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Design and Analysis of Magnetic Torquer for Attitude Control of Microsatellites

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Abstract—*Microsatellites are low in size and weight, use minimum power, launched in low earth orbit. Because of its low available power and size, selection of attitude control actuator is important one and also it should stabilize the satellites even presence of aerodynamics disturbances. The above requirements are fulfilled by the magnetic torquer. The overall design parameters and choosing high permeability material for designing a magnetic torquer has been presented. The dipole moment and torque values for various current inputs are calculated using theoretical formulas. Simulation is done by using Computer Simulation Technology-CST software. The magnetic flux density values for various current inputs are determined through simulation and the dipole moment and torque values are calculated. The required dipole moment is obtained in both theoretical as well as simulation and based on the results, choosing core materials is the important part while designing the magnetic torquer for microsatellites.*

1. INTRODUCTION

Satellites generally get power from solar panel. Increasing the number of solar panels may increase the weight and size of the satellite. The designed magnetic torquer should produce required dipole moment with in available power of the satellite. The magnetic torquer consists of cylindrical core material and wire rolled around the core. The core material should be ferromagnetic material due to its high permeability. Using low power consumption and low mass is the important parameter to be considered while choosing the core material. In most magnetic torquer, the double wire rolled around the core is to avoid the single failure situation. The microsatellites have smaller moment of inertia so the disturbances easily affect the attitude of satellites. To reduce changing attitude, the magnetic torquer should produce high torque within available power. In the literature, several schemes have been proposed for attitude control of microsatellites using magnetic torquer. Particularly, J.Lee, A.Ng, R.Jobanputra [1], described the vicinity of metallic objects, location and orientation of the magnetometer, having significant effects on magnetic flux density produced in the magnetic torquer. Mohamad Fakhari Mehrjardi, Mehran Mirshams [2] explained the design algorithm, choosing core material, driver and demagnetizing circuits. Zhou Meili, Qi Hongyu [3] established the mechanical interface, structure design, material selection, control circuit design based on initial specification. Seon-Ho Lee, Hyun-Ho Seo, and Seung-Wu Rhee [4], used “computer simulation technology” for numerical modeling for the similar problem. Rick Krauland, Adam Salerno, Matt Sams, Asa Wagner [5], briefly explains the theoretical calculation and winding process of magnetic torquer. H.D Arnold, G.W. Elmen [6], gave discussions about permalloy material and its chemical composition. Ali Aydinlioglu, Macro Hammer [8], explained the overview of Attitude Determination and control system (ADCS), hardware components and coil design based on design parameters, winding and testing of the magnetic torquer.

2. PRINCIPLE

When current is passed through the magnetic torquer, the magnetic field is created around it. Placing this magnetic torquer in an external magnetic field like earth magnetic field creates dipole moment (M) in the magnetic torquer. The dipole moment creates torque (T) force on magnetic torquer that will cause the magnetic torquer to rotate and aligned with the direction of earth magnetic field (B_E).

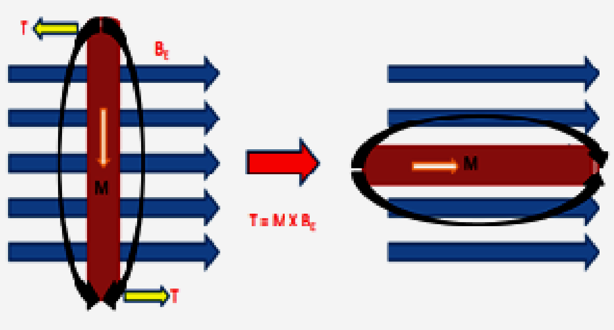


Fig. 1: Principle of magnetic torquer

Working of magnetic torquer fully depends on earth magnetic field, so the application of magnetic torquer is limited with low earth orbit satellites. Earth magnetic field varies with respect to altitude. The earth magnetic field is inversely proportional to third power of orbit height. To determine the magnetic torque values, details about the strength and direction of earth magnetic field, magnetic dipole moment of the spacecraft, and orientation of the dipole relative to the local magnetic field vector are needed, the magnetic flux density at various heights can be obtained using onboard magnetic meter. The strength and direction of dipole moment depends on (i) The amount of current flowing through coil, (ii) The direction of current flowing through coil, (iii) The number of turns in the coil, (iv) The total area enclosed by the coil. From above points, increasing length of wire and number of turns may increase dipole moment. But it also increases the weight of magnetic torquer. The amount of current flowing through the coil cannot be increased, because of limited power available in the satellite.

3. DESIGN ALGORITHM

After explaining the magnetic torquer principles, design algorithm is the next step for designing magnetic torquer.

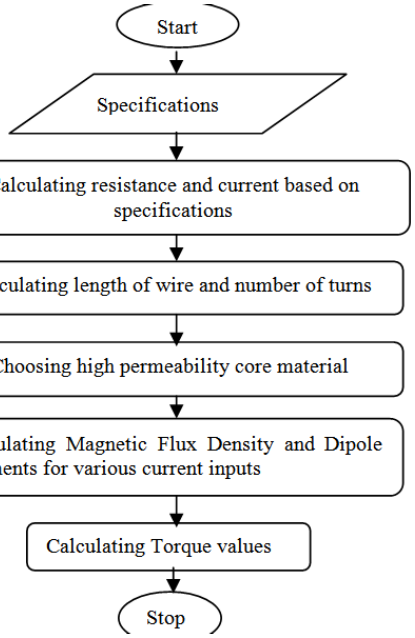


Fig. 2: Design algorithm

4. SPECIFICATIONS

The required specification for designing magnetic torquer with dipole moment is described as follows.

Core dimension:

Length= 325mm

Diameter = 14.5mm

Maximum current = 100mA

Power consumption = 0.5W

Dipole moment = 6Am^2

5. COIL DESIGN

Designing a coil for a satellite differs from that of commercial coils, because of its operation in the vacuum space. The magnetic torquer should produce required dipole moment within available power. 32 AWG copper wire (enameled) chosen for magnetic torquer because of its minimum resistance (0.538Ω/m), minimum resistivity (1.68x10^{-8}Ω.m), high conductivity (5.96x10^{7}S/m) fusing current capacity (0.5A) which in turn fulfill the design specification.

6. CORE SELECTION

Magnetic Materials are grouped into three categories. (i) Diamagnetic material which creates an induced magnetic field in a direction opposite to an externally applied magnetic field, and also repelled by the applied magnetic field. (ii) Paramagnetic material which are slightly attracted by a magnetic field and the material do not retain the magnetic properties when the external field is removed. (iii) Ferromagnetic material which is able to retain their magnetic properties after the external magnetic field has been removed. The ferromagnetic materials are classified into two categories (i) Soft materials (ii) Hard materials. The Hard materials are difficult to magnetize, but once magnetized it's not easy to demagnetize, the magnetization will occur only at high magnetic field. Mostly soft magnetic materials are chosen as core material because of its high permeability, low coercivity, and easy magnetization. In this work, a soft ferromagnetic material- Moly Permalloy (Nickel (80%) – Iron (14.8%) – Molybdenum (4.4%)) was chosen because of its high magnetic permeability low coercivity, and near zero magnetostriction.

7. MATERIALS AND METHODS

7.1 Theoretical formula

Magnetic flux density (B), Dipole moment (M) and Torque (T) are theoretically calculated by the following formulas (7.1)-(7.3)

$$\text{Magnetic flux density(B)}=\frac{\mu_o NI}{L(\frac{1}{\mu_r}+N_d)} \quad \ldots\ldots\ldots \quad \ldots (7.1)$$

$$\text{Dipole Moment(M)} = \frac{\pi r^2 NI}{\frac{1}{\mu_r}+N_d} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7.2)$$

$$\text{Torque (T)}=B*M \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \ldots\ldots\ldots\ldots.. (7.3)$$

Note: Refer table 1 for nomenclature.

7.2 Simulation formula

Magnetic flux densities (B) for various current inputs are obtained from the simulation using the "Computer Simulation

Technology", and the dipole moment calculated using the equation (7.4). The design of magnetic torquer in software is based on our theoretical calculation of design parameters.

$$\text{Dipole Moment (M)} = \frac{1}{\mu_0}\int B\,dv \qquad (7.4)$$

Table 1: Units and Dimensions

Symbol	Name	Unit
B	Magnetic flux density	G (or) T
M	Dipole moment	Am2
T	Torque	N.m
N	Number of turns	---
I	Current	A
L	Length of Coil	m
μ_r	Relative permeability	---
μ_o	Free space permeability	H/m
r	Radius of coil	m

G-Gauss, T- Tesla, A-Amphere, m-meter, N-Newton,

H-Henry

7.2 1 Steps involved in simulation

1. Designing a three dimensional magnetic torque of
Length = 325 mm, Diameter = 14.5 mm
2. Add the material properties to the magnetic torquer. Material properties were updated in the software database.
3. Add coil details to the magnetic torquer. Current, numbers of turns, coil resistance were defined.
4. Define boundary conditions.
5. Symmetry planes and plane which has magnetic flux lines details added to the design.
6. Solve for magnetic flux density.

7.2 2 Material properties and coil details

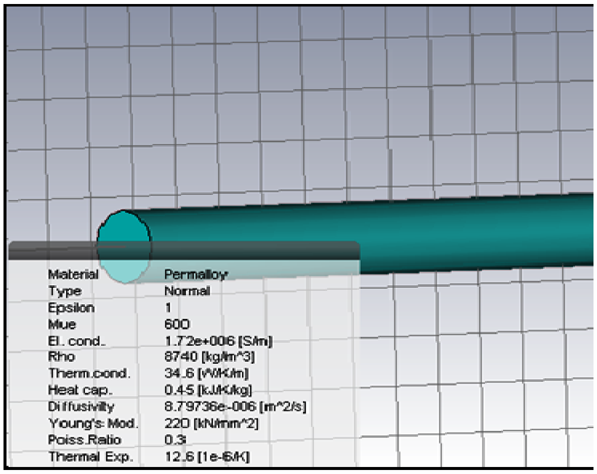
Material properties and coil details used for the design of magnetic torquer are shown in table 2.

Table 2: Properties of material

Name	Value	Unit
Electrical conductivity	1.72*106	S/m
Density	8740	kg/m3
Thermal conductivity	34.6	W/K/m
Heat capacity	0.45	kJ/K/kg
Young's modulus	220	kN/mm2
Thermal expansion	12.6*10-6	1/K
Poisson's ratio	0.3	
Number of turns	2042	
Resistance of coil	0.00003	Ω

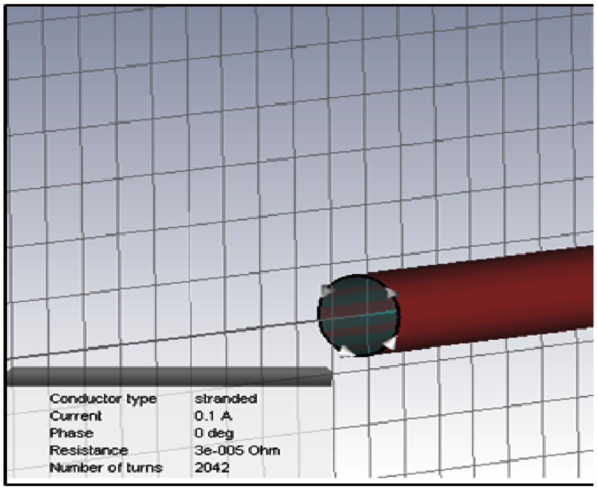
K-Kelvin, m-meter, kg-Kilogram, Ω-Ohm, N-Newton, J-Joule, W-Watt, S-Siemens

Design of solid rod with input material properties and with coil details are shown in Fig. 3 and 4 respectively.



Material Permalloy
Type Normal
Epsilon 1
Mue 600
El. cond. 1.72e+006 [S/m]
Rho 8740 [kg/m^3]
Therm.cond. 34.6 [W/K/m]
Heat cap. 0.45 [kJ/K/kg]
Diffusivity 8.79736e-006 [m^2/s]
Young's Mod. 220 [kN/mm^2]
Poiss.Ratio 0.3
Thermal Exp. 12.6 [1e-6/K]

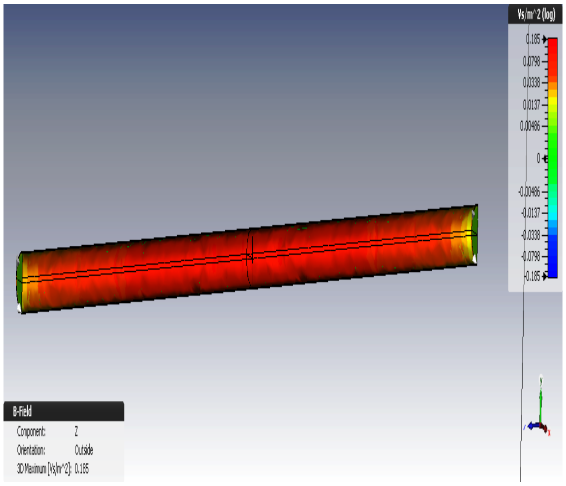
Fig. 3: Design with material properties



Conductor type stranded
Current 0.1 A
Phase 0 deg
Resistance 3e-005 Ohm
Number of turns 2042

Fig. 4: Design with coil details

7.2 3Simulation result



B-Field
Component: Z
Orientation: Outside
3D Maximum [Vs/m^2]: 0.185

Fig. 5: Magnetic flux density produced in magnetic torquer

Fig. 5 shows the magnetic flux density distribution for the material chosen with input current of 100mA. Simulations were done for various input current values and the result values shown in table 4.

8. RESULTS AND DISCUSSIONS

8.1 Dipole moment

Table 3 and table 4 shows the dipole moment for various current and respective magnetic flux density values obtained based on theoretical calculations and numerical simulation. It also shows that required dipole moment (6Am^2) can be obtained by passing 80mA current through the magnetic torquer which in turns saving 20mA.

Table 3: Dipole moments for various current inputs (Theoretical)

No	Current (mA)	Magnetic flux density (G)	Dipole moment (Am2)
1	20	0.03	1.27
2	40	0.06	2.63
3	60	0.09	3.91
4	80	0.12	5.21
5	100	0.15	6.40

Table 4: Dipole moments for various current inputs (Simulation)

No	Current (mA)	Magnetic flux density (T)	Dipole moment (Am2)
1	20	0.03	1.5
2	40	0.07	3.1
3	60	0.11	4.7
4	80	0.15	6.4
5	100	0.18	8

From the tables 3 and 4, its clear that material properties are the important factor to determine the Dipole moment.

8.2 Torque

Table 5 and table 6 shows the values of torque for various current inputs calculated by using theoretical formulas and Numerical simulations respectively. The torque value is mainly depends on magnetic flux density. So the similar trend obtained in the torque values

Table 5: Torque for various current inputs (Theoretical)

No.	Current (mA)	Torque (N.m)
1	20	0.03
2	40	0.16
3	60	0.36
4	80	0.64
5	100	0.98

Table 6: Torque for various current inputs (Simulation)

No.	Current (mA)	Torque (N.m)
1	20	0.05
2	40	0.22
3	60	0.52
4	80	0.96
5	100	1.48

From table 5 and table 6 it's clear that, obtained torque values are high in simulation compared with theoretical result for the corresponding current values.

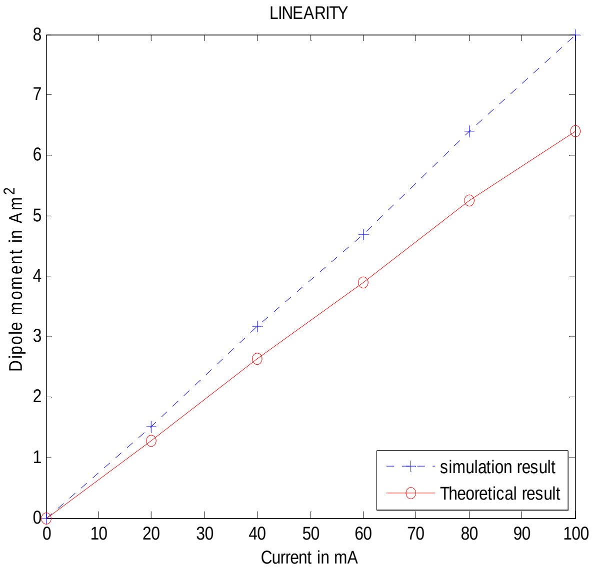


Fig. 6: Current vs Dipole moment

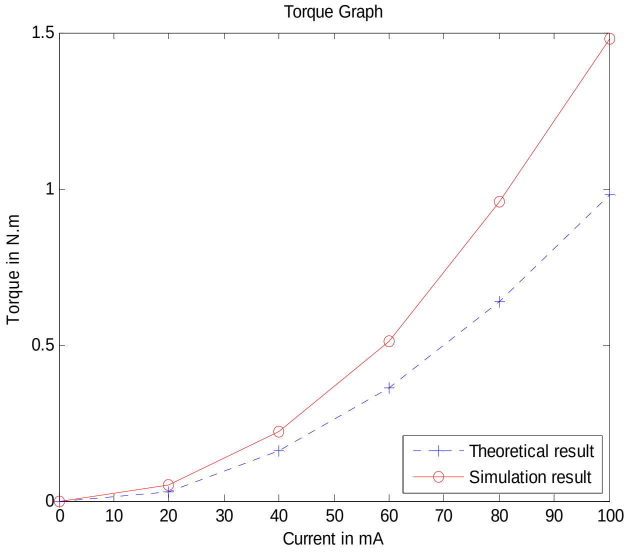


Fig. 7: Current vs Torque

Theoretical and numerical simulation results for dipole moment and torque were plotted against the respective current values is shown in Fig. 6 and 7 respectively. The Fig. 6 and 7 indicates the linear pattern of both the dipole moment and torque values.

9. CONCLUSION

In this paper, specifications for magnetic torque are established first and based on those design parameters, theoretical calculation and simulation results are obtained. The theoretical results are based on electrical properties and simulation results are based on material properties. From the results material properties of the magnetic torquer is an important factor to determine the power consumption to produce the required dipole moment and magnetic torquer.

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