes. Taking the fourth-ranked Halbach 1D, an arrangement that is analytically analyzable, we find for the force density [4]:

$$\frac{F}{A}=\frac{\chi_m}{\mu_0}\left(\frac{B_r M}{\pi}\left(1-\exp\left(-\frac{2\pi h}{\lambda}\right)\right)\sin\left(\frac{\pi}{M}\right)\right)^2 \cdot\exp\left(\frac{-4g\pi}{\lambda}\right)\left(1-\exp\left(\frac{-4\pi p}{\lambda}\right)\right) \quad [\mathrm{N/m^2}] \tag{3}$$

with

M	number of magnets per period
h	thickness of magnet array
k	spatial frequency of the Hallbach array
B_r	remnant field intensity of the magnets
λ	lattice constant of the Hallbach array
p	thickness of diamagnetic rotor
g	air-gap
A	surface

And for the stiffness

$$\frac{dF}{dg}=\frac{-4\pi A\chi_m}{\lambda\mu_0}\left(\frac{B_r M}{\pi}\left(1-\exp\left(-\frac{2\pi h}{\lambda}\right)\right)\sin\left(\frac{\pi}{M}\right)\right)^2 \cdot\exp\left(\frac{-4g\pi}{\lambda}\right)\left(1-\exp\left(\frac{-4\pi p}{\lambda}\right)\right) \quad [\mathrm{N/m}] \tag{4}$$

For a given air-gap, an optimal increment-length λ that maximizes the force density can be found, a finding that confirms previous numerical simulations [2], [3].

It can be seen in equation (4) that stiffness increases strongly with decreasing lattice constant.

The same strong dependency of the diamagnetic repulsion force from the dimensions of the sub-magnets occurs with the other arrays (confirmed by numerical simulation).

The performance of a magnet array is therefore defined by a) the magnet material, b) the chosen array arrangement (see figure 2), c) the dimension of the used sub magnets (array lattice constant), d) the thickness of the magnet array and e) the used diamagnetic material.

Optimization of the weight compensation system

The weight compensation system deals with the interaction between two permanent magnets, or a permanent magnet and a ferromagnetic object.

The application requires as high a stiffness as possible. This stiffness of the system (figure 1) is the difference of the positive stiffness due to the diamagnetic system and the negative one due to the weight compensation system. The first of these two terms is fixed by the desired air-gap between rotor and magnet array. The second is fixed by the interaction between the weight compensation stator magnet and its rotor counterpart (position 4 and 5 in figure 1). This negative stiffness should be minimized.

Finite element simulations confirm that the mutual attraction between two permanent magnets induces a smaller negative stiffness than the mutual attraction between a permanent magnet and a ferromagnetic sphere. Another important parameter, the radial stiffness induced by the 'pendulum effect' between rotor and stator is significantly higher when two permanent magnets are used.

Scale law for weight compensated diamagnetic levitation

The diamagnetic force and the intensity of its gradient are directly proportional to the effective rotor surface. The effect of the thickness of the diamagnetic rotor is asymptotically exponential.

Be r a dimensional factor, we can write for the force:

$$F \propto Surface \propto r^2 \tag{5}$$

and for the gravitational force

$$Mg \propto Volume \propto r^3 \tag{6}$$

therefore

$$\frac{F}{Mg} \propto \frac{r^2}{r^3} = \frac{1}{r} \tag{7}$$

The negative stiffness induced by the weight compensation system is proportional to the generated force, so the proposed levitation concept favors small dimensions.

Diamagnetic levitation prototype

Since scale laws indicate the interest of small diamagnetic levitation systems and since we aim at decomposition of one large flywheel into many small ones, the goal was to levitate a rotor of about 10cm diameter, weighting about 100 grams.

This goal was achieved, the prototype is shown in figure 4. The rotor with its main mass at its outer border, **1**, levitates due to the interaction between a 7 cm diameter disc of pyrolytic graphite **2** (1mm thick) and an 'opposite 2D' array assembled out of 5mm cubic NeFeB magnets **3**. Levitation is enabled by weight compensation using a 5mm diameter cylindrical NeFeB magnet **4** at the rotor, attracted by a 3cm diameter and 5mm thick cylindrical NeFeB stator magnet **5**. The weight of the levitated rotor is 92 gram, the air gap between rotor and magnet array is about 300 μm.

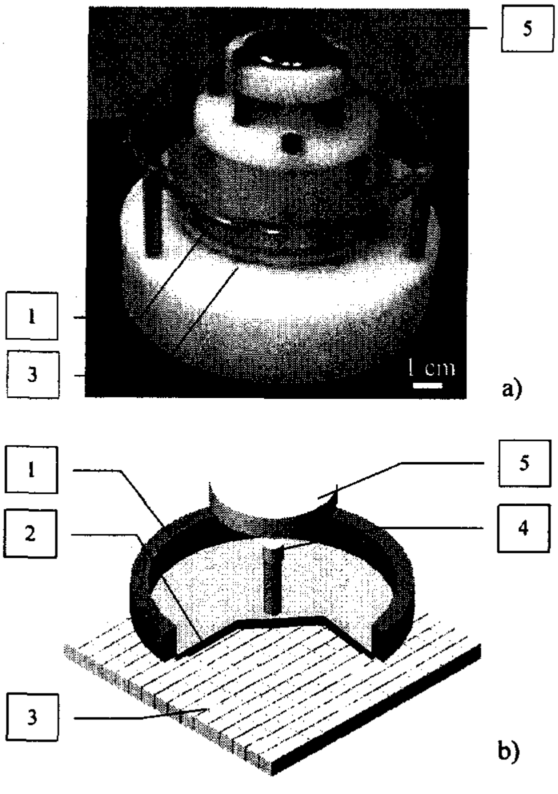

FIGURE 4: a) Photo of levitation prototype
b) schema of the principle

ADDITIONAL STABILIZATION

The previously described diamagnetic bearing is stable along the vertical axis and has a certain radial force when the rotor not centered due to the pendulum effect. This radial force might be insufficient to stabilize a spinning rotor, especially at critical speeds.

Electrodynamic bearing

With the motivation to design a completely passive bearing, electrodynamic vibration control seems to be the solution of choice.

In order to minimize the bearing losses (zero losses), the magnetic fields should be symmetric to the rotation axis. Otherwise the rotor would 'see' a variable field during rotation, inducing losses. Figure 5 shows the studied concepts of electrodynamic bearings. The outer ring (main mass) of the flywheel is supposed to be conductive and interacts with permanent magnet rings. In the center position, no losses occur due to the symmetry of the magnets. Off center, induced eddy currents should center to rotor.

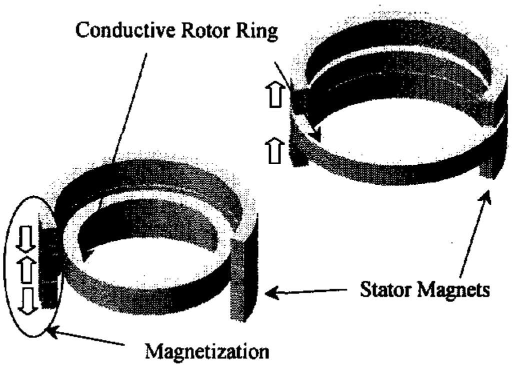

FIGURE 5: Examined electrodynamic bearings

Alas, analytical, numerical and experimental analysis revealed that these kinds of bearings are not apt to stabilize a rotor [4]. Indeed, the presence of the magnet rings introduces a certain damping that is not function of the rotation speed. But the dynamic effects destabilize the rotor. Consider the case where the rotor ring is off center (figure 6):

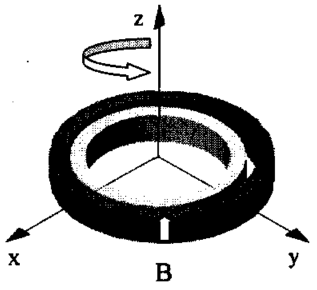

FIGURE 5: Rotor off center in a electro-dynamic bearing with indication of axis and rotation sense.

It can be shown [4] that at low rotation speeds the reaction force is perpendicular to the deviation, i.e. if the rotor is deviated in *x* direction, a force in *y* direction occurs. This is due to the *RL*-circuit properties of such a setup. With increasing rotation speeds, it was observed that the phase shift decreases (due to the increasing importance of the inductance), but the rotation speeds are not realistic (in our case $1\cdot10^6$ rpm for a 45^0 phase shift).

The same comments apply for pitch and roll angle deviations: The restoring torque is out of phase by 90^0.

Alternative solutions

Active magnetic bearings for additional *xy*, pitch and roll stabilization are feasible, as long as the ferromagnetic element on the rotor are sufficiently far away form the magnet array. Since a potential flywheel is probably working under vacuum conditions, active electrostatic bearings are also an interesting alternative.

Additional passive magnetic bearing are imaginable in a case where the diamagnetic repulsion forces stabilize the remaining unstable degree of freedom.

CONCLUSION

Even though the combination of diamagnetic levitation and electrodynamic bearing proved not to be feasible for flywheel applications (at least not in the presented configuration), the present study showed that diamagnetic levitation can be an interesting alternative for compact, zero energy input, low stiffness levitation of considerable objects. The disc shaped rotor of the prototype weighted 92 grams, 7 cm diameter, and levitates at 300µm above the permanent magnet array.

The tempting concept of electrodynamic bearings, where the restoring force is proportional to the rotation speed and therefore predestinated for fast rotating rotors such as flywheels, could not be implemented due to the inherent phase shift between displacement sense and restoring force.

After this study, passive magnetic bearings where the remaining unstable degree of freedom (Earnshaws theorem) is stabilized using the weak diamagnetic repulsion force, seem to be the most promising solution for zero energy input suspension of fast spinning rotors at room temperature.

Another interesting category of applications is the wide filed of the micro-factory, where diamagnetic bearings can be used as contact-less rails, compatible with clean room work environment.

Diamagnetic levitation, correctly used, can definitively become an important technology in precision engineering.

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