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DESIGN AND DEVELOPMENT OF A THREE-AXIS CONTROLLED HELMHOLTZ CAGE AS AN IN-HOUSE MAGNETIC FIELD SIMULATOR FOR CUBESATS

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Abstract

Team Anant is the University Student Satellite Team of Birla Institute of Technology and Science, Pilani, India. The paper presents the details of the design and in-house development of a Three-axis Controlled Helmholtz Cage prepared by the members of the Team as an Attitude Determination and Control test bed for CubeSat type Nano-satellites. The testbed has been designed to provide a testing volume of approximately 90 dm^3 with uniform magnetic field, which is sufficient to test nanosatellites of up to 3U Size (CalPoly Standard). The maximum designed magnetic field intensity for each coil is 120 μT. The cage has been designed so as to simulate the magnetic field over the entire range of Low Earth Orbits. The paper begins from the very basic coil design requirements with brief analysis of the dimensional requirements and materials to be used. The analysis is complemented with a budget optimization model for a cost-effective setup. The cage has an unconventional but improvised Square-Coil design. The methodology applied for the structure design and assembly of the cage has been presented in a thorough manner. Brief information about the internal and external, software and hardware connections has been provided. All other relevant information has been presented to provide a step by step guide for the development of the cage. Aluminum Square Pipes and Aluminum Flats were used to prepare the structure of the Cage supplemented by Copper Wire for the production of the field. MATLAB is used to determine the Magnetic Field Intensities along the orbit which are then translated in real time to current intensities on the three pair of Coils. A brief assessment of the circuitry used for producing the required currents is also presented. The system is able to perform as expected in common configurations and is able to produce the desirable field in all three axes. The paper concludes with the experimental data obtained during the preliminary testing of the structure of the cage.

Keywords: CubeSat Testing, Magnetic Field Simulator, Hardware-in-loop Testbed, Attitude Determination and Control System, Helmholtz Cage

Nomenclature

Permeability of free space: $\mu_o = 4\pi \times 10^{-7}\ NA^{-2}$
Constant of Proportionality: $K = \frac{\mu_o}{4\pi}$

Acronyms/Abbreviations

Birla Institute of Technology and Science (BITS), Attitude Determination and Control System (ADCS), California Polytechnic State University (CalPoly), Pulse Width Modulation (PWM).

1. Introduction

The Student Satellite Team of BITS Pilani is currently building a Hyperspectral Imaging Nano-Satellite. The ADCS Team planned to build a Three Axis Magnetic Field Simulator to test the detumbling control laws designed for the satellite in realistic situations.

The basic idea behind the simulator is the fact that magnetic field is produced when current is passed through a conductor. The ‘cage’ consists of three pair of coils, in three different orthogonal axes to replicate the required magnetic field.

2. The Requirements

The ADCS team had a set of requirements (as shown in Table 1) for the cage that formed the basis of its design.

Table 1. Major Requirements for Helmholtz Cage

	Minimum	Nominal	Maximum
B (μT)	120	150	200
Dimension (m)*	0.40	0.50	0.60
Voltage (V)	9	12	15

*Dimension of the cube with uniform magnetic field created inside the cage.

2.1 Magnetic Field Requirement:

The required Magnetic field in each axis was decided to be at least three times the Earth's Magnetic Field at the point of testing. This ensured that the field inside the cage can be completely reverse of the field outside it. It also ensured that the Earth's magnetic field does not interfere with the testing process.

2.2 Dimensional Requirement:

The cage produces a region of approximate magnetic field uniformity at the centre of the pair of coils. The length of this uniform region depends on the dimensions of the coil and the distance between them. As the team is building a satellite according to the CalPoly 3U Standard, it required the uniform region to be able to completely accommodate the satellite. The principal diagonal of the satellite is 37.28 cm. The cage was designed to produce a uniform region of at least 40 cm.

2.3 Voltage Requirement:

The DC Regulated Power Supply available to the team posed a constraint on the voltage that can be used by the cage. The maximum possible voltage for the supply was 15V hence an appropriate nominal voltage of 12V was decided.

2.4 Miscellaneous Requirements:

Apart from the above requirements, the team needed a stable cage that is easy to manufacture. The cost of building the Cage was capped as well.

3. Theory and Derivations

The Biot-Savart Law describes the differential magnetic field near a current carrying conductor (see Fig. 1) as given by Eq. (1).

$$dB \propto \frac{i\,dl\,sin\theta}{r^2} \qquad (1)$$

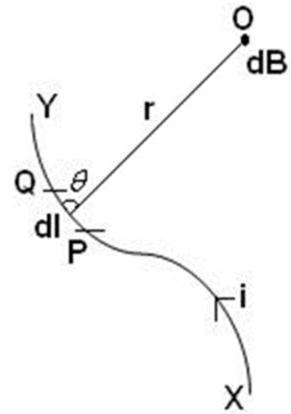


Fig. 1. Magnetic Field near a current carrying conductor

The constant of proportionality for this equation is denoted as K.

3.1 Derivation for Circular Coils:

Let us analyse a circular coil of radius r, having N turns and carrying a current I. Consider a point P, which is at a distance x from the centre of the coil axially (See Fig. 2). Using Eq. (1), the magnetic field intensity B at point P can be calculated as provided in Eq. (2). [1]

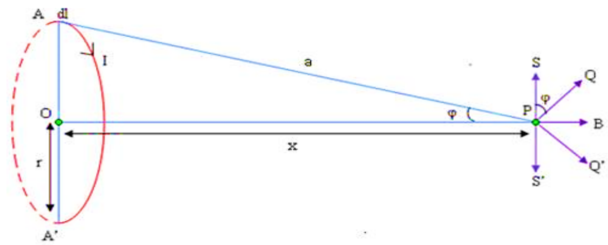
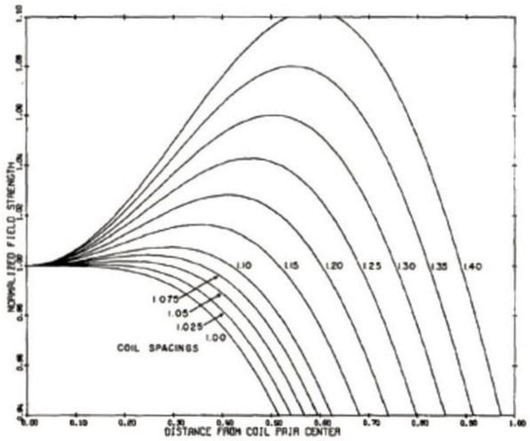


Fig. 2. Magnetic Field at an axial point of a circular coil

$$B = \frac{\mu_o NI}{2} \frac{r^2}{(x^2 + r^2)^{3/2}} \qquad (2)$$

The same equation was simulated in MATLAB for varying distance between the pair of coils. It was found that the magnetic field intensity B is most uniform when the distance between the pair of coils is equal to the radius of the coils. The length of the uniform region was also found out to be 0.5 times the radius of the coils. The change in the uniformity of magnetic field intensity B with the varying distance between the coils is depicted in Graph 1.



Graph 1. Varying Uniformity of B with varying distance between the pair of coils.

3.2 Derivation for Square Coils:

Use of square coils was explored because of the following reasons:

1. They are easier to manufacture than perfectly circular coils.
2. They are more stable as a system. As a cube is more stable than a sphere, they too could be used without using any extra support.
3. They are comparatively less complex to assemble than circular coils.
4. As found out after running various simulations, they provide a wider uniform field region than circular coils. Hence, a smaller square cage can produce the same uniform field region as a large circular cage. [2]

The governing equation for the magnetic field intensity B at the axial point of the square coil (See Fig. 3) was found to be:

$$B = \frac{2\mu_o NI}{\pi a}\frac{1}{(1+\gamma^2)\sqrt{2+\gamma^2}}\ ;\ \gamma = \frac{b}{a} \qquad (3)$$

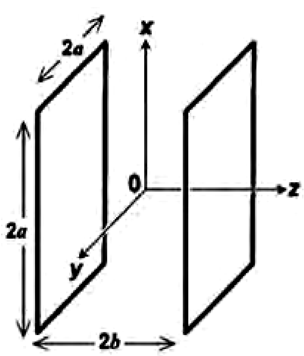


Fig. 3. Square Coil Design

It was determined that in order to achieve the maximum homogenous field between the two coils, the coils should be put apart by a distance of 0.5445 times the side of a square. The length of the uniform region was found out to be 0.4 times the side of the square coil. The variation of magnetic field density with the varying distance between the pair was found to be similar to the result obtained for the circular coils.

4. Coil Parameter Design

For the orthogonal coils to fit together, the coils must have different sizes. The parameter design of the largest coil is provided in this section. The parameters for the other two smaller coils can be found in Appendix A.

The nomenclature used in the following equations is as follows:

$s = Side\ of\ Square\ Coil, in\ metres$

$N = Number\ of\ Turns\ in\ Coil$

$I = Current\ in\ the\ Coil, in\ Amperes$

$B = Magnetic\ field\ intensity\ at\ the\ centre\ of\ the\ coil, in\ Tesla$

$B_e = Magnetic\ field\ internsity\ due\ to\ Earth, in\ Tesla$

$V = Voltage\ through\ the\ Coil, in\ Volts$

$\rho = Resistivity\ of\ Copper\ Wire$

$d = Cross-sectional\ Diameter\ of\ the\ Copper\ Wire, in\ metres$

$A = Cross-sectional\ Area\ of\ the\ Copper\ Wire, in\ squared\ metres$

$I_{th} = Threshold\ Current\ of\ the\ Copper\ Wire, in\ Ampere$

Now, using the Dimensional requirement:

Region with Uniform Field = 0.4s = 50 cm

s = 1.25 m

Note: Incorporating the effects due to multiple wire wounds and the structure, the approximate side of the coils can be assumed to be $s = 1.3$ *m.*

Using the Voltage Requirement, it can be found that:

V = 12V

Using the Magnetic field requirement and Eq. (3), it can be found out that:

$$3B_e = B = (3.2 \times 10^{-6}) \frac{NI}{s} \frac{1}{(1 + 0.5445^2)\sqrt{2 + 0.5445^2}}$$

Using the Ohm's Law, we can calculate the Current *I* as:

$$I = \frac{V}{R} = \frac{VA}{\rho(4Ns)} \qquad (4)$$

Substituting this in the Magnetic field equation above, we get:

$$\frac{A}{s^2} = \frac{B_e}{96.949} \qquad (5)$$

We know that the Earth's magnetic field at the point of testing is *45 uT*.

Hence the value of *A* can be found to be:

$$A = 7.8443 \times 10^{-7}\, m^2$$

We also know the relation between the diameter of the wire and its cross-sectional area.

$$d = \sqrt{\frac{4A}{\pi}} \qquad (6)$$

Hence the value of *d* can be found out to be:

$$d = 0.9993\, mm$$

According to this calculated diameter, the most suitable wire will be the Copper SWG-19 wire with a diameter of *1.02 mm*.

An approximate equation for the threshold current of Copper wire is as given below:

$$I_{th} \approx \frac{d^2}{4.52 \times 10^{-7}} \qquad (7)$$

Using Eq. (7) and the value of diameter for SWG-19 copper wire, threshold current was calculated to be equal to *2.30177A.*

Now using Eq. (4) to calculate *N*, the appropriate value was calculated to be 60. This value was reached after taking into account the theoretical and measurement errors that the team might face while developing the cage.

As the magnetic field produced is inversely proportional to the size of the coil (See Eq. (3)), the secondary and tertiary coils are designed to be smaller than the primary coil. It makes sure that the field intensity inside those coils are greater than the required field and the threshold current is not exceeded.

The lengths of the sides have been fixed so as to make sure the second pair of coils fit exactly inside the first pair of coils and the third pair of coils fit exactly between both the first and second pair of coils. In order to do so, the secondary and tertiary pairs of coil will be rectangular in shape instead of a square. However, the change in the fields due to this change of shape was determined to be negligible.

A simple cost function was calculated for the complete structure and it was found that the function reaches its minima at the calculated parameters. Hence, the setup parameters determined provides the most cost-effective cage.

5. The Structure and its functioning

As structure of the cage was developed from three pair of coils with the parameters as specified by Appendix A. The final dimensions of the coils are as provided in Table 2.

Table 2. Final Coil Dimensions for Helmholtz Cage

	Length (m)	Breadth (m)
Primary Coil	1.3	1.3
Secondary Coil	1.25	1.2
Tertiary Coil	1.2	1.15

Aluminium Flats and Aluminium Square Pipes were used to prepare the structure of the cage. Copper SWG-19 wire was used to be wound around the structure for the production of magnetic field. The Structure was visualised in DS SolidWorks to clearly indicate the positioning of the coils and confirm the dimensions to be finalised. The prepared CAD Model is provided in Fig. 4.

The IGRF Model in MATLAB was used to find the Magnetic Field Intensity at the required point and then calculate the required current to be supplied to each pair of coils to replicate that field. A simple H-bridge driver circuit was used to supply the varying current according to our requirements. Three individual H-bridges were used for the three pairs. The voltage was kept constant and the current was varied using a PWM signal. The setup will be used to test the magnetic actuators that will be used onboard the satellite

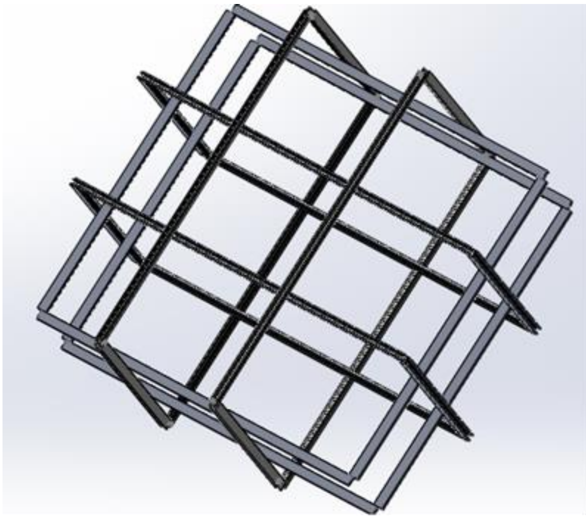


Fig. 4: CAD Model of the proposed Helmholtz Cage

6. Results and Discussion

The cage was completely designed and successfully developed by the team. The preliminary testing of the cage confirmed that the magnetic field intensity inside the cage is well within the required values. The cage was also tested along with the designed H-bridge driver circuit and performed as expected. A preliminary test for the MATLAB interface was successfully carried out as well. The preliminary testing of the various aspects of the cage was done before the final assembly.

Acknowledgements

Team Anant, the Student Satellite Team of BITS Pilani and the BITS Pilani Administration.

Appendix A: Helmholtz Cage Specification Sheet

Refer to Table 3.

References

[1] Magnetic Field Along the Axis of A Circular Coil Carrying Current, Retrieved 7 September 2017, iiith.vlab.co.in/?sub=1&brch=192&sim=972&cnt=1

[2] K. Pramoda, "Square Loop Coil System for Balancing and Calibration of Second-Order SQUID Gradiometers," *Journal of Physics: Conference Series*, 2010

Table 3. Calculated Specifications of the Helmholtz Cage

Constraints	Primary Coil	Secondary Coil	Tertiary Coil
Approximate Length of Side of Square, Metres:	1.3	1.2	1.15
Voltage at Full Load, Volts:	12	12	12
Distance between the Pair, Metres:	0.70785	0.6534	0.59895
Length of Region of Uniform Field, Metres:	0.52	0.48	0.44
Temperature Properties:			
Minimum **temperature, Kelvin**:	283	283	283
Nominal temperature, Kelvin:	293	293	293
Maximum temperature, Kelvin:	323	323	323
Copper Properties:			
Density, KG per metre-cubed:	8960	8960	8960
Resistivity at 20 degrees:	1.68E-08	1.68E-08	1.68E-08
Tempera**ture coefficient of resistivity**:	0.00393	0.00393	0.00393
Coil Parameters:			
Wire diameter:	0.00102	0.00102	0.00102
Manually inserted turns:	60	60	60
Maximum Allowed Current, Amperes:	2.3	2.3	2.3
Cross Section Area of Wire:	8.17128E-07	8.17128E-07	8.17128E-07

		Coil A	
Calculations for above stated specifications:	**Extreme 1**	**Normal**	**Extreme 2**
Resistance (ohms):	5.658371796	6.414660238	6.666756385
Maxim**um current through the coil (A)**:	1.799975776	1.870714824	2.120751416
Maximum Power **Consumption (W)**:	21.59970932	22.44857789	25.449017
Total Magnetic Field at the centre of two coils, Tesla:	0.000135287	0.000140604	0.000159397
Ratio with Earth's Magnetic Field in Pilani:	3.006384156	3.124535053	3.542155145
		Coil B	
Resistance (ohms):	5.223112427	5.921224835	6.153928971
Maxim**um current through the coil (A)**:	1.949973758	2.026607726	2.297480701
Maximum Power Consumption (W):	23.39968509	24.31929272	27.56976841
Total Magnetic Field at the centre of two coils, Tesla:	0.000158775	0.000165015	0.00018707
Ratio with Earth's Magnetic Field in Pilani:	3.52832585	3.666989056	4.157112635
		Coil C	
Resistance **(ohms)**:	4.787853	5.427789432	5.641102
Maxim**um current through the coil (A)**:	2.127244	2.210844792	2.506343
Maximum Power Consumption (W):	25.52693	26.53013751	30.07611
Total Magnetic Field at the centre of two coils, Tesla:	0.000189	0.000196381	0.000223
Ratio with Earth's Magnetic Field in Pilani:	4.198999	4.364020033	4.947308