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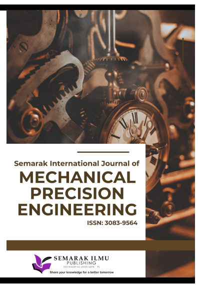

Analysis on the Torque Generation of a Satellite System with Three Reaction Wheels

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ABSTRACT

With the rapid advancement of satellite technology, precise attitude control has become increasingly critical to ensure that satellites perform their intended functions effectively. The reliability of satellite operations heavily depends on the performance of key control actuators. These reaction wheels are typically arranged in either three- or four-wheel configurations, allowing for efficient manoeuvring in three-dimensional space. The torque generated by these spinning wheels plays a vital role in accurately adjusting the satellite's attitude. This project focuses on analysing torque generation in a satellite system utilizing a three-reaction-wheel configuration. Central to this analysis is the development of a mathematical model that captures the principles of torque generation, enabling the computation of the torque contributed by each wheel in a given setup. The torque outputs are analysed using MATLAB simulations, which visualize the torque envelope also known as the convex hull of each configuration. MATLAB code was used calculate torque combinations, generate convex hulls, and compare different configurations. Based on the research, it is found that various configuration will produce strength and weaknesses in particular axis of rotation. Depending on the needs of the satellite mission, the torque envelope can be applied to optimize the torque.

1. Introduction

Satellites play a crucial role in modern digital systems, supporting applications such as communication, navigation, and space research. A key performance aspect of a satellite is attitude control, which ensures the satellite maintains the correct orientation in space. This is commonly achieved using reaction wheels that provide control over three rotational axes: yaw, pitch, and roll using a PD controller [1]. Reaction wheels are cost effective actuators commonly used in spacecraft attitude control due to their ability to perform with high precision, accuracy, and agility [2,3].

At least three reaction wheels are required for full 3-axis attitude control of a spacecraft [4]. Nevertheless, despite their well-known advantages, reaction wheels suffer from a limitation known as torque saturation, which can impact long-term performance and reliability [5]. Configuration of

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these reaction wheels also plays an important role. This is proved in Posani *et al*., [6] that various reaction wheel configurations show different configurations could affect the precision of torque generation. Illustration of different configuration of reaction wheels can be shown by the technique shown in Yoon *et al*., [7] which contributed by proposing a method for analyzing the torque and momentum envelopes for various configurations. Hence, the configuration optimization has also been a hot topic for discussion. Kasiri *et al*., [8] developed a pyramidal configuration to reduce angular momentum thus demonstrating how geometry configurations affect the systems' performance but despite these advancements they did not assess other configurations and leaving behind a gap in the understanding of torque generation dynamics. In the case when the reaction wheel configuration is not properly design, this can lead to under-actuation issue. The term underactuated refers to systems that have fewer actuators than the number of degrees of freedom they need to control. This condition can arise due to design limitations or actuator malfunctions. In satellite systems, under-actuation during operation can significantly degrade in-orbit performance and may even lead to mission failure [9].

This research aims to address these gaps by designing and analyzing various reaction wheel configurations, developing dynamic mathematical models for each setup, and examining their torque generation capabilities through simulation. The foundational step in designing a satellite's attitude control system is gaining a thorough understanding of its dynamics [10]. Using transformation matrices, MATLAB simulations, and 3D modeling, the study systematically evaluates both three-wheel arrangements. The ultimate goal is to enhance the accuracy and efficiency of satellite attitude control systems by providing deeper insight into how configuration choices such as wheel placement and orientation which can impact torque performance and overall system effectiveness.

2. Methodology

2.1 Derivation of Mathematical Modeling for Reaction Wheels

The basic configuration of a three-axis reaction wheel system is illustrated in Fig. 1. To enhance the precision of torque generation, the reaction wheels are tilted according to specific mission requirements.

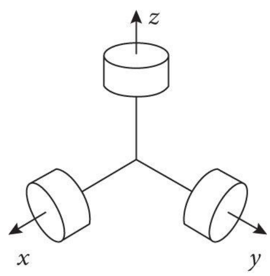

Fig. 1. Three-reaction wheel orthogonal configuration

This tilting is performed along the global axis, specifically in the X'-direction, and is represented by the variable α_i, where i denotes the corresponding reaction wheel, as shown in Fig. 2.

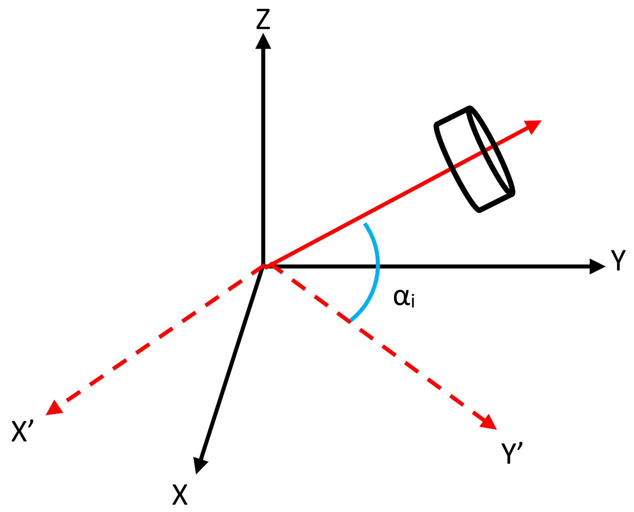

Fig. 2. Rotation in Global X' axis of a single reaction wheel

The orientation of each reaction wheel relative to the satellite's global coordinate system is depicted in Fig. 3, where the angle β_i represents the rotation of the reaction wheel about the reference frame [11].

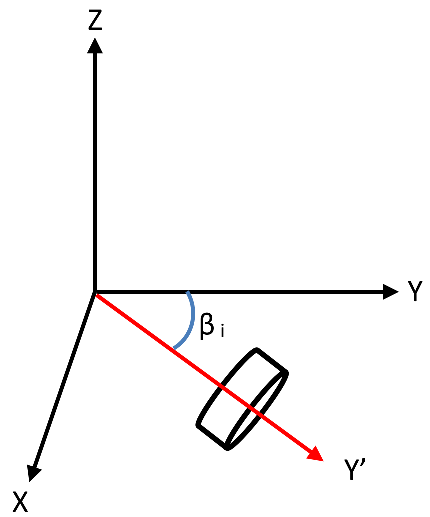

Fig. 3. Rotation in global Z axis of a single reaction wheel

As a result, the development of mathematical modeling requires two transformation that involves α_i and β_i. The combined transformation matrix, R will be represented as below in Eq. (1).

$$R = \begin{bmatrix} cos\ \beta_i cos\ \alpha_i & -sin\ \beta_i & cos\ \beta_i \sin\ \alpha_i \\ sin\ \beta_i \cos\ \alpha_i & \cos \beta_i & sin\ \beta_i \sin\ \alpha_i \\ -\sin\ \alpha_i & 0 & \cos\ \alpha_i \end{bmatrix} \quad (1)$$

Consequently, the torque vector of the reaction wheel is based on the Blue Canyon Technologies RW1 which generates torque in the local coordinate z-component with a maximum torque of 0.1 Nm as shown in Fig 4 [12].

z

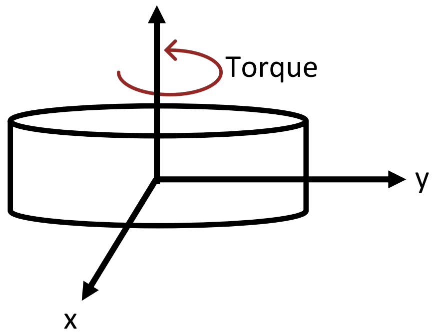

Fig. 4. Torque generation on local coordinate

The torque on the local coordinate of the reaction wheel can be expressed in the matrix form as in the mathematical modeling in Eq. (2)

$$\tau_i = \begin{bmatrix} 0 \\ 0 \\ 0.1 \end{bmatrix} N \tag{2}$$

2.2 Case Study for Reaction Wheels Configuration

The case study is done on 3 configurations which is shown in Table 1. The configuration of based on the research paper Ismail *et al*., [13].

Table 1
Configuration of the reaction wheels

Case Study	Reaction wheel 1		Reaction wheel 2		Reaction wheel 3	
	α_1	β_1	α_2	β_2	α_3	β_3
1	90°	90°	60°	30°	60°	150°
2	90°	90°	60°	45°	75°	135°
3	90°	0°	90°	90°	0°	0°

The analysis from each of these configurations were calculated using transformation matrix of Eq. (2) using the MATLAB simulation with the output of the configuration resulting in visualization of convex hull to show the possible torque outputs using the angles from Table 1. Most importantly, this analysis was performed based on the assumption of the simulation under an idealized environment with no external disturbances.

3. Results

The simulation phase of the project initiates with a configuration consisting of three reaction wheels, strategically positioned to create a robust and balanced foundation for further testing and analysis. This configuration is deliberately chosen because it allows the generation of torque about all three principal axes of the satellite—namely the X, Y, and Z axes. By ensuring full three-axis control, this setup offers a comprehensive platform for evaluating the dynamic behaviour and control capabilities of the satellite under various conditions.

The goal of these simulations is to examine how different configurations and orientations of the reaction wheels influence the system's ability to generate torque across its full range of motion. The torque envelope, which is derived from these simulations, represents the maximum attainable torque at every possible orientation in the 360-degree rotational space of the satellite. This envelope serves as a critical performance indicator, highlighting both the strengths and limitations of the given configuration in terms of attitude control authority.

The case study is conducted using a representative satellite model, which serves as the reference system for all simulation scenarios. The physical and operational specifications of this satellite—such as mass properties, inertia tensor, and geometry—are provided in Table 2. These parameters are essential for accurately simulating the interaction between the reaction wheel torques and the satellite's dynamic response.

3.1 Case Study 1

Using a combined transformation matrix, the torque vectors generated by each of the individual reaction wheels were computed and vectorially summed to obtain the system's net torque envelope. This process enabled the mapping of the satellite's control authority in three-dimensional space, providing insight into the directional strengths and limitations of the current reaction wheel configuration. The resulting peak torque values were found to be 0.15 Nm along the X-axis, 0.1866 Nm along the Y-axis, and 0.1 Nm along the Z-axis. These values directly reflect the mechanical orientation and distribution of the reaction wheels, as well as their relative contribution to each principal axis.

The dominance of the Y-axis torque capacity—reaching a maximum of ±0.1866 Nm. This is particularly significant in satellite applications where mission profiles may demand higher precision or agility in a specific axis, such as Earth observation satellites, which often require fine attitude adjustments in pitch (commonly aligned with the Y-axis).

Fig. 5 illustrates the convex hull of the torque envelope, generated through MATLAB simulations, which visualizes the boundary of all achievable torque vectors. The convex hull serves as a geometric representation of the system's maximum torque capabilities in all spatial directions and provides a clear visual cue of anisotropy in torque distribution. The envelope shows a slight elongation along the Y-axis, confirming the increased control authority in that direction.

This characteristic makes the configuration particularly well-suited for missions that involve frequent or critical manoeuvres along the Y-axis, such as precise pointing, attitude stabilization, or fast slewing motions in pitch. Additionally, this torque distribution may inform further optimization efforts—such as reorienting wheel axes or adjusting wheel momentum capacities—to achieve more balanced control authority if mission requirements change. Ultimately, understanding the directional torque envelope is crucial in tailoring the satellite's attitude control system to the specific needs of its mission profile.

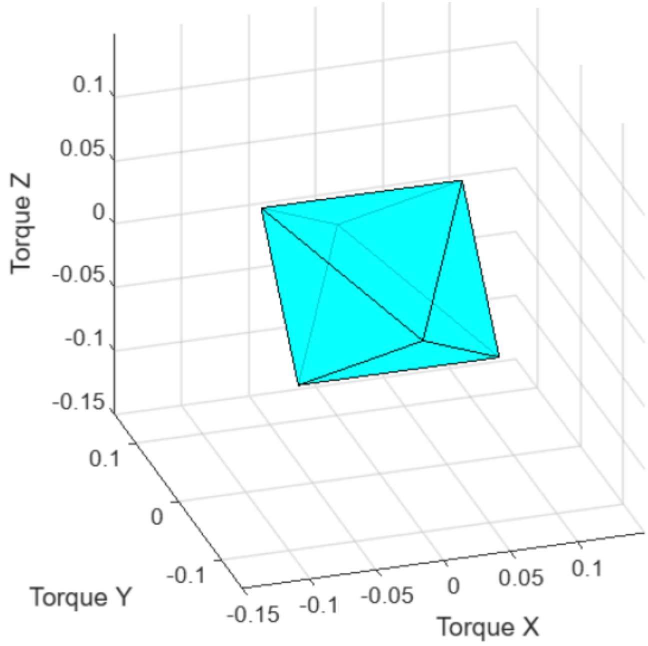

Fig. 5. Torque envelope for case study 1

3.2 Case Study 2

As illustrated in Fig. 6, this particular reaction wheel configuration is designed to enhance torque generation primarily around the Y-axis. Using transformation matrices to compute the resulting torque vectors, the aggregated torque capacities were determined to be 0.1295 Nm along the X-axis, 0.2295 Nm along the Y-axis, and 0.0759 Nm along the Z-axis.

This configuration clearly exhibits a significant improvement in Y-axis torque generation compared to the earlier configuration shown in Figure 5. Notably, this enhancement does not come at the expense of acceptable torque values in the X and Z axes, maintaining a degree of balance while favouring Y-axis control. Such a configuration is particularly advantageous in mission scenarios where fine attitude adjustments or sustained pointing precision are required along the Y-axis.

The comparative analysis between Case 1 and Case 2 demonstrates the importance of iterative optimization in reaction wheel system design. By systematically adjusting wheel orientations, the torque distribution can be steered to prioritize any desired axis. In this case, the Y-axis torque output in Case 2 significantly surpasses that of Case 1, validating the effectiveness of this iterative approach. This confirms that through careful adjustment of reaction wheel placement and orientation, it is possible to fine-tune the system's control authority to meet mission-specific requirements.

Therefore, the enhanced Y-axis control achieved in Case 2 not only supports the theoretical foundation of axis-dominant configurations but also provides practical justification for its use in satellite missions that demand superior performance in pitch control or orientation stability along the Y-axis.

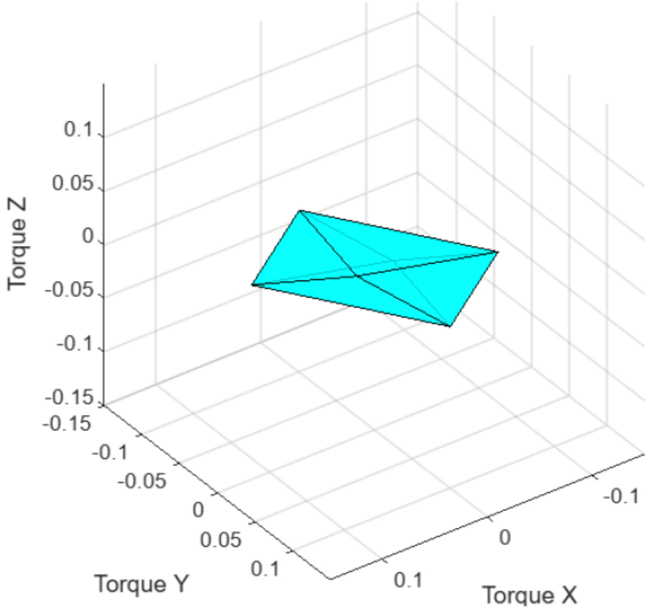

Fig. 6. Torque envelope for case study 2

3.3 Case Study 3

In Case Study 3, the configuration involves aligning each of the three reaction wheels along one of the principal axes—X, Y, and Z. This orthogonal arrangement ensures that each wheel contributes torque independently and directly along its respective axis, maximizing control authority in those directions. As a result, the system achieves a well-balanced and symmetrical torque distribution across all three axes.

The torque envelope generated from this configuration, as shown in Figure 7, forms a geometrically ideal shape resembling a perfect octahedron. This is indicative of equal maximum torque magnitudes achievable along each axis, with simulation results confirming torque limits of approximately ±0.1 Nm in the X, Y, and Z directions.

Such a configuration is highly advantageous when uniform control capability is desired across all axes, making it particularly suitable for satellite missions requiring isotropic torque responses—such as general-purpose Earth observation or scientific payload stabilization, where no single axis demands dominant control. The octahedral shape of the torque envelope also provides a clear visual representation of this uniformity in three-dimensional space, reinforcing the effectiveness of the axis-aligned reaction wheel setup in achieving balanced torque generation.

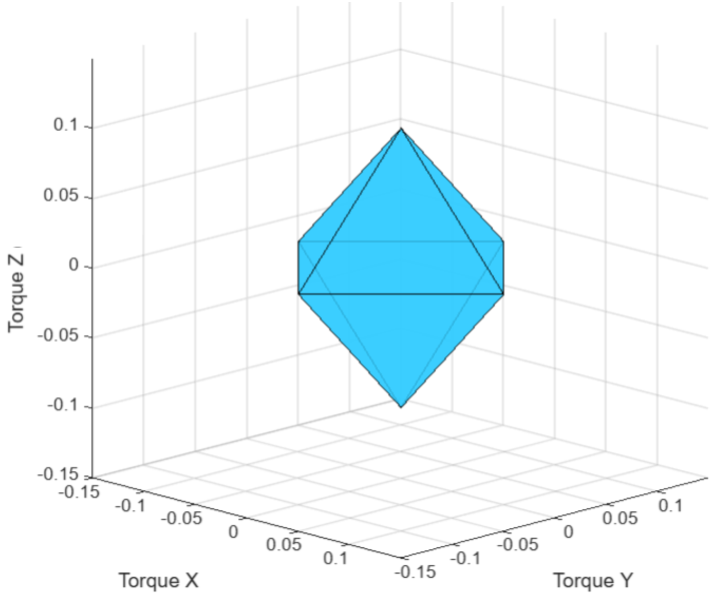

Fig. 7. Torque envelope for case study 3

4. Conclusions

In summary, the analysis of torque generation across various reaction wheel configurations offers valuable insights into their critical role within a satellite's attitude control system. Designing an efficient configuration is essential not only for achieving precise orientation control but also for ensuring the reliability and responsiveness of data feedback during satellite operations. The comparative evaluation of the three case studies highlights the trade-offs and advantages of different configurations. Case Study 3, which aligns each reaction wheel with one of the principal axes, delivers a well-balanced torque distribution, providing equal control authority in all directions. This makes it ideal for missions requiring uniform agility and stability. In contrast, Case Study 2 demonstrates a Y-axis-dominant configuration, offering enhanced torque along the Y-axis at the cost of reduced torque on the X and Z axes. Nevertheless, it maintains a reasonably balanced output, making it suitable for missions with a higher demand for control in a specific axis. These findings emphasize the importance of tailoring reaction wheel configurations to specific mission requirements. A well-optimized setup not only improves control precision but also reduces energy consumption by delivering targeted torque where it is most needed [14]. Furthermore, strategic configuration planning can incorporate redundancy, enhancing the fault tolerance of the attitude control system and increasing the overall reliability of the satellite mission [15].

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