Department of Electrical Engineering

Design and Analysis of a Rectangular PCB Printed Magnetorquer for Nanosatellites

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Contents

Introduction

- A nanosatellite is any satellite with mass from 1 kg to 10 kg.
- A CubeSat is a common type of nanosatellite.
- Used in many areas, such as science experiments, environmental and climate monitoring, Earth observation, air and sea surveillance, and global positioning systems.

Satellite Subsystems

- Payload Subsytem
- Mechanical Subsytem
- Electrical Subsytem
- Communication Subsytem
- Attitude Determination and Control Subsystem

Satellite Subsytems

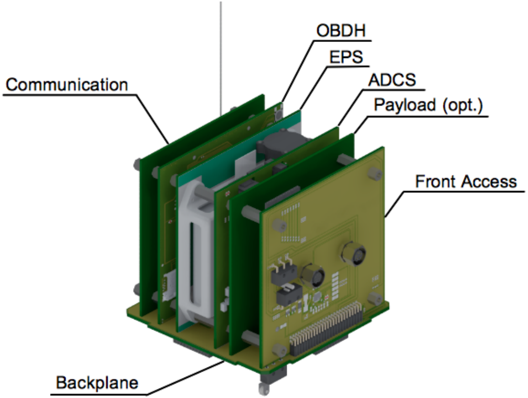

Figure: Subsystems overview of UWE-3 student satellite

ADCS

$$ADS + ACS \rightarrow ADCS$$

- ADS : determines the satellite's orientation on board in real time.
- ACS : controls the orientation of the satellite in space.
- Stabilize the satellite in case of unwanted rotations (detumbling).
- Keep the orientation fixed w.r.t. reference frame.
- Inertially orient the satellite in a particular direction of interest.

Components of ADCS

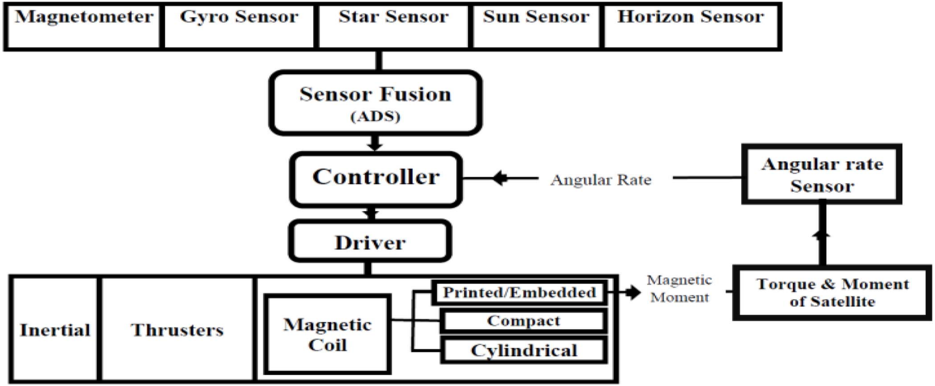

Figure: ADCS sensors, controllers and actuators

Magnetic Actuators

Magnetorquer consist of copper wire wound around a solid core (torquer rods) or wound in a round or rectangular shape without any core material (air core). Magnetic moment for current carrying loop is given by:

$$\vec{\mu} = N \cdot \vec{A} \cdot I_{coil} \tag{1}$$

$$\vec{T} = \vec{\mu}_{MT} \times \vec{B}_{earth} \tag{2}$$

B Dot Control Law

B-Dot control is a popular control law used to detumble CubeSats.

$$\mu = -k\dot{B} \tag{3}$$

where,

$$\dot{B} = -\omega \times B_{earth} \tag{4}$$

μ is the generated magnetic moment, ω is the angular velocity vector of satellite

Types of Magnetorquers

- Printed/Embedded
- Compact/ Air-cored
- Cylindrical/Iron-cored

Embedded coil

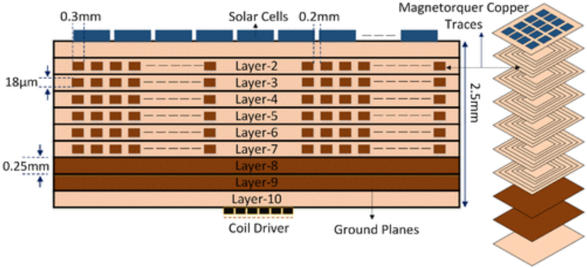

Figure: Multi layered printed magnetorquer

- Copper turns are printed into the internal layers of printed circuit board (PCB) which uses less power, has negligible mass, and occupies no extra space.

Circular Printed Magnetorquer

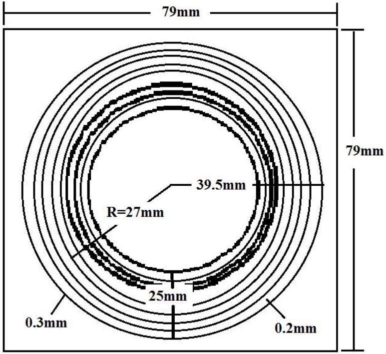

Figure: Dimensions of a single layer circular magnetorquer coil

Square Printed Magnetorquer

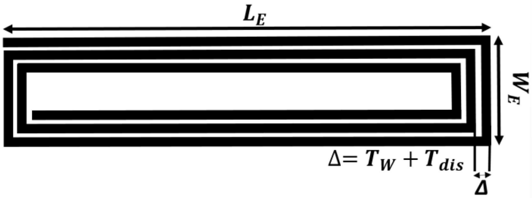

Figure: Design Parameters of PCB Magnetorquer

Circular and Square Coil Design Comparison

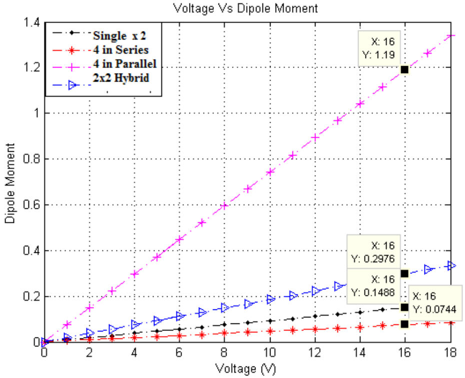

Figure: Voltage versus Dipole moment of Square Magnetorquers

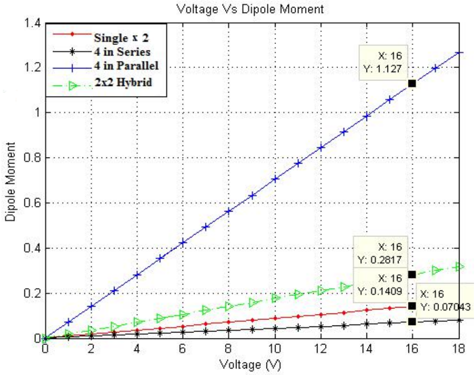

Figure: Voltage versus Dipole moment of Circular Magnetorquers

Comparison (continued...)

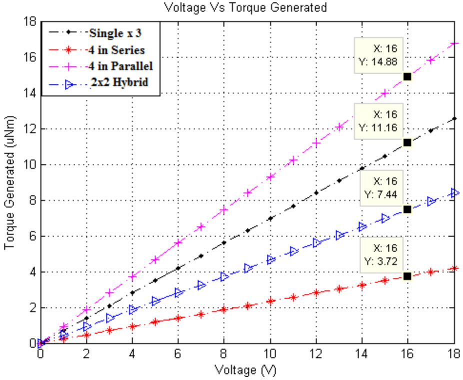

Figure: Voltage versus Torque generated of Square Magnetorquers

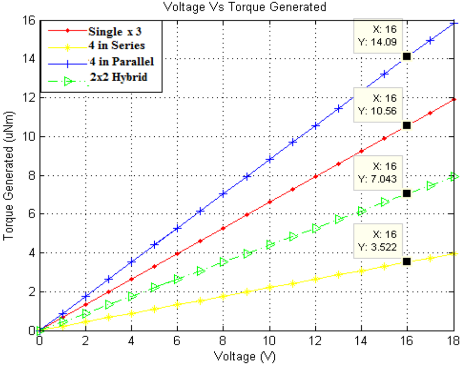

Figure: Voltage versus Torque generated of Circular Magnetorquers

Results

- The comparison shows that square magnetorquers produce better dipole moment than circular magnetorquers in all four cases.
- Square magnetorquers generate better torque than circular magnetorquers for given supply in all four cases.
- Power dissipation is comparatively less in square design.

Rectangular Coil Design

$\Delta = T_w + T_{dis}$
nth Turn Area $= \mathrm{L}_e - 2n\Delta * W_e - 2n\Delta$,
where, $\mathrm{L}_e = External\ length, W_e = External\ Width, W_i = Internal,$
n=N-1

$$N = \frac{W_e - W_i}{2\Delta}$$

Total Area $= \Sigma Areaofall Turns$

$$A = L_e * W_e + \sum_{n=1}^{N-1} L_e - 2n\Delta * W_e - 2n\Delta \tag{5}$$

Length and Resistance calculation

nth Turn Length $= 2*(\mathrm{L}_e - 2n\Delta + W_e - 2n\Delta)$

Total Length $= \Sigma Length\ of\ \ all\ \ Turns$

$$L = 2(L_e + W_e) + \sum_{n=1}^{N-1} 2 * (L_e - 2n\Delta + W_e - 2n\Delta) \tag{6}$$

where L is the total length of copper trace in one coil, ρ is the resistivity of copper.

$$R = \frac{\rho * L}{A_{cross}} = \frac{\rho * 2((L_e + W_e) + \sum_{n=1}^{N-1}(L_e - 2n\Delta + W_e - 2n\Delta))}{A_{cross}} \tag{7}$$

Power and Torque

$$Power, P = \frac{V^2}{R} = \frac{V^2 * A_{cross}}{\rho * 2((L_e + W_e) + \sum_{n=1}^{N-1}(L_e - 2n\Delta + W_e - 2n\Delta))} \tag{8}$$

$$Current, I = \frac{V}{R} = \frac{V * A_{cross}}{\rho * 2((L_e + W_e) + \sum_{n=1}^{N-1}(L_e - 2n\Delta + W_e - 2n\Delta))} \tag{9}$$

Power and Torque (contd.)

$$Torque, \tau = \frac{(L_e * W_e + \sum_{n=1}^{N-1} L_e - 2n\Delta * W_e - 2n\Delta) * V * A_{cross} * B}{\rho * 2((L_e + W_e) + \sum_{n=1}^{N-1}(L_e - 2n\Delta + W_e - 2n\Delta))} \tag{10}$$

$$\frac{\tau}{P} = \frac{(L_e * W_e + \sum_{n=1} N - 1 L_e - 2n\Delta * W_e - 2n\Delta) * B}{V} \tag{11}$$

Analysis

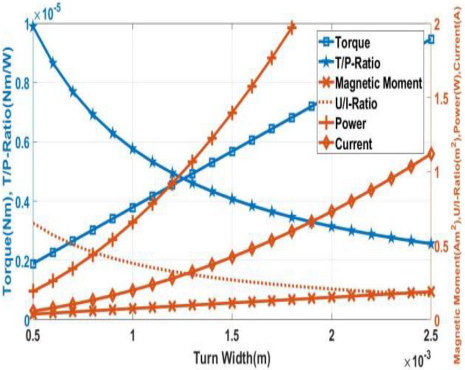

Figure: Torque Vs Turn Width

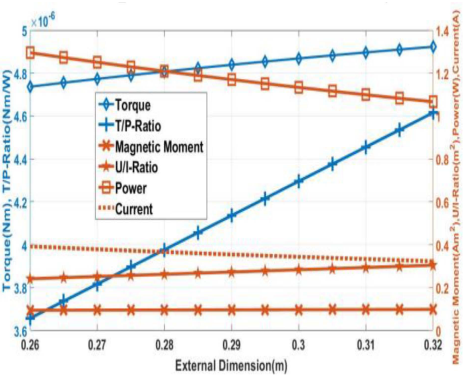

Figure: Torque Vs External Dimension

Analysis (Continued...)

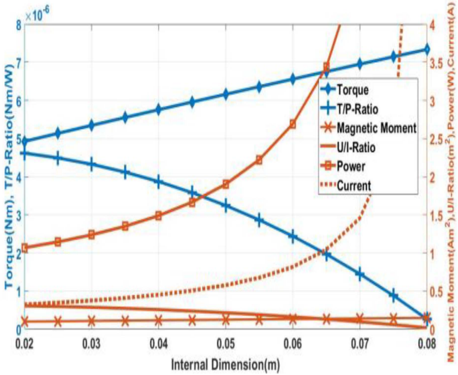

Figure: Torque Vs Internal Dimension

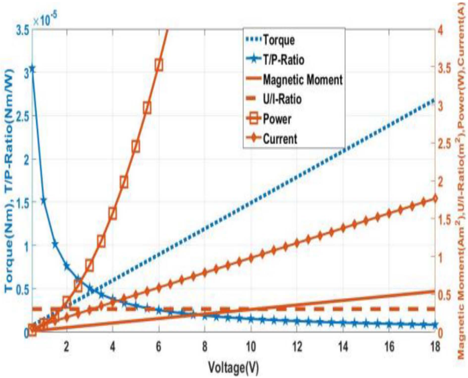

Figure: Torque Vs Voltage

Multilayered Panels

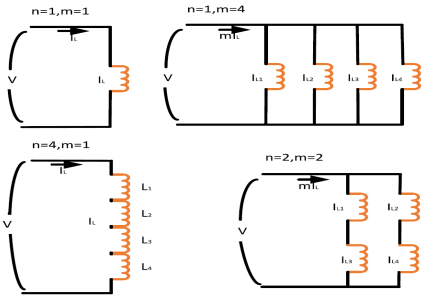

Figure: Reconfigurable printed magnetorquers

TABLE III

PERFORMANCE COMPARISON OF SQUARE AND RECTANGULAR PRINTED MAGNETORQUERS AT 3.3 V

Magnetorquer configuration	Magnetic moment Am^2	Power (W)	Current (A)	X×Y dimensions (mm)
Ref [19]	0.0284	0.56	0.169	90×90
Ref [31] Geometry 3	0.2202	1	0.303	300×100
Proposed Hybrid (2×2)	0.4281	1.026	0.311	320×80

Results

- On increasing turn width, torque-to-power ratio, magnetic moment to current ratio decreases and power consumption increases.
- As the printed traces enclose larger area of the panel, the resultant torque and torque-to-power ratio increases.
- Smaller the internal-most length, the greater the torque-to-power ratio.
- Increasing the applied voltage, torque-to-power ratio decreases rapidly.

Parameters of selected Design

TABLE IV
RECTANGULAR PRINTED MAGNETORQUER COIL DIMENSION
PARAMETERS OF SELECTED DESIGN

Parameter	Values
Length of coil (1 layer)	14604 mm
External Width side	82 mm
Internal width side	20 mm
External Length side	320 mm
Internal Length side	258 mm
Trace thickness	1.8 µm
Turn Width	1.3 mm
Area occupied (1 layer)	0.3441 m^2
Distance between adjacent turns	0.2 mm
Copper resistivity	$1.7\times 10^{-8}\ \Omega m$
Resistance (1 layer)	10.6097 Ω
Max. Current (2×2)	311.03 mA
Power consumed (2×2)	1.0264 W
Nominal Magnetic moment (2×2)	0.4281 Am^2
Working voltage	2V to 7V

Air-core Magnetorquer

Figure: Magnetorquer mounted on a side panel of UWE-3

Air core Characteristics

Parameter	Values
Average length of single turn	340 mm
Total length of Coil	65,200 mm
External turn side	90mm
Internal turn side	80mm
Cross sectional area of wire	1.02*10^-7 m^2
Area occupied by all turns	1.38 m^2
Resistance per meter	168.9mΩ
Single coil resistance	11.01 Ω
Magnetic moment by coil	0.4152 Am^2
Max power consumption	0.9 Watt
Working voltage	3.2V-10V

Figure: Compact coil magnetorquer design parameters

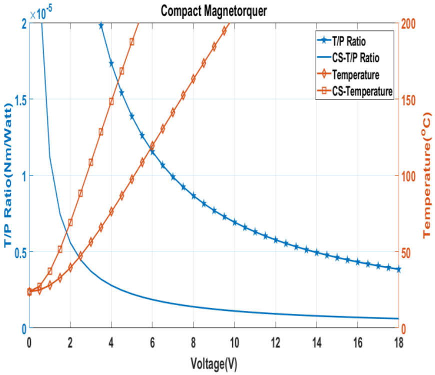

Figure: Voltage versus T/P

Torquerod

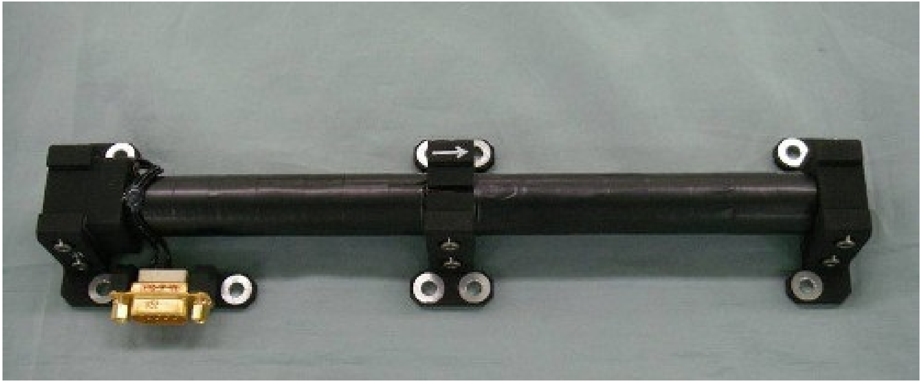

Figure: Magnetic torque rod actuator for spacecraft

Torquerod Characteristics

Parameter	Values
length of wire	48.9m
Length	75mm
Diameter	10mm
Cross sectional area of wire	0.065m^2
Area occupied by coil	0.0612m^2
Resistance per meter	268.5mΩ
Single coil resistance	13.14 Ω
Magnetic moment by coil	2.7 Am^2
Max power consumption	0.82 Watt
Working voltage	2V-10V

Figure: Magnetorquer rod design parameters

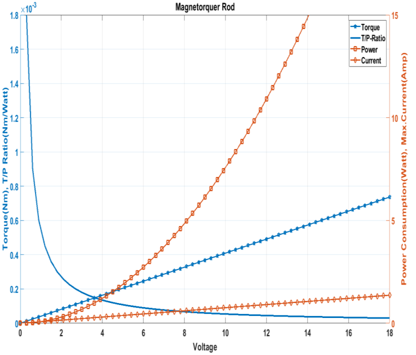

Figure: Voltage versus T/P

Conclusion

- Magnetorquer rod produce greater torque, but its power consumption is lower than compact coil and greater than printed coil..
- The PCB printed magnetorquers can be more beneficial in small form factor CubeSats and picosatellites since they are scalable, modular and reconfigurable.
- Square printed magnetorquer was analysed and optimised based on key parameter variations with respect to voltage, turnwidth and coil dimensions.

References

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2. Muhammad Rizwan Mughal,Hassan Ali,Jaan Praks,Leonardo M. Reyneri,"Optimized Design and Thermal Analysis of Printed Magnetorquer for Attitude Control of Reconfigurable Nanosatellites",IEEE Transactions on Aerospace and Electronic Systems VOL. 56, NO. 1 february 2020.

3. J. Li, M. Post, T. Wright, and R. Lee,"Design of attitude control systems for CubeSat-class nanosatellite",Control Sci. Eng., vol. 2013, p. 15,May 2013..

Thankyou!