Embedded Magnetorquer Coil Design for Micro-Satellite

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Embedded Magnetorquer Coil Design for Micro-Satellite

Muhammad Musiab Aleem Dildar, Anwar Ali, Haider Ali, Muhammad Sadiq Khattak, Farhan Pervez

Abstract— This paper discusses magnetorquer coil design embedded in the microsatellite solar panel unit printed circuit board (PCB). Embedded magnetorquer is a good choice for attitude control and stabilization of nanosatellites because of their low weight, low heat dissipation and size compatible with the satellite dimensions. The proposed embedded magnetorquer coil is designed for a micro satellite (50kg mass and 450mm × 450mm × 450mm dimension).The designed parameters of the coil such as number of turns, trace material, thickness and width of the traces are selected according to the required magnetic moment to be generated. Theses coils are incorporated within the PCB four inner layers to generate the required torque and orientate the satellite in desired direction. Each PCB internal layer has 60 turns and the four inner layers have a total of 240 turns. Coil in each layer is a separate coil and has their terminals on the PCB surface. These terminals can be connected through switches. Altering the arrangement of these switches one can use individual coil, two coils in series or parallel, four coils in series or parallel and any hybrid arrangement. These different arrangements can provide an option for generating different amounts of magnetic moment and resultant torque to stabilize and rotate the satellite.

Key Terms— **PCB, ACS, Micro-Satellite**

I.   INTRODUCTION

Many universities around the globe are developing small satellites [1, 2], because of their relative design simplicity, shot development time and small budget requirement. They are launched in Low Earth Orbit (LEO) having low mass and small size. The concept starts from CubeSats developed at Stanford University and California Polytechnic State University in 1999. Many small and medium enterprises (SMEs) used CubeSats idea to build micro satellites for space research and application purposes for which the design and development efforts come from universities. Micro satellite is a good option for fulfilling the students desire to know and explore the space environment. It needs simple rights to use space and practicable option for universities across the world. With this idea, students can expand a valuable hands-on

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learning and experience in large space related projects and applications.

According to the spacecraft mass (1kg to 100kg) and size, small satellites are classified in different categories [3]. On the basis of mass and size they are characterized in Nano-satellite, Pico-satellite, and Micro-satellite [4]. A Micro-Satellite photo is shown in Fig. 1.
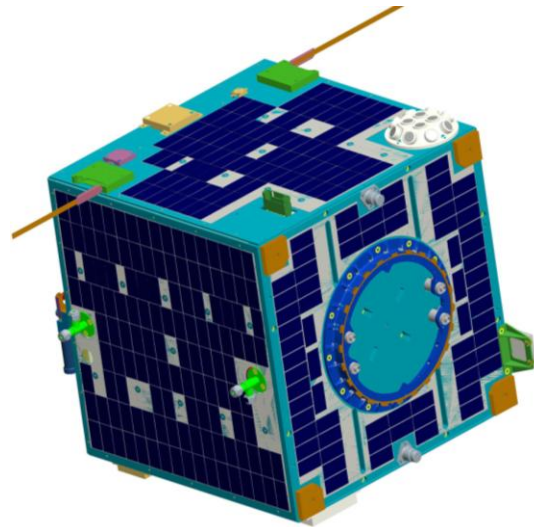

Fig. 1: Micro-Satellite photo [5]

Satellites require a suitable attitude control system (ACS) [2] to orientate and stabilize their position in space [3]. ACS is an integral part of any satellite that must be carefully designed and evaluated in the satellite development cycle. The ACS is normally categorized into two types' i.e. passive attitude control (satellite position control not according to the requirement) and active attitude control (satellite orientation control according to the need). Active attitude control is a wide subject which involves a variety of different fields such as power management and control theory. For this purpose ACS design is one of the most critical stage of the complete satellite development.

Different choices for ACS are available in the market such as magnetic torque rods, reaction wheels, permanent magnets and thrusters. Each of these systems have their pros and cons which are discussed briefly in the coming topics.

A.   Magnetic torque rod

A magnetic torque rod or torque bar is an actuator used for satellite attitude control. The principle is to produce a controllable magnetic moment which interacts with the Earth's magnetic field to produce a mechanical torque and rotate the satellite [6].

The generated magnetic moment can be controlled by the amount of current flow through these rods. These rods require

mounting space on the satellites and consume power. The torque level is relatively low therefore the spinning of satellite is relatively slow and inaccurate [7]. A Magnetic torque rod photo is shown in Fig. 2.

Fig. 2- Magnetic Torque rod [8]

B. Thrusters

Low thrust propellant or electric systems used to produce torques in the satellite. The drawback of thrusters is their cost, weight, high power consumption and the limited amount of propellant. Due to these limitations, thrusters are not commonly used in microsatellites. A Thrusters photo is shown in Fig. 3.

Fig. 3: Thrusters [9]

C. Reaction Wheel

The power consumption, mass, size and price of these devices are very high and therefore not compatible with micro and nano-satellite [7]. CubeSat reaction wheel photo is shown in Fig. 4.
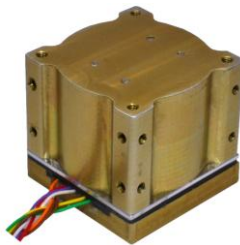

Fig. 4: Reactions wheel [10]

The paper is organized according to the following sequence. part 1 provides magnetorquer introduction, part 2 describes magnetorquer coil design procedure, part 3 provides simulation results of single coil, four coils in series and four coils in parallel and 2×2 Hybrid arrangement embeded in solar panel PCB and part 4 discusses the conclusion of proposed design.

II. THE EMBEDDED MAGNETORQUER DESIGN

Our aim is to design a magnetorquer coil that is embedded in solar panel PCB inner layers. The dimensions of the coil should be compatible with the solar panel unit dimensions (450mm × 450mm). The coil should be almost weightless (PCB traces), consume low power and generate the required amount of magnetic moment and intended torque. The generated torque should be enough to rotate 50kg microsatellite by $90°$ within three minutes. One of the critical issues on microsatellites is the available power. Utilizing the reconfigurable magnetorquer design concept, coils will be connected in different arrangements and power consumption can be altered according to the requirement. The available power bus voltage for the designed magnetorquer is 18 V. By changing the coil arrangements, from the same bus voltage (18V) different current is drawn and hence different power will be consumed. The generated magnetic moment direction can be changed by altering the direction of current through the coils.

The embedded magnetorquer works on the motor principle i.e. the generated magnetic moment ($\vec{D}$) of the coil, interacts with earth magnetic field ($\vec{B}$) which provides torque to orientate the satellite in the desired direction. The variation of the earth magnetic field in LEO is around ±0.5 G [11].

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A photo of the embedded magnetorquer coil, which is incorporated within the four interior layers (2, 3, 4 and 5) of an eight layers PCB, as is shown in Fig. 5. Coil in each layer has 60 turns and the four internal layers have a total of 240 turns. These coils are actually PCB copper traces with 18μm thickness and 1.8 mm width. Space between neighboring traces is 0.2 mm. The resistance of the magnetorquer coil depends on the area of trace and number of turns. When area and number of turns of each coil changes the resistance will also change. Resistance is linked with the generated magnetic moment, power consumption, and heat dissipation in the solar panel PCB.
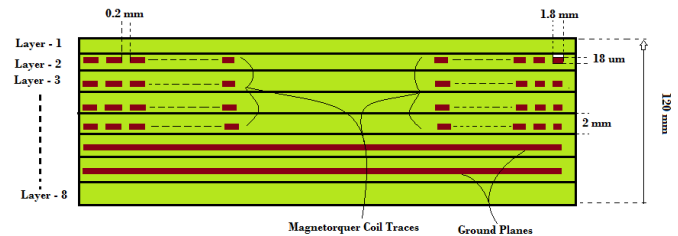

Fig. 5: Cross sectional view of the magnetorquer coil traces within PCB.

During the design phase construct the magnetorquer coil, compatible with the micro satellite size not only being lighter as well as able to produce the required magnetic moment. Magnetic moment is calculated through the following equation

$$\vec{D} = NSI \qquad (1)$$

Where N is the number of turns, S is the area of the single turn and I is the current passes through the coil. The required magnetic moment generated versus width of the trace for a fixed thickness (18μm) and fixed number of turns (240) is shown in Fig 6. The proposed magnetorquer coil design key parameters are illustrated in table I.
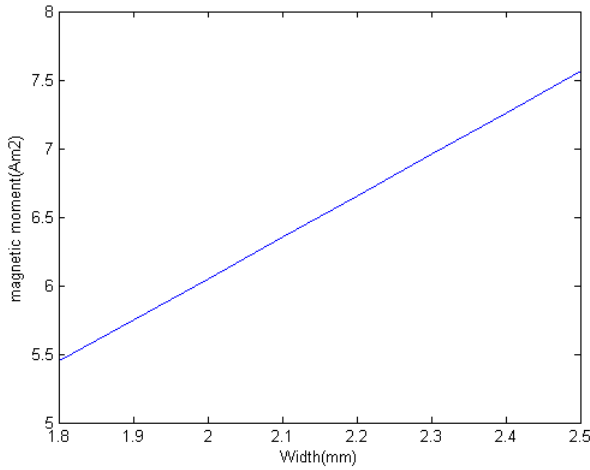
Fig. 6: Trace width versus magnetic moment generated

TABLE I
Embedded magnetorquer coil dimension parameters of single Coil

Parameter	Values
Single turn average length	1040mm
Total length of single coil	62.4m
Trace thickness	18μm
Trace width	1.8mm
Trace cross sectional Area	0.0324mm²
Distance between two adjacent traces	0.2mm
Bundle width (60 traces)	120mm
Copper resistivity (from manufacturer)	$1.7 \times 10^{-8} \Omega m$
Single coil resistance	29.27 Ω
Magnetic moment (Maximum, By using 4 coils in parallel)	6.5 Am²
Current for one coil	0.170A

A single coil has a bundle of 60 traces in single PCB layer and has a bundle width of 120mm and dimension of $400\,mm \times 400\,mm$ on the outside edge and $280\,mm \times 280\,mm$ on the inner side. Single coil dimensions and traces are shown in Fig. 7.
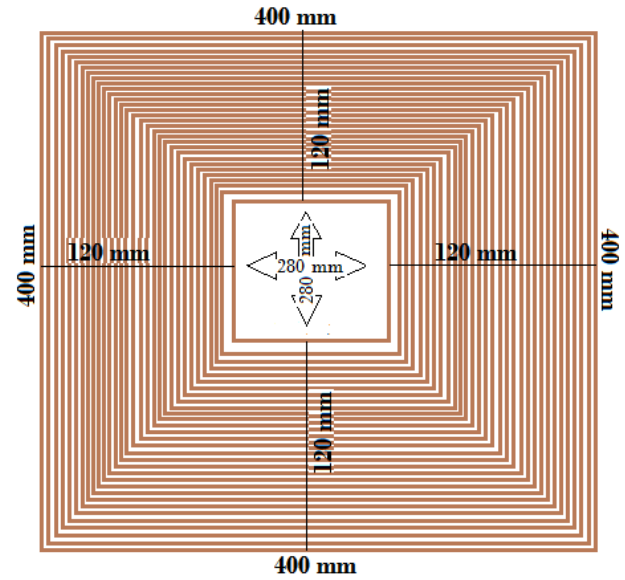

Fig. 7: Dimensions of single magnetorquer coil inside PCB internal layer.

When current carrying coil which generates a magnetic moment is placed in a magnetic field ($\vec{B}$), it produces a torque ($\vec{\tau}$) and is given by the following formula:

$$\vec{\tau} = \vec{D} \times \vec{B} = |\vec{D}||\vec{B}|\sin\theta \qquad (2)$$

Where $\vec{D}$ is the magnetic moment, $\vec{B}$ is the earth magnetic field and θ is the angle between $\vec{D}$ and $\vec{B}$.
The amount of current flowing through the magnetorquer coil controls the magnetic moment and the resultant torque. A magnetorquer coil is divided into 4 secondary coils; each coil is embedded in the interior layer and coupled through switches as shown in Fig. 8.
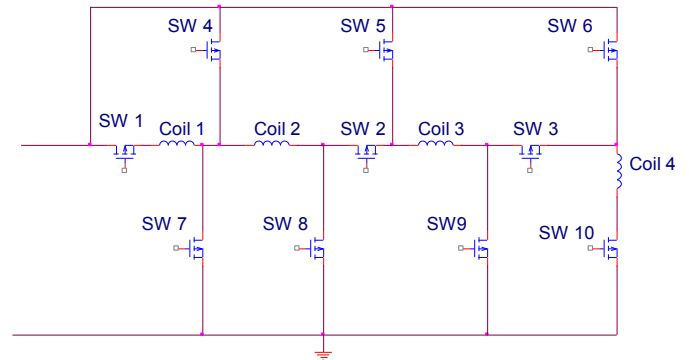

Fig 8: Magnetorquer coils connected through MOSFETs Switches.

Each coil is treaded individually and configure in any achievable arrangement. According to the requirements different arrangements can be chosen. In case of low voltage, all the four secondary coils are connected in parallel fashion and the essential magnetic moment can be achieved. Through this arrangement high current will draw and achieved high magnetic moment. Where as in case of high voltage, all the four secondary coils are connected in series and the essential

magnetic moment can be achieved. This array will draw a smaller current and achieved low magnetic moment. By altering the configuration of these resistors, we can use only 1 coil, 2 coils, 3 and 4 coils connected in series, parallel or hybrid combination. This design allows controlling the magnetic moment ($\vec{D}$), power dissipation and the resultatnt torque. The possible configuration is able to calculate on the basis of these three parameters. The relative amount of power dissipation and magnetic moment remains stable where the number of coils connected in parallel or in series. When increasing the number of coils connected in parallel or in series, the power consumption and magnetic moment also increase in the same percentage. Current remains constant for the coils connected in series while voltage remains constant in their parallel connection [13].

III.   SIMULATION RESULTS

A.   Generated Torque

Torque is produced when current flows through the magnetorquer coil. This torque is used to orient and stabilize the satellite in any desired direction. The exerted Torque mainly depends on the amount of current flowing through different combinations of coils, this current depends on apply voltages and resistance of a coil.The produced torque are plotted against applied voltage and current is shown in Fig. 10.
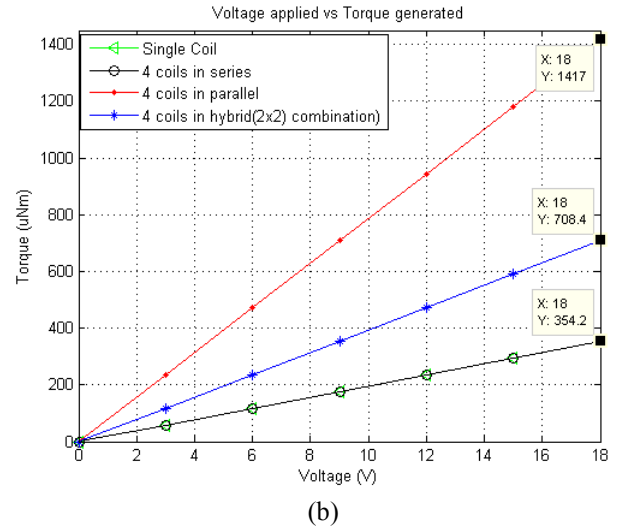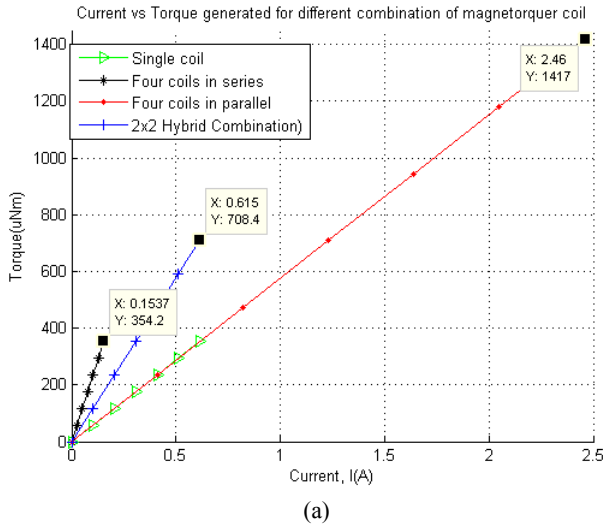
(a)

(b)

Fig 10: Plots of currents and voltage against generated torque in the presence of 0.5 G Earth magnetic field. (a) Current Vs torque, (b) Applied voltage Vs torque

B.   Magnetic moment versus Power Consumption

When current flows through the magnetorquer coils, the Magnetic moment is produced at the expense of power dissipation. The $\vec{D}_\circ$ is a magnetic moment of a single. In the case of M coils connected in series, parallel, or any hybrid combination, the magnetic moment is increased M times, where M is the number of coils connected in any possible combination. Similarly, power consumed by a single coil is P_o, and by M coils connected in any possible combination, it becomes M times that of single coil ($M P_o$). The ratio between magnetic moment produced and power consumed is given by;

$$\frac{D_\circ}{P_\circ} = \frac{N.S.I_\circ}{R_\circ.I_\circ^2} = \frac{(N.S)}{R_\circ}.\frac{1}{I_\circ} \qquad (3)$$

$$D_\circ^2 = \frac{(N.S)^2}{R_\circ}.P_\circ \qquad (4)$$

$$D^2 = n.m.\frac{(N.S)^2}{R_\circ}.P = k.P \qquad (5)$$

Where, k is a constant parameter that depends on the number of coils connected in series or in parallel and their dimensions. D^2/P_o or k is considered an important performance evaluation parameter for magnetorquer coils. Table II, shows that when the number of coils is increased, either in series or in parallel, the magnetic moment and power consumption also increase with the same ratio. The current remains constant in the case of series-connected coils, and voltage is constant in the case of parallel-connected coils. The ratio of magnetic moment to power consumption remains constant for any number of coils connected in series or in parallel [13].

TABLE II
Comparison of Current, Voltage, Dipole Moment, and Power Consumption for Different Combinations with Reference to Single Coil

Coil arrangement	Current (I)	Voltage (V)	Magnetic moment ($|D|$)	Power consumption (P)	$|D|/P$	$V/|D|$
1 coil	I	V	D	P	D/P	V/D
4 coils in series	I	4V	4D	4P	D/P	V/D
4 coils in parallel	4I	V	4D	4P	D/P	V/4D
4 coils in hybrid	2I	2V	4D	4P	D/P	V/2D

Table III

Coil arrangement	Current (I)	Voltage (V)	Magnetic Magnetic moment ($|D|$)	Power consumption (P)
1 coil	0.5	17.21	2.784	10.12
4 coils in series	0.14	17.1	2.74	2.498
4 coils in parallel	2.3	17.1	11.13	41
4 coils in hybrid	0.5	17.21	5.88	10.12

C.   Rotary motion

The angular speed (ω) of a satellite depends on the torque exerted and the moment of inertia J of the satellite. Suppose the satellite has to be rotated by an angle φ. The satellite angular speed ω increases linearly when applying a constant torque τ max for a certain time ($T/2$). To stop the satellite, an opposite torque of the same magnitude ($-τ$ max) and same duration ($T/2$) is applied. The opposite torque performs a braking action against the satellite spin so as to seize the satellite spin after covering the desired angle ϕ. According to Newton's second law of rotation,

$$\tau = J\dot{\omega} \tag{6}$$

The following expression illustrates the angular position φ:

$$\varphi = \dot{\omega}(\frac{T}{2})^2 + \dot{\omega}(\frac{T}{2})^2 = \frac{1}{2}\frac{\tau}{J}T^2 \tag{7}$$

The time T required for the magnetorquer coil to rotate the satellite through a certain angle ϕ can be obtained and is given by the following:

$$T = \sqrt{\frac{2J\theta}{\tau}} \tag{8}$$

It is apparent from (8) that torque exerted and time taken to rotate the satellite is inversely proportional. Fig. 11 shows the torque generated and the corresponding time to rotate the satellite at an angle of 90∘ by energizing different combinations of coils. The value of J for microsatellite is 6.23 kg m2. The torque generated by 4 coils in parallel is 944.6 μNm, which takes 204 s to rotate satellite through an angle of 90∘. In the case of 1 and 4 coils connected in series, generated torque is 354.2 μNm, which takes 333.1 s to rotate the satellite through an angle of 90∘. In the case of 2×2 hybrid combination, torque production is 708.4 μNm, which requires 235.5 s for 90∘ rotation.

D.   Comparison for Different Arrangement Of Coils

Comparisons of Current, Voltage, Magnetic Moment, and Power Consumption for Different arrangement with Reference to Single Coil are illustrated in table III and compare it with the help of plots. Fig. 12 shows the comparison between single coil versus 2×2 hybrid arrangement and four coils in series versus parallel arrangement

Fig 11: Produced Torque versus time taken

(a)

Plot(B) Four coils in series/parallel ambient T=25oC

X: 17.32
Y: 41

X: 17.32
Y: 23.67

X: 17.32
Y: 11.13

X: 17.32
Y: 4.643

X: 17.1
Y: 2.498

(b)
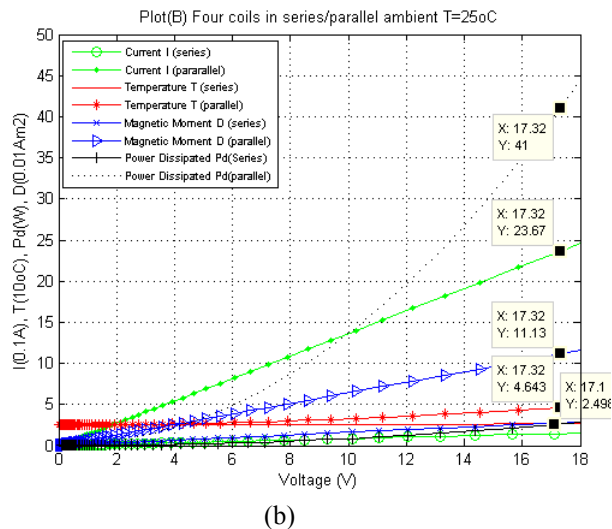
Fig 12: Comparison for Different Arrangement of Coils. (a) Single coil versus 2×2 hybrid arrangement, (b) four coils in series versus four coils in parallel arrangement

IV. CONCLUSION

The proposed magnetorquer coil design is compatible with the solar panel unit dimensions for this innovative design. Parallel arrangement of coils was used to control rotation and stabilization of the satellite. Parallel coil arrangement produces maximum magnetic moment and the resultant torque and lower power consumption. The designed magnetorquer is integrated inside the 4 interior layers of the PCB and occupies no extra space in the microsatellite. The coils traces are makes from copper extremely small dimensions, which result in very low weight. Different coils arrangement can be used depends on the application and requirements.

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