Thermal Influence on the Diamagnetic Properties of Pyrolytic Graphite: Applications in Space and High Speed Transportation

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Abstract

Attitude control system of satellites must be fast and accurate for applications such as camera or antenna pointing using the least energy possible. Current attitude control systems required fuel and a considerable amount of power, and can sometimes be hindered by mechanical systems failure. Here, a novel attitude control system is proposed using the diamagnetic characteristics of levitating pyrolytic graphite in the Earth's magnetic field. Diamagnetic materials are used to stabilize magnetic levitation, however, these materials can self-levitate when subjected to a magnetic field. Furthermore, the diamagnetic properties of pyrolytic graphite depend on temperature. Using this characteristic, it is possible for the graphite to generate a torque by heating small sections of it. In this thesis, this phenomenon is studied and analyzed and its applications are discussed. In particular, the ECOSat cubesat, currently being developed by the University of Victoria, will carry a payload experiment designed to explore and validate this phenomenon. This payload will have various experiments, one of which will be composed of a plate of pyrolytic graphite that, under the influence of the Earth's magnetic field, will produce a torque when a section of it is heated using an infrared laser.

A novel levitation and propulsion method for maglev trains is also proposed, designed and analyzed. This method would require a plate of pyrolytic graphite underneath the train which would levitate on the electromagnet train track.

This thermal effect on the diamagnetic properties of pyrolytic graphite has never been fully explored, nor applied for satellite attitude control of small satellites.

Keywords: Optical control, attitude control, diamagnetism, pyrolytic graphite, magnetic actuator, LASER

1. Introduction

Diamagnetism is a property of materials that has been studied for a long time and is nowadays quite well understood. Bismuth and pyrolytic graphite are known as the most diamagnetic materials at room temperature.

The Earnshaw Theorem does not allow stabilized levitation of a body only subjected to [1]. inverse-square law forces However, introducing diamagnetic materials in the levitation system enables а complete stabilization of the levitating body [2].Furthermore, a magnetic field exerts a repulsive force in a diamagnetic material, enabling it to levitate on its own.

Unlike some other magnetic properties, diamagnetism isindependent from the temperature of the material. Notwithstanding, it was discovered that the motion of a plate of pyrolytic graphite levitating on a magnet array could be optically controlled [3], this is evidence that, in the case of graphite, there must be some change in the irradiated area to produce the forces which created this motion.

Having in mind the possibility of creating a force in a pyrolytic graphite plate that is subjected to a magnetic field using simply a LASER, the ECOSat team, from the University of Victoria, idealized a system capable of creating a torque to control the attitude of a satellite. This system

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would use a few LASERs pointed near the borders of a pyrolytic graphite plate under the influence of the Earth's magnetic field, in orbit. The unbalancing forces created during this act would create a torque that would be capable of controlling the satellite's attitude.

2. Background

2.1. The Earth's magnetic field

The dynamo effect describes how the motion of the fluid inside the Earth's outer core can generate and maintain a magnetic field [4] strong enough to involve the entire planet. The pressure, gravitational and thermal gradients in the outer core dictate the laws by which the fluid is ruled and determine its movement. This movement of charges and ferromagnetic particles created the magnetic field that is surrounding the planet.

As opposed to a simple dipolar magnet, the north and south poles of the Earth's magnetic field are not aligned, neither with the center of the Earth neither with its rotational axis. Besides this irregularity, the field is also not stationary: its intensity changes with time as well as the position of the poles on the planet's surface. However, this changes are slow enough for it to still be used for orientation, attitude determination and navigation.

At the Earth's surface, the magnetic field intensity ranges from 22 mT to 67 mT, being the most intense near the magnetic poles and the least intensive close to the magnetic aclinic line [5]. Then, with increasing altitude, the field's magnitude decreases, for example: at 100 km height, the field's mean intensity is 16 μ T [6]. The field dependence with altitude, or distance to the center of the planet, cannot be described using simple mathematical formulations, ergo, usually Fourier models based on field spherical harmonics are used.

2.2. Diamagnetism

Whenever a material is subjected to a magnetic field, it will react to it in a certain way, characteristic of the material. The basis of this thesis stands on this property: diamagnetism. All materials present a diamagnetic behavior, however, in most of them this behavior is very weak and so it is negligible compared to the other forms of magnetism that the material can present. A diamagnetic material has a magnetic permeability lower than one, ergo, a magnetic material will repel any magnetic field that it is subjected to. Imposing the magnetic field to circle the material around it as much as possible will create a repelling force between the diamagnet and the magnetic field.

The diamagnetic properties of a material are usually characterized by a property called magnetic susceptibility, χ . The magnetic susceptibility is related to the magnetic permeability by the Equation (1). A diamagnetic material has a magnetic susceptibility inferior to zero and with minimum value of -1:

$$\chi_V = \mu_V - 1. \tag{1}$$

 μ_V is the magnetic permeability of the material. The most diamagnetic material is pyrolytic graphite, with $\chi_V = -6.1e^{-4}$, [7], just followed by bismuth, with $\chi_V = -1.7e^{-4}$, [8].

Diamagnetic forces induced in materials by a magnetic field have a very different behavior from inverse-square law forces. While the attraction forces for other types of magnetism have an inverse quadratic relation with distance from the origin of the field, diamagnetic forced depend on the gradient of the squared magnetic field, as it is demonstrated in [9] and the final expression for the magnetic forces is shown:

$$\overrightarrow{F_d} = \frac{\chi V}{2\mu_0} \overrightarrow{\nabla B^2} . \tag{2}$$

In this expression, V is the volume of the diamagnetic material, μ_0 is the vacuum magnetic permeability and B is the magnetic field. Although the diamagnetic behavior is weakly present of all materials, there are some that have all other types of magnetism suppressed, so diamagnetism is the only observable interaction. Especially pyrolytic graphite and bismuth have the strongest diamagnetic behavior known (besides superconductors), this materials are used to stabilize magnetic levitation and can also levitate by themselves above an array of small Neodymium magnets or under the effect of a strong magnetic field.

2.3. Magnetic susceptibility, function of temperature



Figure 1: Variation on magnetic susceptibility of various types of magnetic materials with temperature [9].

The effect of temperature in the magnetic behavior of materials is a phenomenon that has been studied for a long time and is today well understood. Paramagnets and ferromagnets have their magnetic susceptibility decreased with increasing temperature, while anti-ferromagnets have their magnetic susceptibility increasing along with temperature, until the Neel Point is reached and then the magnetic susceptibility, χ , will drop with further temperature increased. These effects are shown in Figure 1.

Diamagnetism has never shown a variation with temperature and, besides the empirical evidence, it is mathematically understood this lack of dependence: as it is shown on the online page [10]. It is known that diamagnetism is not affected by temperature, however, in the empirical research made by Kobayashi and Abe, it is shown that pyrolytic graphite has its magnetic susceptibility decreased when the temperature of the material is increased [3].

Pyrolytic graphite is a very unique material, as it is the only known material which its magnetic susceptibility has a strong dependence with temperature. This behavior is shown in Figure 2. In the work by Kobayashi and Abe [3], the measurements on the variation of magnetic



Figure 2: Variation on magnetic susceptibility of pyrolytic graphite with temperature [3].

susceptibility were made along with the measurement on the levitation height of a plate of graphite above an array of rare earth permanent magnets assembled in an antiparallel fashion. The plot in Figure 2 shows two lines: the blue one represents the decreasing (in absolute value) of the magnetic susceptibility of the graphite plate, as a consequence of this decrease in the diamagnetic behavior, the levitation height will decrease, as it is shown on the red line. It is noticeable that, for this range of temperatures, the magnetic susceptibility of the pyrolytic graphite plate has its dependence with temperature extremely close to a linear dependence.

3. Implementation

3.1. Experiment: Magnetic susceptibility change with temperature

The purpose of this experiment is to acquire data on the evolution of the magnetic susceptibility of graphite with varying temperature.

It is now known that the magnetic susceptibility of pyrolytic graphite should decrease, in absolute value, with temperature with a nearly linear relation, as it was discussed before. Furthermore, the levitation height will decrease with the increase of the temperature of the material. One of the goals of this experiment is to verify the data gathered by Kobayashi and Abe [3] and expand it for a wider temperature spectrum, with a special focus on lower temperatures.

With the data about this unique property of pyrolytic graphite, the understanding on how to create an acceleration or a torque in a plate of graphite subjected to a magnetic field will be highly enhanced. With a special regard to the lower temperatures found $_{in}$ a space environment, a broader temperature spectrum with relevant magnetic data is essential to develop the best design possible for an attitude control system using this technology. It is expected that the dependence from temperature of the magnetic susceptibility continues to present the nearly linear behavior even for much lower temperatures than the ones shown in Figure 2.

In this experiment, the data for the magnetization and magnetic susceptibility of a sample of pyrolytic graphite was gathered using a SQUID magnetometer. The pyrolytic graphite sample was subjected to a magnetic field of 1000 Oersted and the temperature of the sample was variated in the range of 2.1 °K to 300 °K.

3.2. Magnet array simulation



Figure 3: A CAD render of a plate of pyrolytic graphite levitating over a 10 by 10 array of neodymium magnets.

For a better comprehension of the physical phenomenon that is on the basis of this thesis, as well as an exercise to test the knowledge acquired during the research developed on its ambit, a MatLab[®] simulation was design and produced. On this simulation, the mechanics that rule the optical motion control of maglev graphite are explored, scrutinized and translated on a computational simulation. The tempe-rature increase in the LASER irradiated area is computed, using the thermal and optical properties of pyrolytic graphite. Then, the deficit in magnetic susceptibility is calculated, using the trend-line obtained in the experiment, in order to make an analysis of the torque and acceleration that is applied in the plate by the local change in its magnetic properties. As the magnetic susceptibility of the irradiated area

decreases, the levitation height will also decrease slightly and the plate will tilt in the direction of the irradiated area. This will created an unbalancing force that will propel the plate in that direction.

With a real assembly like the one rendered in Figure 3, it is possible, using a LASER, to control the motion of the levitating plate over the array of magnets, as it was done by Kobayashi and Abe, [3]. When the LASER is focused near the border of the plate, it will quickly move on that direction. Focusing it on the center of the plate has no apparent effect in its horizontal motion.

The simulation returns the horizontal components of the plate's acceleration, the resulting levitation height and the tilt angles of the plate on the two horizontal angles.

3.3. Attitude control system

3.3.1. System design

The attitude control system designed and the physical concepts of operation were thoroughly studied and analyzed in the ambit of this thesis and can be explained in a simple way.

The main components of this actuator are: the various LASERs, the pyrolytic graphite plate, the satellite and, as the source of the diamagnetic force that the system exploits, the Earth's magnetic field. The LASER will be turned on in order to rise the temperature of the section of the PG that it is focused on, close to the border, for maximum torque. This temperature rise will cause a decrease on the PG magnetic susceptibility, in absolute terms. This will result in a lower magnitude of the diamagnetic force that the Earth's magnetic field is subjecting on the plate, for that irradiated section. As there is a force deficit in only one of the sides of the plate, this will result in a torque that will spin the satellite. With various LASERs, pointing at different spots on the plate, the irradiated spot's location can be determined, enabling the creation of any torque required. By controlling the frequency at which the LASER is turned on, the temperature can be controlled, providing the chance to control the magnitude of the torque created.

Figure 4 shows a model of the system. The pyrolytic graphite plate is represented by the



Figure 4: Simple model of the attitude control system and ECOSat scientific payload that is being developed on the ambit of this work.

square, shown in perspective, the LASER beam is represented as the red column on the right and the effect of the Earth's magnetic field is represented in the figure as the gradient of its square value. This mathematical entity is directed in the direction of decreasing intensity of the field, in this case it points away from the Earth. The magnetic field is actuating on the plate according to the law described by Equation (2). When the section under the laser beam is heated by it, and has its magnetic susceptibility decreased (in absolute value), there will be an unbalance of the force created by that section relative to its analogous, symmetric relatively to the center of the plate. This force deficit is shown in Figure 4 as $\overrightarrow{dF_m}$. This difference of forces between two symmetrical sections of the plate will create a torque, \overline{M} .

By controlling the irradiated section of the plate, the direction of the torque can be controlled, furthermore, controlling the exposure time, the intensity of the torque can be also controlled.

3.3.2. Orbital simulation

The main objective of this thesis is to design an attitude control system resorting to the optical control of maglev graphite. As such, the first, and most important, computer simulation is based precisely on this system. The simulation was developed using the MatLab platform. The model of the Earth's magnetic field was based on the CHAOS-5 [11] model using a compatible MatLab version which can compute the three

components of the magnetic field for a given position.

The simulation computes the torque that the system induces in the satellite by having one of the lasers powered in an Earth Centered Inertial spherical coordinate system.

The Technical University of Denmark (DTU) has developed several models for the Earth's magnetic field using data from various satellites. The first CHAOS model of the magnetic field was accurate up to the fiftieth harmonic degree, for the static field, and up to the eighteenth for the first time derivative [11]. In 2014 the DTU publishes the CHAOS-5 model for the Earth's magnetic field. The great importance of the data recovered by ESA's three SWARM Satellites is of utter importance for this model [12]. The data for this model was selected and treated with several criteria used previously for the older versions of the model. Emphasizing some of this criteria: only night-side data from geomagnetically quiet times, suitable for use in the CHAOS modelling scheme; geomagnetic activity at non-polar latitudes was sufficiently low; merging electric field at the magnetopause was sufficiently small for data from polar regions. The DTU provided a version of the model compatible with MatLab. This version was used along with the simulation every time that the three components of the magnetic field for a given position were needed.

Similarly to the magnet array simulation, using the same algorithm, this simulation begins by computing the temperature in the irradiated section and its modified magnetic susceptibility. Then the gradient of the squared magnetic field is computed for the orbital position the satellite is, as well as the force it creates in the plate. The force deficit and torque are then computed. The simulation takes into account the attitude of the satellite, ergo, the orientation of the plate relative to the magnetic field.

4. Results

4.1. Magnetic susceptibility change with temperature

The data gathered during this experiment is very extensive, a total of 490 measurements



Figure 5: Variation of the magnetic susceptibility (volume) of the sample of pyrolytic graphite measured by the SQUID magnetometer.

were made. These are shown in the plot in Figure 5.

The plot shows very clearly the evolution of magnetic susceptibility of the pyrolytic graphite sample with the temperature. The equation shown in the plot corresponds to a trend line (computed using Microsoft Excel) that, as it can be seen, has a close correlation with the data. A polynomial curve of seventh order was chosen as it was the lowest order to give a value of R squared of 1. This equation is used in the simulations to compute the magnetic susceptibility of the plate at the temperature reached with the LASER beam. As the temperature in the simulations will not rise much above 300 °K, the same curve will be used for temperatures outside the measured spectrum.

It is obvious that, contrarily to what is generally thought about diamagnetism, the magnetic susceptibility of pyrolytic graphite depends on temperature.

4.2. Magnet array simulation

The results of this simulation show values similar to what can be observed with an assembly like the one depicted in Figure 3. According to the simulation, the values of the



Figure 6: Variation of the levitating height with iteration step.

final temperature and corresponding magnetic susceptibility of the irradiated section are:

 $T = 395.92 \ ^{o}K$

 $\chi_V=1.5404\text{e-}06$

Furthermore, the plot showing the convergence for the value of levitation height computed can be seen in Figure 6.

It is noticeable the quick convergence in the beginning of the process and then a slower phase. This is due to the convergence of the tilt angles and consequent cancellation of the torque in the plate. When the torque in the plate is zero, the final height is then reached.

Finally, the accelerations created by the LASER in the plate are:

 $a_x=0.1659\ m/s$

 $a_y=0.1712\ m/s$

These values were the outputs of a simulation in which the LASER was pointed with a vector (0.02, 0.02) cm from the center of the plate. The different values of the acceleration computed are due to the difference in length and width of the plate, not being perfectly square.

4.3. Orbital Simulation

The results from the orbital simulation have a decisive action on the implementation of the attitude control system designed.

The simulation was computed using the best conditions possible: the plate is perpendicular to the divergence of the squared magnetic field, and the circular section to which the laser is beaming is at one of the corners of the plate. The pyrolytic graphite plate is a 10 by 10 cm plate, considered to be at 300 °K inside the cubesat. The results from the simulation predict that the temperature of the irradiated section will only rise 3.3 °K, consequently, the change in magnetic susceptibility of that section will also be small: 7.46e-7. This variation will result in a maximum torque with the components: $M_x = -3.894e-24$ N m,

 $M_y = 1.361e-21$ N m,

$$M_z = -1.354e-21$$
 N m.

Having in mind that the torque perturbations in orbit are only considered to be of the order of magnitude of -6, it is obvious that this system will not be capable of creating a torque strong enough to control the satellite in orbit. As an improvement upon the first design for the attitude control system, a second design was developed. The aim of this design is to manipulate the working conditions of the system in order to maximize the effect of each variables in Equation (2) on the torque created.

The system would have several modifications. First: the plate would not be made of pyrolytic graphite but rather of a superconductive alloy. Second: assembling the plate outside the satellite would provide the low temperature needed for the superconductor to operate. Third: the plate would be divided into four quadrants with a thermal insulator in between. Choosing the appropriate superconductor alloy, it would be possible for the laser to heat a quadrant of the plate high enough to stop the superconductive behavior. This would enable a variation on the magnetic susceptibility of more than 1, depending on the magnetic susceptibility of the alloy at high temperature.

However, even with this modifications, the torque created would still only have a magnitude of 1e-12.

5. Other applications

Magnetic levitation (maglev) is a highly advanced technology. It is used on various areas of engineering, including clean energy (small and big wind turbines: at home, office, industry, etc.), building facilities, transportation systems (magnetically levitated train, Personal Rapid (PRT), etc.), Transit weapon, nuclear engineering, civil engineering, advertising and so on. The common point in all these applications is the lack of contact and thus no wear and no friction. This increases efficiency, reduces maintenance costs and increases the useful life of the system. The magnetic levitation technology can be used as a highly advanced and efficient technology in various industrial applications. Already many countries invested on maglev systems [13]. One of the most common applications of maglev, and one of increasing demand and development, are maglev trains. These trains have the important advantage of not being supported by contact force, therefore, there is no energy loss due to the friction between the wheels and the train track. Maglev suspension systems are divided into two groups of electromagnetic suspension (EMS) and electrodynamic suspension (EDS). Another method to achieve levitation of a maglev train proposed: Diamagnetic isSuspension. This method of levitation would use electromagnets inthe track, just like electromagnetic suspension, however, the train would have a base covered by pyrolytic graphite. Some calculations were computed to evaluate the viability of this method of suspension. Several approximations were made, which grand these calculation only an estimative value.

Using current technology electromagnetic tracks, and considering a 17,000 kg train, it would require a plate of graphite underneath it covering all its base. This plate would require a thickness of 8.3 mm. A train with this description could levitate at 2.5 cm from the track with a maximum velocity of 395 km/h.

6. Conclusions

In conclusion, it is certain that, contrarily to the general idea that diamagnetism is not dependent on temperature, the magnetic susceptibility of pyrolytic graphite certainly is. This means that, with a capable magnetic field it is possible to create accelerations and torques inа diamagnetic material subjected to that field. However, it is obvious that the Earth's magnetic field does not provide the necessary conditions in orbit for this effect to be used on attitude control of small spacecrafts.

It is crucial to further study this characteristic of pyrolytic graphite and explore its applications and unique properties.

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