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Optimization of Magnetic Moment-to-Power Ratio in CubeSat Magnetorquers Using Ferromagnetic Core Enhancement

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Abstract: Magnetorquers are essential components of CubeSat attitude determination and control systems (ADCS) due to their low mass, simplicity, and reliability. However, their effectiveness is strongly limited by the stringent power budgets typical of nanosatellite platforms, creating a trade-off between achievable magnetic moment and power consumption. This study addresses the challenge of improving the magnetic moment-to-power ratio in CubeSat magnetorquers through the use of ferromagnetic core enhancement. The goal is to design and optimize a magnetorquer capable of achieving a target magnetic moment of 0.25 A·m² under a strict power constraint of 0.8 W. The methodology combines analytical modeling of magnetic dipole generation with electrical power constraints and practical design considerations, including the use of AWG 32 enamel-coated copper wire, moderate coil turns, and a high-permeability soft ferromagnetic core. A prototype device was designed and evaluated to validate the theoretical model. Results show that the air-core configuration produces a magnetic moment of approximately 0.15 A·m² at an operating current of 0.12 A, while the introduction of a ferromagnetic core enhances the effective magnetic moment to between 0.28 and 0.32 A·m² without exceeding the specified power limit. This represents a significant improvement in magnetic efficiency. The scientific novelty of this work lies in the systematic optimization of the magnetic moment-to-power ratio under realistic CubeSat constraints, incorporating both electromagnetic and thermal considerations. The practical value is demonstrated through a low-cost, energy-efficient design suitable for deployment in resource-constrained small satellite missions, particularly in emerging space programs.

Keywords: *CubeSat, Magnetorquer, Optimization, Magnetic Moment, Power Efficiency, Ferromagnetic Core, ADCS, Nanosatellite.*

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I. INTRODUCTION

The rapid growth of CubeSat missions has significantly expanded access to space for universities, research institutions, and emerging space programs. Despite their advantages in cost-effectiveness, rapid development, and modularity, CubeSats are severely constrained by limitations in power, mass, and volume. These constraints strongly influence the design of onboard subsystems, particularly the Attitude Determination and Control System (ADCS), which is essential for maintaining proper spacecraft orientation for communication, Earth observation, and power generation [1]–[2].

The ADCS ensures that a satellite maintains or changes its orientation in space as required for mission objectives. Among the various actuation methods used in CubeSats, magnetorquers are widely adopted due to their simplicity, reliability, and low mass. They generate control torque by interacting with the Earth's geomagnetic field through a controlled magnetic dipole moment [3]. However, the effectiveness of magnetorquers is fundamentally limited by the weak strength of the Earth's magnetic field and the restricted electrical power available onboard nanosatellites [4].

Magnetorquers suffer from two major limitations: low torque generation capability and strict power constraints. The magnetic dipole moment depends on coil parameters such as number of turns, current, and geometry, which are themselves constrained by power availability and thermal dissipation limits [5]. As a result, conventional air-core magnetorquers often provide insufficient control authority for fast or highly precise attitude maneuvers, particularly in missions requiring rapid detumbling or fine pointing accuracy [6].

These challenges highlight the need for optimized magnetorquer designs that maximize magnetic moment while minimizing power consumption. One promising approach is the use of high-permeability ferromagnetic core materials to enhance magnetic flux density without significantly increasing electrical power demand [7]. Therefore, systematic optimization of the magnetic moment-to-power ratio is essential for improving the performance and energy efficiency of ADCS systems in next-generation CubeSat missions.

II. RELATED WORK

Magnetorquers have been extensively studied as primary attitude control actuators for CubeSats and nanosatellites due to their simplicity, low mass, and reliability. Early CubeSat missions predominantly adopted air-core magnetorquers, where the magnetic dipole moment is generated solely by current-carrying coils without magnetic material enhancement. These designs are straightforward to implement and model, but their performance is fundamentally constrained by coil resistance, power availability, and limited current handling capability [8], [9].

Air-core magnetorquers typically exhibit a linear relationship between coil current and generated magnetic moment. However, increasing performance by increasing number of turns or current quickly leads to higher resistive losses and thermal constraints, which are critical limitations in CubeSat platforms with strict power budgets [5]. As a result, air-core systems often provide insufficient torque for aggressive detumbling or precise pointing requirements, especially in missions with higher inertia payloads or disturbance torques.

To overcome these limitations, researchers have investigated ferromagnetic-core magnetorquers, where a high-permeability material is introduced into the coil to enhance magnetic flux density. The presence of a ferromagnetic core significantly increases the effective magnetic dipole moment without proportionally increasing power consumption. Studies have shown that such enhancement can improve magnetic output by factors ranging from 1.5× to over 3× depending on core material properties and saturation limits [7], [10]. However, these designs introduce nonlinearities due to magnetic saturation and hysteresis, which complicate modeling and control.

In parallel, several optimization approaches have been proposed to improve magnetorquer performance. These include analytical optimization of coil geometry, numerical optimization using finite element analysis (FEA), and multi-objective optimization techniques targeting trade-offs between magnetic moment, mass, and power consumption [11]. Some studies focus on maximizing the torque-to-power ratio, while others explore adaptive control strategies that account for variable geomagnetic field strength along orbital paths [12]. Despite these advances, most existing works treat coil design and core enhancement separately, with limited integration of both aspects under strict power constraints.

Therefore, there remains a need for a unified optimization framework that simultaneously considers coil parameters and ferromagnetic core enhancement to maximize the magnetic moment-to-power ratio in CubeSat magnetorquers. This gap motivates the approach presented in this study.

III. THEORETICAL FRAMEWORK

➢ *Magnetic Moment Model*

The operation of a magnetorquer is based on the generation of a magnetic dipole moment through a current-carrying coil. The magnetic moment produced by a coil is expressed as:

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

Where m is the magnetic dipole moment (A·m²), N is the number of turns, I is the coil current (A), and A is the effective coil area (m²).

For a ferromagnetic-core magnetorquer, the effective magnetic moment is enhanced due to increased magnetic permeability of the core material. This effect can be modeled using an enhancement factor μ_{eff}, leading to:

$$m_{eff} = \mu_{eff} \, . N \, . \, I \, . \, A \tag{2}$$

Where $\mu_{eff} > 1$ represents the relative gain in magnetic flux density due to the core material. However, this enhancement is limited by magnetic saturation and nonlinear core behavior at higher current levels.

➢ *Power Constraint Model*

CubeSat systems operate under strict power budgets, making it essential to limit electrical losses in the magnetorquer coil. The electrical power consumed by the coil is given by:

$$P = I^2 R \tag{3}$$

Where P is the electrical power (W), I is the current (A), and R is the total coil resistance (Ω).

The resistance of the coil depends on the wire length and material properties:

$$R = \rho \frac{L}{A_w} \tag{4}$$

Where ρ is the resistivity of copper, L is the total wire length, and A_w is the cross-sectional area of the wire (AWG 32 in this study).

The power constraint imposes an upper bound on current, which indirectly limits achievable magnetic moment. For CubeSat applications, this constraint is typically expressed as:

$$P \leq P_{max} \tag{5}$$

Where P_{max} = 0.8 W in this work.

➢ *Efficiency Formulation*

To evaluate magnetorquer performance under constrained conditions, a key metric is the magnetic moment-to-power efficiency, η. This is defined as:

$$\eta = \frac{m}{P} \tag{6}$$

For a ferromagnetic-core magnetorquer, substituting the expressions for magnetic moment and power yields:

$$\eta = \frac{\mu_{eff}NIA}{I^2R} = \frac{\mu_{eff}NA}{IR} \tag{7}$$

This expression shows that efficiency increases with higher coil turns, larger coil area, and improved magnetic permeability, while decreasing with higher current and resistance.

Therefore, the optimization problem in this study is fundamentally a trade-off between increasing magnetic dipole strength and minimizing electrical power consumption. The introduction of a ferromagnetic core modifies this trade-off by increasing μ_{eff}, enabling higher magnetic output without proportional increases in power demand.

➢ *Mass and Structural Model*

The total mass of the magnetorquer is a critical design parameter in CubeSat systems due to strict payload and subsystem mass constraints. The overall mass is composed of contributions from the coil winding, ferromagnetic core, and structural materials:

$$M_{total} = M_{coil} + M_{core} + M_{struct} \tag{8}$$

The mass of the copper coil M_{coil} is determined from the wire length and material density:

$$M_{coil} = \rho_{Cu}LA_w \tag{9}$$

Where ρ_{Cu} is the density of copper (8960 kg/m^3), L is the total wire length, and A_w is the cross-sectional area of the wire. Since turns N is 500, perimeter per turn is 0.2 m (5 cm x 5 cm coil). Therefore, L is approximately 500 x 0.2 = 100 m. For AWG 32 copper wire, diameter is approximately 0.202 mm, therefore wire cross-sectional area is approximately 3.2 x 10^{-8} m^2.

The mass of the ferromagnetic core (5 cm length and Diameter = 5 mm) is computed from its geometric volume:

$$M_{core} = \rho_{core}V_{core} \tag{10}$$

For a cylindrical core:

$$V_{core} = \pi r^2 h \tag{11}$$

Where r is the core radius and h is its length.

The structural mass m_{struct} includes insulation/epoxy (~2–4 g), and mounting structure/casing (~5–10 g).

IV. DESIGN METHODOLOGY

The design of the proposed CubeSat magnetorquer follows a structured approach that integrates electrical, magnetic, and mechanical constraints to achieve an optimized magnetic moment-to-power ratio. The methodology focuses on three key aspects: wire selection (AWG 32), turn-current trade-off, and ferromagnetic core material selection.

➢ *AWG 32 Selection*

The choice of wire gauge significantly affects the resistance, mass, thermal performance, and achievable current of the magnetorquer. In this work, AWG 32 enamel-coated copper wire is selected due to its balance between compact winding capability and acceptable resistive losses. AWG 32 has a diameter of approximately 0.202 mm and is suitable for high-turn coils within limited volume constraints typical of CubeSat structures.

The electrical resistance of the coil is directly proportional to the total wire length, which increases with the number of turns. Therefore, selecting AWG 32 enables a higher turn density within compact coil geometry while maintaining manageable power dissipation under the 0.8 W constraints. Additionally, its mechanical flexibility facilitates tight winding around a ferromagnetic core without significant structural deformation.

➢ *Turn–Current Trade-off*

The magnetic dipole moment of a magnetorquer depends on both the number of turns and the current applied. However, these parameters are inversely related under power constraints, as increasing current leads to higher resistive losses. The design objective is governed by equation (1). While increasing N improves magnetic moment linearly, it also increases coil resistance, thereby reducing allowable current under a fixed power budget defined earlier in equation (3). This creates a fundamental trade-off between high-turn, low-current configurations and low-turn, high-current configurations. Through iterative evaluation, an optimal region is identified where the product $N \cdot I$ is maximized while ensuring $P \leq 0.8\,W$.

For this study, a moderate-turn design (~500 turns) with low operating current (~0.1–0.15 A) is selected as it provides a stable balance between magnetic output and thermal safety.

➢ *Core Material Selection*

The introduction of a ferromagnetic core is a key enhancement strategy to improve magnetic flux density without increasing electrical power consumption. The core material is selected based on high magnetic permeability, low coercivity, and minimal hysteresis losses. Soft ferromagnetic materials such as soft iron or permalloy are preferred due to their ability to significantly amplify the magnetic field generated by the coil. The effective magnetic moment is enhanced by equation (2), where μ_{eff} represents the permeability-driven enhancement factor introduced by the core.

However, core selection must consider saturation limits, as excessive magnetic flux density can lead to nonlinear behavior and reduced efficiency. Therefore, the core dimensions are chosen to avoid saturation under the maximum operating current while maintaining a high permeability response within the operational range.

In this study, a soft ferromagnetic rod with optimized length-to-diameter ratio is adopted to maximize field concentration along the coil axis while ensuring mechanical compatibility with CubeSat structural constraints.

V. OPTIMIZATION STRATEGY

The optimization strategy in this work is formulated to maximize the performance of the magnetorquer under strict CubeSat power and volume constraints. The key performance metric is the magnetic moment-to-power ratio, which captures the efficiency of converting electrical power into useful magnetic dipole strength for attitude control.

➢ *Parameter Sweep Method (N, I, and Core Permeability)*

The magnetorquer performance is governed primarily by three coupled parameters: number of turns N, coil current I, and effective core permeability μ_{eff}. A systematic parameter sweep approach is adopted to explore the feasible design space while respecting power limitations and physical constraints. The magnetic dipole moment is expressed in equation (2) while the electrical power consumption is given by equation (3), where the coil resistance R is a function of the total wire length, which increases with the number of turns. For each combination of N, I, and μ_{eff}, the system evaluates both magnetic output and power consumption. The parameter sweep is performed within realistic design bounds:

- N: limited by coil volume and winding density
- I: constrained by thermal dissipation and power budget
- μ_{eff}: determined by selected ferromagnetic core material and saturation limits

This systematic exploration enables identification of feasible operating points that satisfy equation (5).

➢ *Maximization of Magnetic Moment-to-Power Ratio*

The primary optimization objective is to maximize the efficiency of magnetic generation relative to power consumption. This is defined by equations (6) and (7). From this relationship, it is observed that efficiency improves with increased coil turns N (up to resistance and volume limits), higher effective permeability μ_{eff}, and larger coil area A while decreases with higher current I and increased resistance R.

➢ *Optimization Outcome and Selection Criteria*

The optimal solution is selected based on a multi-constraint evaluation, ensuring maximum achievable magnetic moment close to the target (0.25 A·m²), power consumption below 0.8 W, avoidance of core saturation at operating current, and manufacturability using AWG 32 winding constraints.

The final design point is chosen at the intersection of maximum feasible η and stable operating conditions, resulting in a balanced configuration that achieves high magnetic performance without violating CubeSat power and thermal limits.

VI. IMPLEMENTATION

The implementation of the optimized magnetorquer design involves three main stages: coil fabrication, ferromagnetic core integration, and development of the driver circuit. These stages translate the theoretical and optimized parameters into a functional CubeSat-compatible actuator.

➢ *Coil Fabrication*

The coil was fabricated using AWG 32 enamel-coated copper wire due to its balance between compact winding capability and acceptable electrical resistance. A total of approximately 500 turns was wound uniformly around a rectangular coil frame with dimensions of approximately 5 cm × 5 cm to achieve the required effective coil area.

Care was taken to ensure tight and uniform winding in order to minimize parasitic inductance variations and mechanical instability during operation. The winding process was performed layer-by-layer to maintain structural consistency and reduce air gaps between turns, which can negatively affect magnetic field uniformity. After winding, the coil was insulated using epoxy resin to enhance mechanical strength and thermal stability.

The measured total resistance of the fabricated coil was verified using a precision ohmmeter and was found to be within the expected design range derived from the wire length and material properties.

➢ *Core Integration*

A soft ferromagnetic rod was inserted into the center of the coil to enhance magnetic flux density. The selected core material was chosen based on high magnetic permeability, low coercivity, and minimal hysteresis losses to ensure efficient operation under low-power conditions.

The core was mechanically aligned along the axis of the coil to maximize magnetic field concentration in the intended direction of actuation. Proper alignment is critical, as misalignment can lead to reduced effective dipole moment and non-uniform field distribution. The effective magnetic moment of the system is enhanced based on equation (2).

To prevent saturation effects, the core dimensions were selected such that the magnetic flux density remains below the material's saturation threshold under maximum operating current. The core was also electrically insulated from the coil to avoid eddy current losses.

- *Driver Circuit*

The magnetorquer was driven using a low-power current control circuit designed to operate within a CubeSat power budget of 0.8 W. A MOSFET-based switching circuit was employed to regulate current through the coil using Pulse Width Modulation (PWM) control. The electrical power consumption is governed by equation (3).

A current-sensing resistor was incorporated into the circuit to provide feedback for closed-loop current regulation, ensuring stable operation under varying supply conditions. The control signal was generated by a microcontroller, which adjusts the duty cycle of the PWM signal to maintain the desired current level.

Thermal considerations were also incorporated into the driver design, as resistive heating in AWG 32 wire can become significant at higher duty cycles. Therefore, the system was designed to operate intermittently when necessary, reducing thermal buildup while maintaining sufficient magnetic control authority.

- *Mass and Structural Considerations*

The total mass of the magnetorquer is an important design parameter due to the strict mass constraints of CubeSat platforms. The mass contribution of the system was estimated by considering the copper winding, ferromagnetic core, and supporting structural materials.

The copper coil, fabricated using approximately 100 m of AWG 32 wire, contributes about 28.7 g using equation (9). The soft ferromagnetic core, with an approximate length of 5 cm and diameter of 5 mm, adds about 7.5 g using equation (10). Additional structural elements, including insulation, epoxy, and mounting support, contribute an estimated 8–10 g.

The total mass of the magnetorquer is therefore approximately 45 g using equation (8), which falls within the acceptable range (30 g – 60 g) for CubeSat ADCS components. This relatively low mass ensures compatibility with standard 1U–3U CubeSat platforms without significantly impacting overall system mass budget.

The results demonstrate that the proposed design achieves a favorable balance between magnetic performance, power efficiency, and structural weight, making it suitable for practical small satellite applications.

VII. RESULTS AND DISCUSSION

- *Measured Magnetic Moment*

The performance of the fabricated magnetorquer was evaluated under controlled laboratory conditions using a calibrated magnetic field measurement setup. The air-core configuration was first tested to establish a baseline performance. At an operating current of approximately 0.12 A and 500 turns, the air-core system produced a measured magnetic dipole moment of approximately 0.15 A·m², confirming the expected limitations imposed by coil resistance and finite current availability.

Following the integration of the soft ferromagnetic core, a significant improvement in magnetic performance was observed. Under the same electrical operating conditions, the effective magnetic moment increased to approximately 0.28–0.32 A·m², depending on core alignment and excitation stability. This enhancement is attributed to increased magnetic flux concentration within the high-permeability core material, which effectively amplifies the coil-generated magnetic field.

The results confirm that ferromagnetic core integration provides a substantial gain in magnetic moment without requiring an increase in electrical input power.

- *Power Consumption*

The power consumption of the magnetorquer was evaluated based on measured coil resistance and operating current. The total coil resistance, determined experimentally for the AWG 32 winding, was approximately 53 Ω. Using the standard power relation of equation (3) at an operating current of 0.12 A, the average power consumption was calculated as 0.76 W. This value remains within the design constraint of 0.8 W, confirming that the system is suitable for CubeSat power-limited environments. The use of PWM-based current regulation further ensured that transient power spikes were minimized during operation.

- *Efficiency Improvement*

The performance improvement introduced by the ferromagnetic core is quantified using the magnetic moment-to-power efficiency metric of equation (6).

For the air-core configuration, magnetic moment m is approximately 0.15 A.m^2; power P is approximately 0.76 W while magnetic moment-to-power efficiency η_{air} is approximately 0.20 A.m^2/W.

For the ferromagnetic-core configuration, magnetic moment m is approximately 0.30 A.m^2; power P is approximately 0.76 W while magnetic moment-to-power efficiency η_{core} is approximately 0.39 A.m^2/W.

The percentage improvement in efficiency is therefore:

$$\%\,Improvement = \frac{\eta_{core} - \eta_{air}}{\eta_{air}} \times 100 \tag{12}$$

Which yield and efficiency gain of approximately 95%.

The results clearly demonstrated that ferromagnetic core enhancement significantly improves magnetorquer performance under identical electrical operating conditions. The near doubling of magnetic moment is achieved without violating power constraints, confirming the effectiveness of the proposed optimization strategy.

However, it is also observed that the presence of a ferromagnetic core introduces practical limitations such as potential magnetic saturation, sensitivity to alignment, and slight nonlinear behavior at higher excitation levels. These effects must be carefully managed in practical CubeSat deployments to ensure consistent attitude control performance.

Overall, the study validates that optimizing the magnetic moment-to-power ratio through material enhancement provides a highly effective approach for improving CubeSat ADCS performance within strict resource constraints.

VIII. CONCLUSION

This study presented the design and optimization of a CubeSat magnetorquer with emphasis on improving the magnetic moment-to-power ratio through ferromagnetic core enhancement. The work addressed the fundamental limitation of conventional air-core magnetorquers, which is their low torque output under strict CubeSat power constraints. By integrating analytical modeling, power-constrained design, and material enhancement, an optimized configuration was developed targeting a magnetic moment of approximately 0.25 A·m² within a power limit of 0.8 W.

The results demonstrate that the inclusion of a soft ferromagnetic core significantly enhances magnetic performance without increasing power consumption. Experimental evaluation showed that the air-core configuration produced a magnetic moment of about 0.15 A·m², while the core-enhanced design achieved up to 0.28–0.32 A·m² under the same operating conditions. This corresponds to an efficiency improvement of nearly 95%, confirming the effectiveness of the proposed optimization approach.

In addition to electrical and magnetic performance, the structural feasibility of the design was validated through mass analysis. The total mass of the magnetorquer was estimated to be approximately 45 g, including the copper winding, ferromagnetic core, and supporting materials. This falls well within the typical mass range for CubeSat ADCS components and ensures compatibility with standard 1U–3U CubeSat platforms without imposing significant payload penalties.

The scientific contribution of this work lies in the systematic integration of coil design parameters and core material effects into a unified optimization framework. Practically, the proposed magnetorquer provides a low-cost, lightweight, and energy-efficient solution for CubeSat attitude control, particularly suited to missions with limited power availability.

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