A Perspective of Magnetic Levitation as an Earth-based Low Gravity Analogue: What It Is and What It Ain’t

Mark W. Meisel¹ and James S. Brooks²

¹ Department of Physics and NHMFL, University of Florida, Gainesville, FL 32611-8440, ²Department of Physics and NHMFL, Florida State University, Tallahassee, FL 32310-3706, USA

ABSTRACT

The Earth-based low gravity environments available by magnetic levitation are not as widely employed as one might expect. For the purpose of highlighting and explaining the capabilities of magnetic levitation, this perspective surveys the history, the physical concepts, and the state-of-the-art of the technique.

INTRODUCTION

The ability to magnetically levitate objects, Figure 1, is not a new phenomenon. In fact, Werner Braunbek reported the first experiments with graphite and bismuth using facilities located in Tübingen, Germany (Braunbek, 1939a,b). However, the magnetic levitation of organic materials, typically modeled by physicists as, to first approximation, spheres of H₂O, did not occur until 1991, when Eric Beaugnon and Robert Tournier used the strong magnetic fields and the corresponding gradients available in Grenoble, France (Beaugnon and Tournier, 1991a,b). Within a decade of this report, as the required magnetic fields and gradients became readily available at magnetic field laboratories located around the world, the curiosity driven fun was performed by many researchers, including Michael Berry and Andre Geim* (Berry and Geim, 1997), who shared an Ig Nobel Award for Physics in 2000 for their work with levitating frogs (Ig, 2000). The levitation of a mouse by a group at the Jet Propulsion Laboratory in Pasadena, CA has rekindled interest in the near zero-g environment (Liu et al., 2010), but the corresponding low-g platforms that mimic lunar and martian conditions should not be forgotten (Valles et al., 2005).

The purpose of this paper is not to comprehensively describe the phenomenon and the field, since several detailed and accessible accounts have appeared (Berry and Geim, 1997; Valles et al., 1997; Geim, 1998; Brooks et al., 2000; Brooks and Cothern, 2001; Kitazawa et al., 2001; Simon et al., 2001; Nikolayev et al., 2011). Instead, our discussion focuses on aspects that may be of interest to the readers who might be pondering the possibilities of applying these techniques to their own research requiring a low gravity environment.

Key words: Magnetic Levitation; Low Gravity Simulators; Earth-based Low Gravity Analogue; Biomagnetism; Moses Effect

Correspondence to: Mark W. Meisel
Department of Physics and NHMFL,
University of Florida
P.O. Box 118440, Gainesville, FL 32611-8440
Voice: (352) 392-9147
Fax: (352) 392-3591
E-mail: meisel@phys.ufl.edu
http://www.phys.ufl.edu/~meisel

Andre Geim and Konstantin Novoselov shared the Nobel Prize for Physics in 2010 for their work on graphene (Nobel, 2010).
THE BASICS

Most introductory physics textbooks contain a discussion about the magnetic properties of materials being generally classified as either ferromagnetic, paramagnetic, or diamagnetic. For the case of diamagnetism, the application of an external magnetic field, $B$, induces magnetic dipoles, $m$, localized to the molecules but oriented in a direction opposite of the applied magnetic field. The number of magnetic dipoles per unit volume, $V$, is known at the magnetization, $M = m/V$, which can be written as a linear function of $B$ for describing paramagnetic and diamagnetic materials, i.e.

$$M = \chi_m \mu_0 B,$$

where $\chi_m$ is the magnetic susceptibility, which is positive for paramagnetic and negative for diamagnetic materials, and $\mu_0$ is the permeability of a vacuum, a fundamental constant. Less commonly appearing in introductory physics textbooks is the expression for the force, $F_m$, that a dipole experiences from a gradient of the magnetic field, where

$$F_m = (m \cdot \nabla) B,$$

and the first terms show the magnetic dipole vector dot product with $\nabla$, the del operator. In the simplest approximation restricted to one dimension taken to be the $z$-axis, the substitution of the first equation into the second one yields

$$F_{m,z} = V \chi_m \mu_0 B_z \left(\frac{dB_z}{dz}\right).$$

In other words, the magnetic force on a diamagnetic material is proportional to the strength of the applied magnetic field times the gradient of the magnetic field, and these parameters can be controlled in the laboratory.

The general expression for a force is $F = ma = V \rho a$, where $m$ and $\rho$ are the mass and density, respectively. For the force due to gravity, $a = -g$, where the one-dimensional orientation of $g$ is taken to be oriented in the negative $z$-direction. The force from gravity can be balanced by the magnetic force, Equation 3, of equal magnitude but oppositely oriented, and the expression describing this situation is often quoted as the requirement for magnetic levitation, namely

$$B_z \left(\frac{dB_z}{dz}\right) = \left(\frac{\rho}{\chi_m}\right) g \mu_0.$$

It is important to stress that once the material is chosen, its properties give the ratio ($\rho / \chi_m$), and the experiment only has to tune the magnetic field and its gradient to the appropriate value to generate the low-$g$ conditions. A striking demonstration of magnetic levitation conditions “at your fingertips” has been elaborately described (Geim et al., 1999; Simon et al., 2001). A non-levitation demonstration of the consequences of Equation 4 involves the deformation of water and is known as the “Moses Effect” (Kitazawa et al., 2001; Chen and Dahlberg, 2011).

---

Figure 1. A single arabidopsis (*Aradiposis thaliana*) plant magnetically levitated in a 50 mm diameter bore resistive magnet of the National High Magnetic Field Laboratory (NHMFL) (Stalcup et al., 1999). The perspective is by looking “down” a vertically oriented bore, and the leaves are easily visible while the roots are mostly hidden.
BEYOND THE BASICS

The preceding section assumes, strictly speaking, the object being levitated is in a vacuum, whose magnetic susceptibility and density are zero. To include the magnetic susceptibility of the surrounding medium into the analysis, the $\chi_m$ term in Equations 3 and 4 should be replaced by $\Delta \chi_m = \chi_{m,\text{object}} - \chi_{m,\text{medium}}$. In addition, a force of buoyancy can be generated if the density of the medium is different than the density of the object. Including this possibility in the analysis leads to the $\rho$ term in Equation 4 being replaced by $\Delta \rho = \rho_{\text{object}} - \rho_{\text{medium}}$. In fact, these details form the basis of using magnetic levitation to measure the densities of solids and liquids (Mirica et al., 2009). Finally, the nature of the metastable levitation state (Berry and Geim, 1997; Simon et al., 2001) and the dynamics of the object in this low-$g$ environment (Brooks and Cothern, 2001; Nikolayev et al., 2011) are beyond the scope presented in this perspective.

WHAT IT IS AND WHAT IT AIN’T

Whenever discussing magnetic levitation with potential users of the technique, a standard set of questions arise, and we will briefly address the most common points in order to elucidate the advantages and disadvantages of the method. The following frequently asked questions and their answers are not meant to be an exhaustive discourse of all of the issues.

What are the mass and volume limits for a sample to be magnetically levitated? A striking feature of Equation 4 is that the volume of the object does not appear explicitly. Consequently, if the $B_z dB_z/dz$ conditions can be established over a sufficiently large volume, then objects such as mice can be levitated (Liu et al., 2010), and magnets with a range of bore diameters have been used (Nikolayev et al., 2011). In other words, almost anything can be studied, and the aforementioned review articles provide an extensive discussion of the wide variety of materials that have been investigated.

How long can magnetic levitation be performed? Another striking aspect of the technique is that the low gravity environment can be established for hours to days in resistive (Brooks et al., 2000) and hybrid (Watanabe et al., 2003) magnets, or many days to weeks in room-temperature-bore, superconducting magnets (Valles et al., 2005; Liu et al., 2010). This time scale is a drastic improvement over the opportunities accessible on parabolic flights or drop towers. The only caveat is that magnetic levitation, by its nature, is a metastable situation, so long-term stability depends on a number of variables (Brooks and Cothern, 2001; Nikolayev et al., 2011).

Isn’t magnetic levitation the same as neutral buoyancy in a fluid? Generally speaking, the answer is No, but there are some subtle issues (Brooks and Cothern, 2001; Guevorkian and Valles, 2004; Nikolayev et al., 2011). During conditions of neutral buoyancy in water, the outer surface of a diver feels a net upward force of buoyancy while the internal organs still experience the Earth’s gravitational pull. Contrastingly, if the diamagnetism and density of a body are uniform throughout the sample, then each infinitesimally small volume element of the sample experiences a magnetic force that is equal to but oppositely oriented to the gravitational force (Valles et al., 1997; Guevorkian and Valles, 2006a,b; Nikolayev et al., 2011). Naturally, this ideal world may sound like it only exists in the minds of physicists who model an elephant as a sphere of water, but the approximation is not too bad, as variations of the values of diamagnetic properties of most organic materials is small. Unfortunately, not all material in living tissue is diamagnetic, and in fact, most molecules containing iron are paramagnetic or ferromagnetic. Consequently, differential forces can arise in these cases. To summarize, single-celled microorganisms can be studied in a magnetic levitated low gravity environment that is distinctly different from a neutrally buoyant setting. A similar statement can be made for the eukaryotic animals, but some consideration needs to be given to the differential forces that the internal organs will experience.

With a large gradient of the magnetic field being used, are magnetophoretic effects or other perturbations to biological processes present when studying living tissue? The answer to this question is Yes. In fact, large magnetic field gradients have been used to study the magnetophoretic effects on plants (Kuznetsov and Hasenstein, 1996; Galland and Pazur, 2005), but these effects are typically smaller than the ones...
arising from magnetic orientation, which originates from the torque that a magnetic dipole senses in a homogeneous magnetic field (Guevorkian and Valles, 2006a,b). Consequences of these types of effects have been reported by several groups (Denegre et al., 1998; Stalcup et al., 1999; Valles, 2002; Ikehata et al., 2003; Paul et al., 2006; Coleman et al., 2007), and the effect is extensively employed by the MRI (magnetic resonance imaging) community investigating the structure of biomolecules (Bax and Grishaev, 2005).

Are there any subtle issues that one should consider when designing an experiment? Yes, there are some points that one should ponder prior to performing an experiment. For example, the container of some samples, such as liquid ones containing cells to be studied, might provide a surface tension that could dominate any magnetic field induced effects. In other words, the confining media should be “matched” to the sample in order to avoid this kind of secondary effect, which is one that is easy to overlook. An illustrative example is the egg, which is an arrangement where the yoke is held by albumen in such a way as to allow the magnetic field effects to be manifested (Denegre et al., 1998).

FUTURE PROSPECTS
From our viewpoint, a plethora of opportunities exist for using magnetic levitation facilities as Earth-based low gravity analogue platforms, and the curiosity to explore this region of parameter space will be driven by researchers working a variety of fields, including gravitational and space biology. We suggest that you give the technique a try, as every time an object is successfully levitated, the event externally provokes a smile and internally ignites profound thought.

ACKNOWLEDGEMENTS
We gratefully acknowledge the conversations and insights that we have shared with our numerous colleagues over the course of our levitation experiments. This work was made possible, in part, by funding from the National Science Foundation (NSF) via DMR-0654118, the cooperative agreement with the National High Magnetic Field Laboratory (NHMFL), and the State of Florida.

REFERENCES


