Study and design of an active magnetorquer actuator model for nanosatellites

Aziz EL FATIMI [1,*], *Adnane ADDAIM* [1], and *Zouhair GUENNOUN* [1]

[1] Smart Communications Research Team (SCRT), University Center for Research in Space Technologies (CURTS), Mohammadia School of Engineers (EMI), Mohammed V University in Rabat (UM5R), Morocco

Abstract. This paper focuses on the study and the design of an air core magnetorquer model dedicated to the 1U CubeSat ($10 \times 10 \times 10\ cm^3$). The objective is to obtain a solution which is able to provide accurate attitude control while having the smallest possible dimensions, electrical power, and total mass. To this end, the first part will provide theoretical mathematical knowledge on the laws of the coil to design an electromagnetic air core actuator. Then, this paper presents comparisons of the performances obtained by varying the type of material and the shape of the coil. Towards the end, the effect of temperature variation in LEO orbit is taken into consideration to predict the generated magnetic moment.

1 Introduction

According to the standardization of nanosatellites, a CubeSat is composed of a payload, defined specifically for the mission to be fulfilled, and an often standardized platform providing support functions such as energy supply, propulsion, thermal control, maintaining orientation and communications [1].

To ensure its mission, the CubeSat must remain in a reference orbit by orienting its instruments precisely. From time to time, interventions are necessary at irregular intervals to correct the natural disturbances of the orbit generated by the irregularities of the gradient of the gravity field, the influence of the sun and the moon as well as the drag created by the atmosphere which remains in low orbit [2]. There is a panoply of actuators intended for attitude control. The three main types of magnetorquer currently used in nanosatellites are:

- *Air core magnetorquer:* This is the most basic design, which consists of a wire wrapped with many wells turns and integrated into the satellite. It has a constant magnetic dipole and a light weight. (Fig. 1) [3].

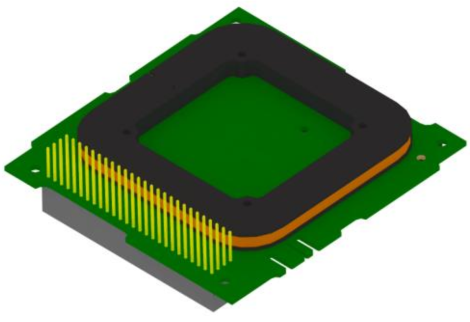

Figure 1. Air core electromagnetic actuator for controlling the z-axis.

- *Metal core magnetorquer:* It works on the same concept as an air core, except in this instance, a magnetic material core is encircled by a wire that is wrapped like a solenoid. Because the core creates a greater dipole when it's activated by the coil, this is the most efficient form of magnetorquer. However, the magnetization curve of the core is not linear and it presents a hysteresis phenomenon. Moreover, the material retains a residual magnetic dipole that does not dissipate when the coil is switched off. A significant gain in bulk is also a significant disadvantage. (Fig. 2) [4].

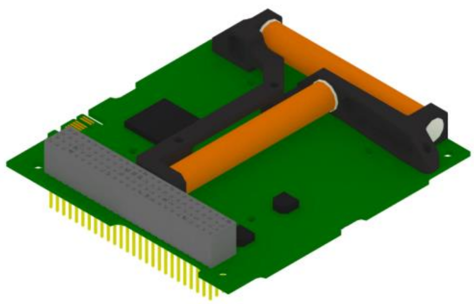

Figure 2. Air core electromagnetic actuator for controlling the x and y axis.

- *Printed magnetorquer:* The coil is reproduced on the PCB by copper traces. It is often integrated inside the solar panel, consuming less area inside the satellite. On the other hand, the thickness of the PCB and the presence of the solar panel's components limits the value of the magnetic dipole [5].

Magnetorquers provide several positive qualities that make them good candidates for nanosatellite application. These characteristics include minimal weight and power

* Corresponding author: azizelfatimi@research.emi.ac.ma

consumption, as well as installation due to the absence of moving components. In addition, it has an infinite operating cycle. However, because of the intensity of the terrestrial magnetic field varies with the geographical position such as longitude and latitude, their performance are restricted by the fact that they depend on an external variable which is the magnetic field. Furthermore, the unpredictability of magnetic models and errors in earth-field measurements might result an unstable control [6].

The rest of this document will deal, in the first part with the theoretical notions of the coil, then a comparative study of the material effect of the conductive wire of the coil, the shape of the coil as well as the effect of the temperature variation on the air core magnetorquer performances.

2 Theoretical formulation

An air core magnetorquer (electromagnetic actuator) is a multi-turned coil which uses the existing magnetic field in LEO orbit to adjust the CubeSat's orientation. The magnetic moment of a coil with N turns is given by the equation (1) below, where $\vec{n}$ is a unit vector perpendicular to the coil's plane, N is the number of turns, A is the coil's area, and I is the current [7].

$$\vec{m} = N.A.I.\vec{n} \tag{1}$$

The desired adjustment in attitude is produced by the magnetic torque, which enables the satellite to move around its center of mass. The dipole moment created by the magnetorquer $\vec{m}$ interacts with the magnetic field $\vec{B}$ present in low altitude orbit to produce the magnetic torque. The formula (2) expresses this interaction [7]. The magnetic torque which is created is perpendicular to both the magnetic field and the magnetic dipole moment. According to the equation (2), the torque vector direction attempts to match the magnetic field.

$$\vec{r} = \vec{m} \wedge \vec{B} \tag{2}$$

The torque generated by this equation is orthogonal to both the magnetic dipole moment $\vec{m}$ and the magnetic field $\vec{B}$. The torque vector's direction attempts to correspond with the magnetic field. For this purpose, it is interesting to maximize the magnetic moment produced by the turns. The response of the coil activated by electrical energy is well approximated by Equation (1). As a result, an ideal design must maximize the number of turns through the length of the wire constituting the coil, the electric current consumed I, or the coil's surface A as far as possible. A is mainly restricted by the CubeSat's dimensions, but an increase of N and/or I impacts the system's mass and/or energy consumption.

Considering the square coil as an ideal electrical conductor with constant section and uniform distribution mass, the resistance of the wire R may be calculated as a function of the wire's length L and section S [7]:

$$R = \sigma\frac{L}{S} = \sigma\frac{4aN}{S} \Rightarrow N = \frac{RS}{4a\sigma} \tag{3}$$

where a denotes the side of the square coil and σ denotes the electrical resistivity of the wire material.

The mass M of the loops may be estimated using the wire volume V and the material volume density ρ [7].

$$M = \rho V = \rho LS = 4a\rho NS \Rightarrow N = \frac{M}{4a\rho S} \tag{4}$$

Equation (5) explains the relation between the electric power P and the resistance of the wire R and the current I.

$$R = RI^2 \tag{5}$$

Finally, merging the equations (1), (3)-(5) gives the following expression.

$$m = A\sqrt{N^2I^2} = a^2\sqrt{\frac{RS}{4a\sigma}\frac{M}{4a\rho S}I^2} = \frac{a}{4}\sqrt{\frac{PM}{\sigma\rho}} \tag{6}$$

According to this equation, the magnetic dipole increases linearly with the side of the coil named a. Hence it is interesting to select the maximum value, taking into consideration the restrictions set by the CubeSat standard. Another comment is that the total consumption of electricity P appears to be multiplied by the total mass M, which means that the energy consumption can be reduced with an increase in the mass of the system. The same approach is valid for the reduction of the mass M. The role for each parameter is determined by changing the number of turns.

3 Study of active magnetorquer actuator

3.1 Design of the reference air core magnetorquer

The preliminary work consists of determining the requirements concerning the electric power, the mass, and the dimensions. In the perspective to design an active magnetic actuator, the numerical reference values for each requirement are based on the literature [8, 9]. The different numerical values adopted are summarized in the table 1.

The graph 3 represents a parametric study on the effect of varying the number of turns on the total mass, the power consumed, and the generated magnetic moment. For a chosen voltage of 5 V, an increase in the number of turns increases the mass of the system (linear proportionality) and considerably reduces the power consumed (quadratic proportionality). However, the magnetic moment obtained does not depend on the number of turns. Taking into account the requirements imposed previously, we will take the following values: Voltage = 5 V, Number of turns = 500, square shape, temperature = 20 $°C$ as reference values for the future comparisons studied in the sections 3.2 and 3.3.

Table 1. Design requirements of the air core magnetorquer.

Description	Parameter	Numeric value
Magnetic torque strength	$\vec{m}$	Maximization
Electrical power	P	< 200 mW
Operating temperature range	T	- 40 to 85 $°C$
Supply voltage	U	$\leq 5\ V$
Mass	M	< 30 g
Available area (PC/104 standard)	$L_{pcb} \times l_{pcb}$	96.5 × 90.5 mm^2

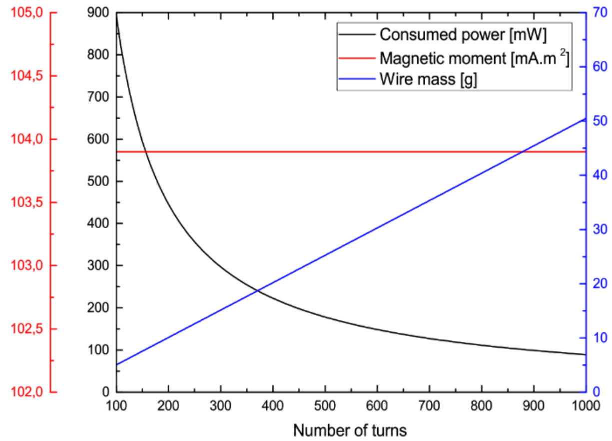

Figure 3. Behavior of the magnetorquer according to the number of turns.

3.2 Study of the effect of the coil's material on the magnetorquer performance

This section is devoted to the study of and the analysis of the effect of the coil's material on the magnetorquer performance. The coil taken as reference is a square coil of side 80 mm, having 500 turns and operating at a temperature of 20 $°C$. The most notable characteristics of gold, silver, copper, and aluminum are shown in the table 2 below [10-12]. The numerical calculations carried out show that there are important considerations to observe when designing an electromagnetic actuator.

According to the table 3, the choice of a silver coil considerably increases the magnetic moment generated and reaches an acceptable mass that meets the imposed requirement (< 30 g). The disadvantage of this material is the relatively high power consumption. Aluminum offers very low mass and energy consumption, but unfortunately, it offers a low magnetic moment compared to silver and copper.

Table 2. Physical properties of gold, silver, copper, and aluminum.

	Gold	Silver	Copper	Aluminum
Density ρ [$\times 10^3\ kg/g$]	19.3	10.49	8.94	2.71
Electrical resistivity σ at (20 $°C$) [$\times 10^{-8}\ \Omega.m$]	2.2	1.6	1.7	2.8
Temperature coefficient of resistivity at (20 $°C$) [$\times 10^{-3}\ 1/K$]	3.4	3.8	3.86	4.29

Table 3. Numerical results obtained by the variation of the material of the coil.

Wire material	Consumed power [mW]	Total mass [g]	Magnetic moment [$mA.m$]
Gold	125.5	54.6	80.3
Silver	172.6	29.7	110.4
Copper	162.4	25.3	103.9
Aluminum	98.6	7.7	63.1

3.3 Study of the effect of the coil's shape on the magnetorquer performance

The analysis procedure continues in the same way to see the effect of coil's shape on the performance of the system studied (N = 500 turns, T = 20 $°C$). The size and shape are chosen to respect the imposed requirement (Available area $L_{pcb} \times l_{pcb}$ = 96.5 × 90.5 mm^2). The figures 4.a - 4.d represent the ordinary geometries candidates for the design of magnetorquers.

As for the choice of material, the change in the shape of the coil radically modifies the variables involved in the design of the magnetorquer, the most notable being the magnetic moment generated, the current consumption, and the mass of the system. According to the table 4, the triangular and pentagon shapes have weak magnetic moments which do not justify the large consumption of energy. The square and circular shapes represent an interest to be used in magnetorquers. Their choice depends essentially on the budget in terms of mass and energy allocated to the attitude and orbit control system.

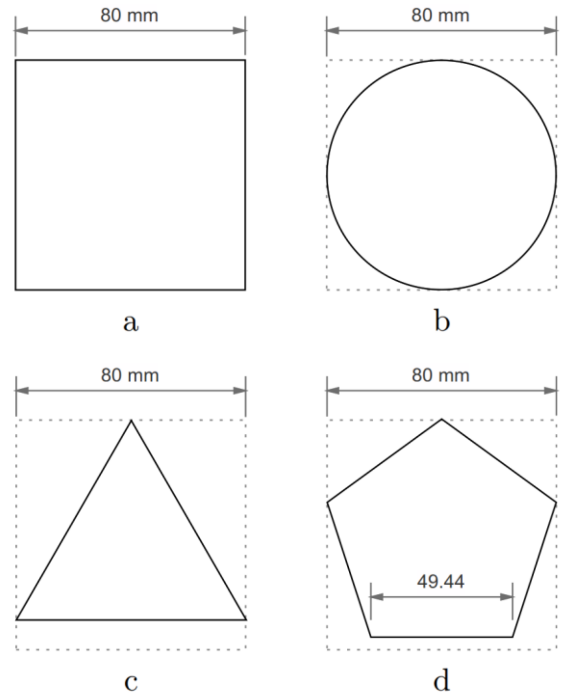

Figure 4. Ordinary geometries studied.

Table 4. Numerical results obtained by the variation of the shape of the coil.

Coil shape	Consumed power $[mW]$	Total mass $[g]$	Magnetic moment $[mA.m]$
Square	162.4	25.3	103.9
Circle	206.8	19.9	103.9
Triangular	216.6	19	60
Pentagon	210.3	19.5	88.42

3.4 Effect of the temperature variation on the magnetic moment

The effect of the change in temperature on the performance of the coil on the low orbit is an essential parameter to take into consideration. The temperature alteration modifies the wire resistance R, which varies both the energy consumption P and the produced magnetic moment m. As indicated in the equation (7), the electrical resistivity σ of the material may be represented as a function of temperature.

$$\sigma(T) = \sigma_0[1 + \alpha_0(T - T_0)] \quad (7)$$

where σ_0 represent the value of the electrical resistivity at T_0, and α_0 is the temperature coefficient [13]. From figure 5, it is interesting to note that the change of temperature in low orbit has a strong influence on the behavior of the coil, especially on the magnetic moment generated.

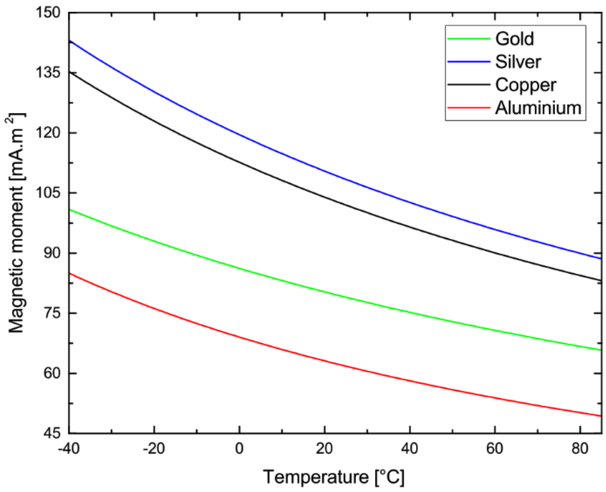

Figure 5. Effect of temperature on the magnetic moment generated by the coil.

4 Conclusion

In summary, the proposed work in this paper is intended for the study and analysis of an air core magnetorquer model that could be implemented in nanosatellites, in particular the 1U CubeSat $(10 \times 10 \times 10\ cm^3)$. The dimensions of the coil are chosen so that they are easily integrated on a PCB having the dimensions of $96.5 \times 90.5\ mm^2$. The numerical results confirm that silver is a good candidate for the realization of magnetorquers. In addition, the circular and square shapes are desirable to optimize both the size, the tolerated mass, and the power allocated to the actuators. The performance obtained is based on mathematical models where manufacturing precision errors and environmental disturbances are neglected. Then, the experimental validation is requested to evaluate each material and shape of the coil.

Acknowledgment

This work is carried out within the framework of the nanosatellite project which is a part of the partnership between the Royal Centre for Space Studies and Research (CRERS), and Mohammed V University (UM5R). So, the authors of this paper gratefully acknowledge the support of all who have contributed to the realization of this work.

References

1. C. L. G. Batista, A. C. Weller, E. Martins, et F. Mattiello-Francisco, Towards increasing nano-satellite subsystem robustness, Acta Astronautica, vol. 156, p. 187-196, mars (2019), doi:10.1016/j.actaastro.2018.11.011
2. M. Bouras et H. Berbia, Review of Attitude Control Approaches for ADCS Optimization and Faults Tolerance, in 2019 8th International Conference on Modeling Simulation and Applied Optimization (ICMSAO), avr. (2019), p. 1-4. doi: 10.1109/ICMSAO.2019.8880358

3. B. Bai, J. Zhou, et S. Wang, Design of High-Performance Magnetorquer with Air Core for CubeSat, JNWPU, vol. 36, n. 1, Art. n. 1, feb. (2018), doi:10.1051/jnwpu/20183610001
4. J. Li, M. Post, T. Wright, R. Lee, Design of attitude control systems for CubeSatclass nanosatellite. Journal of Control Science and Engineering, (2013), doi.org/10.1155/2013/657182
5. H. Ali, Q. ul Islam, M. R. Mughal, R. Mahmood, M. R. Anjum, et L. M. Reyneri, Design and Analysis of a Rectangular PCB Printed Magnetorquer for Nanosatellites, IEEE Journal on Miniaturization for Air and Space Systems, p. 1-1, (2020), doi:10.1109/JMASS.2020.3029489
6. N. Muhammad, et al, Component selection for magnetic attitude subsystem of PNSS-1 small satellite, 8th international conference on recent advances in space technologies (rast). IEEE, 2017, doi:10.1109/RAST.2017.8002959
7. S. Jayaram, Design of template to fabricate magnetic torquer coils for nano and picosatellite missions, J of Eng, Design and Tech, vol. 8, n. 2, p. 158-167, juill. (2010), doi:10.1108/17260531011062537
8. Magnetorquers MTQ3X, satsearch, [available at] https://satsearch.co/products/nanoavionics-magnetorquers-mtq3x, (accessed June 11, 2021)
9. I. S. K. Ishioka, S. Battistini, C. Cappelletti, et R. A. Borges, Design and development of an active magnetic actuator for attitude control system of nanosatellites, 4th IAA Conference on Small Satellites. International Academy of Astronautics, p. 16, (2017)
10. ASTM G1-03. Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens, dans Annual Book of ASTM Standards, vol. 03.02, West Conshohocken (Pennsylvanie), American Society for Testing and Materials, p. 1725, (2006)
11. Coefficient de température de résistance, https://riverglennapts.com/fr/resistance/748-temperature-coefficient-of-resistance.html, accessed June 12, 2021
12. Kurt Gieck, Formulaire technique (translated into French by G. Bendit, Engineering school of Biel - Switzerland), Gieck-Verlag, Heilbronn (RFA), chap. Z1
13. M.R. Ward, Electrical Engineering Science, McGraw-Hill, pp. 36{40, (1971