On verifying magnetic dipole moment of a magnetic torquer by experiments

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Abstract. Magnetic torquers are used for the attitude control of small satellites, such as CubeSats with Low Earth Orbit (LEO). During the design of magnetic torquers, it is necessary to confirm if its magnetic dipole moment is enough to control the satellite attitude. The magnetic dipole moment can affect the detumbling time and the satellite rotation time. In addition, it is also necessary to understand how to design the magnetic torquer for operation in a CubeSat under the space environment at LEO. This paper reports an investigation of the magnetic dipole moment and the magnetic field generated by a circular air-coil magnetic torquer using experimental measurements. The experiment testbed was built on an air-bearing under a magnetic field generated by a Helmholtz coil. This paper also describes the procedure to determine and verify the magnetic dipole moment value of the designed circular air-core magnetic torquer. The experimental results are compared with the design calculations. According to the comparison results, the designed magnetic torquer reaches the required magnetic dipole moment. This designed magnetic torquer will be applied to the attitude control systems of a 1U CubeSat satellite in the project “KNACKSAT.”

1. Introduction

In recent years, satellite technologies have been developed greatly. In many satellite projects, the most important priority is to control the movement of the satellite for pointing any instrument or equipment it carries in a desired direction. Currently, there are many techniques for attitude control of a satellite such as thrusters, spin stabilization, momentum wheels, control moment gyros, solar sails, gravity-gradient stabilization, magnetic torquers and pure passive attitude control. All of these attitude control devices are called “actuators.” Several factors such as satellite dimensions, satellite operating time, satellite mission, must be considered for choosing an appropriate actuator type for a satellite.

This report focuses on a type of actuators which will be used in “KNACKSAT” (figure 1), a CubeSat satellite project in King Mongkut's University of Technology North Bangkok, Thailand [1]. In this case, three magnetic torquers for 3-axis attitude control have been selected for the CubeSat. The CubeSat category of interest is a CubeSat 1U which weighs 1 kg and has dimensions of 10 x 10 x 10 cm approximately, as shown in figure 1. Magnetic torquers are coils or permanent magnets which provide a moment against the local magnetic field. In the case of CubeSat 1U, magnetic torquers are appropriate for this satellite because their sizes can be minimized in the manufacturing process and they require a
low power supply. Magnetic torquer hardware is not complicated, because a magnetic torquer is a simple electromagnetic coil. However, one problem is to generate sufficient torque for the satellite mission. This report presents a methodology for measuring the torque of a magnetic torquer by placing it on an air-bearing inside a generated magnetic field provided by a Helmholtz coil. The torque produced by the magnetic torquer can be directly measured from the force acting on a gram gauge.

![Figure 1. KNACKSAT [1]](http://n-avionics.com)

2. Magnetic torquer
A magnetic torquer (MTQ) is one of the actuators which are widely used for attitude control in low Earth orbit satellites because MTQs are lightweight, reliable and energy-efficient [2-5]. The torque produced by an MTQ is required only to accelerate or decelerate the change in a satellite’s attitude by minute amounts. The MTQs are used in attitude determination and control subsystems (ADCS) for attitude control, detumbling, and stabilization. The MTQs are classified into two types, permanent magnets and electromagnetic coils, as shown in figure 2. Both types of the actuators produce a magnetic dipole moment which interacts with the Earth’s magnetic field to generate external torques on the satellite.

![Figure 2. Magnetic torquer types](https://www.magnetsource.com)

a. electromagnetic coils

b. permanent magnets
2.1. Magnetic field generation
This paper focuses on the electromagnetic coils MTQ. The MTQ produces mechanical torque to the satellite by generating its own magnetic field which interacts with the Earth’s magnetic field. The torquer is built in form of a copper winding. Once a current flows through the copper wire, a magnetic field is created, as shown in figure 3.

![MTQ operating concept](image)

The torque about an arbitrary point generated by a magnetic dipole in a uniform magnetic field is given as

$$\vec{T} = \vec{M} \times \vec{B}$$  \hspace{1cm} (1)

where
- $\vec{M}$ = magnetic dipole moment [Am²]
- $\vec{B}$ = flux density of the magnetic field [Tesla]
- $\vec{T}$ = torque generated by the magnetic dipole [Nm]

2.2. Design of MTQ
First of all, the restricting parameters in the design such as magnetic dipole moment, power loss due to coil resistance, voltage, mass, and also dimension parameters have to be determined. To be able to control the angular momentum of the satellite, the actuator must have enough control capability to overcome on-orbit disturbances such as external torque due to aerodynamic drag, solar radiation pressure and the Earth’s magnetic field as well.

![MTQ prototypes used in KNACKSAT](image)
Three MTQ circular coils were designed for a CubeSat 1U satellite named KNACKSAT, as shown in figure 4. The design specification of the MTQs under the satellite conditions must be taken into account. Due to the construction constraints, the concept of coreless electromagnetic coils for 3-axis attitude control is chosen. To create torque, two parameters need to considered, the magnetic dipole moment (\(\vec{M}\)) and the Earth’s magnetic field (\(\vec{B}\)) from equation (1). The magnetic dipole moment is calculated from the equation below.

\[
M = ANI
\]  

(2)

where

- \(M\) = magnetic dipole moment [Am²]
- \(A\) = cross section area of the MTQ [m²]
- \(N\) = number of turns of the MTQ
- \(I\) = current [A]

The MTQ is required to produce a magnetic dipole moment of 0.15 Am² at a maximum power input of 1 W. Table 1 summarizes the specification of the designed MTQs.

| Parameters                           | Value   |
|--------------------------------------|---------|
| Magnetic dipole moment, Am²          | 0.15    |
| Outer and Inner diameter, mm         | 82 and 72 |
| Thickness, mm                        | 3       |
| Cross section area, mm²              | 5,281   |
| Number of turn                       | 370     |
| Copper wire No.                      | AWG34   |
| Coil resistance, Ohm                 | ~38     |
| Coil inductance, mH                  | ~18     |

3. MTQ verification

3.1. Test principle

This experiment for verifying the designed MTQs involves the torque measurement methodology. The experiment is a direct method to measure a magnetic dipole moment of the MTQ by applying the methodology of the cross product of two magnetic fields interaction, as seen in the equation (1). In the experiment, the value of a magnetic field (\(B\)) is created by the Helmholtz coil, and the produced force of the MTQ can be measured using a gram gauge. We can calculate the torque (\(T\)) of the MTQ from an equation below where \(r\) is a distance from origin of the MTQ to the trailing edge of the gram gauge shaft.

\[
\vec{T} = \vec{F} \times \vec{r}
\]  

(3)

This experimental test-bed is set on an air-bearing to ensure that, when the test-bed is rolling, there is no effect of friction. The test-bed is shown in figure 5.
3.2. Test equipment

3.2.1. Helmholtz coil. A Helmholtz coil is a device for generating a region of nearly uniform magnetic field [6]. It consists of two identical coils placed symmetrically along a common axis with equal currents flowing in the same direction.

For generating a uniform magnetic field, the coils are parallel to each other and separated by a distance equal to the coil radius, R. The magnetic field lines for a Helmholtz coil are shown in figure 6. Figure 7 shows our implemented Helmholtz coil. The specification of the coil is summarizes in table 2.

![Helmholtz coil diagram](https://en.wikipedia.org/wiki/Helmholtz_coil)

**Figure 6. Magnetic field lines of Helmholtz coil**

| Parameters                          | Value    |
|-------------------------------------|----------|
| Magnetic field, M                   | 3.2382 mT|
| Maximum error at closed to coils    | 5.4 %    |
| Coil size                           | 20 AWG   |
| Number of turn in each coil, N      | 150 turns|
| Diameter of AWG20                   | 0.8128 mm|
| Maximum current for chassis wiring | 11 A     |
| Weight of a coil                    | 1.7541 kg|
| Coil Radius, R                      | 40 cm    |
| Current, I                          | 9 A      |
| Voltage, V                          | 226 V    |

**Table 2. Specification of the Helmholtz coil**

![MTQ torque measuring test-bed](image)

**Figure 5. MTQ torque measuring test-bed**
3.2.2. Air-bearing. Air-bearing (figure 8) is a bearing that uses a thin film of pressurized air to provide an exceedingly low friction load-bearing interface between surfaces. The two surfaces do not touch. As they are contact-free, air bearings avoid the traditional bearing-related problems of friction, wear, particulates, and lubricant handling, and offer distinct advantages in precision positioning, such as lacking backlash and static friction, as well as in high-speed applications.

3.2.3. Gram gauge. A gram gauge (figure 9) offers a very quick and easy method of measuring very low force between 0 and 0.1 N. The gram gauge scale has a resolution of 0.005N.
3.2.4 Electronic hardware The electronic hardware is needed for controlling the input current of the MTQ. To avoid friction caused by cable connections, the input current is controlled via a wireless communication system, as shown in figure 10. The system consists of a microcontroller, a current sensor, a coil driver, a Bluetooth module and a Lithium polymer battery.

![Electronic hardware diagram](image)

**Figure 10.** Electronic hardware diagram

4. Results
As mentioned in section 2.2, the maximum magnetic dipole moment of the MTQ should be 0.15 Am². In this experiment, the created magnetic fields are stronger than the Earth’s magnetic field at LEO, as shown in figure 11, so that the produced force is sufficiently large for the measurement range of the gram gauge. Therefore, the magnetic dipole moment in the experiment is more than 0.15 Am², as shown in table 3.

![World map of magnetic field at 600-800 km](image)

**Figure 11.** World map of magnetic field at 600-800 km by using ‘Tsyganenko 96’ model
(The magnetic field plot was taken from SPENVIS: http://www.spenvis.ome.be)
Table 3. Experimental result data

| Parameters                        | Values       |
|-----------------------------------|--------------|
| Force (F), N                      | 0.019        |
| Distance (R), m                   | 3.6 x 10⁻²   |
| Voltage supply to the MTQ, V      | 5            |
| Current supply to the MTQ (i), A | 0.142        |
| Current supply to the Helmholtz coil, A | 7.73       |
| Magnetic field of the Helmholtz coil (B), mT | 2.58     |
| Magnetic dipole moment (M), Am²   | 0.2651       |

5. Conclusion
In this experiment, the magnetic field generated by the Helmholtz coil was stronger than the Earth’s magnetic field, so that the generated force will be large enough for the measurement range of the gram gauge. From the relationship between magnetic dipole moment and input current of the MTQ in equation (2) we can plot a graph, as shown in figure 12.

![Figure 12. Magnetic dipole moment vs. current from the calculation](image)

In the experiment, only the maximum torque generated by the MTQ was measured. In this case, the maximum torque will be obtained when we supply a maximum voltage (5V) to the MTQ. From the calculation at the input current of 0.1 A, we get a magnetic dipole moment value of 0.19 Am². For the experiment, the input current of the MTQ coil was not precisely regulated because it was supplied by a voltage-controlled source at 5V. Therefore, the actual current depends on the coil resistance. From the experiment, a magnetic dipole moment of 0.265 Am² is measured at the input current of 0.142 A. Note that the input current is larger than expected, since the actual coil resistance is about 35.21 Ω, which is less than the calculated value of 38 Ω. When recalculating the theoretical magnetic dipole moment value with the actual current, the calculated magnetic dipole moment is 0.264 Am². Therefore, there is a very small deviation of 0.343% between the design calculation and the experiment. From the proportional calculation, the built MTQ coil is able to generate a magnetic dipole moment of 0.186 Am² at the input current of 0.1 A, which exceeds the required value of 0.15 Am². This result demonstrates a good accuracy of the MTQ design process and it confirms that the designed MTQ can deliver the expected magnetic dipole moment to fulfill the required task.
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