Prototype of Micro Reaction Wheel for Cubesat

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***Abstract*— Tel-USat is a Cubesat 1U which is designed to capture the Earth surface photograph using serial camera. To support the mission, an attitude control is needed such as Attitude and Determination Control Subsystem (ADCS). This spacecraft is designed with a Micro Reaction Wheel (MRW). This is a type of reaction wheel that has a small size which fit with cubesat dimension. It consists of flywheel attached to BLDC motor and Electronic Wheel Drive (WDE). The Micro Reaction Wheel has been designed to have a minimum speed of 64021rpm with a voltage of 8V and a duty cycle of 9.95% or 4.47% and the maximum speed with a rigid of 1, 9V and a 7.55% duty cycle or 6.69%. With these results, the Micro Reaction Wheel can generate a torque of 0.74 mNm. Consume battery energy at a maximum speed of 16,67 mAh/minute.**

Keywords: ***Cubesat, ADCS, Micro Reaction Wheel, Flywheel.***

I. Introduction

Cubesat is a type of nanosatellite which has total mass 1-10 Kg and has a form factor 10 × 10 × 10 cm^3 called with '1U'. In this recent years, it becomes popular because it needs low development cost and fast production time so it is able to do even by an university research group [1-3]. They contribute to about 32% of nanosatellite orbitting on the orbit at this moment [nanosats.eu]. Telkom University, with its first cubesat named Tel-USat, also join the race in developing cubesat subsystem and payload [4-6]. This paper explains one of our work that has been done which is the prototype of Micro-Reaction Wheel (MRW) for cubesat.

A cubesat generally contains a few subsystems such as Telemetry, Tracking, and Command (TTC), On-Board Computer (OBC), Electronic Power Subsystem (EPS), and Attitude and Determination Control Subsystem (ADCS). Moreover, it is also usually equipped with a single or more mission payloads. This module needs assistant in order to place its heading to a certain position when it is being operated. To support it, an active attitude control is needed and the options can be magnetorquer, thruster, or reaction wheel [5][7-8]. Reaction wheel is the one that ideal for cubesat mission because it produces more stable attitude control than magnetorquer and it is more light and has longer lifetime than thruster. Those are a few consideration in determining the reaction wheel as the active actuator for Tel-USat. The challenge is how to make it smaller in size so it can fit in 1U cubesat form factor.

This paper is focusing on developing micro reaction wheel that fit in a 1U cubesat and it will be planned to be part of Tel-USat. The reaction wheel is designed to be able to rotate the orientation of satellites with a maximum angular speed of the satellite of 5deg/s.

II. Micro Reaction Wheel

Micro Reaction Wheel is an active actuator that control the spacecraft attitude to a certain position. The purpose of this MRW is working by using torque from the wheel to manage the motion of a satellite rotation so that the satellites can face a certain axis. By knowing the reference position of a spacecraft, the actuators work based on how much the discrepancy of a satellite position to its reference orientation, then the actuator will rotate by relying on a large rotation and torque-speed to return to its reference position. MRW consists of two or three flywheel attached to the Brushless DC (BLDC) motors and the Electronic Wheel Drive (WDE) [7].

A. Equation of Satellite Motion

In the satellite movement, there are 3 DOF (Degrees of Freedom) motion models [9]. The motion Model is called free body designated by Fig. 1.

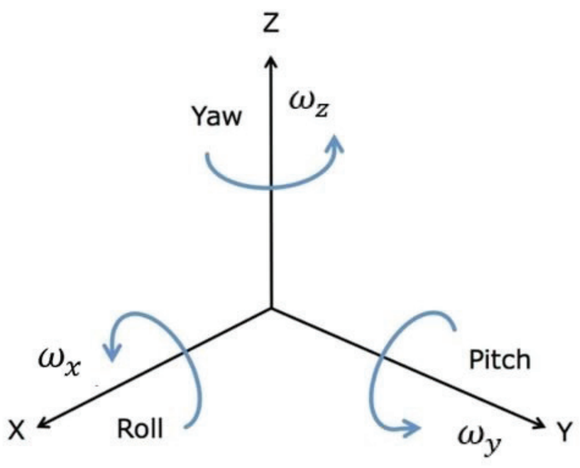

Fig. 1. Angular Gyroscope Axis

According to Fig. 1, General Euler motion shown by Eq. (1) is used to determine the motion characteristic for each axis.

$$\dot{H} = I\dot{\omega} + \omega \times H \tag{1}$$

Equations that are shown in the Eq. (1); $\dot{H}$ is a rotation moment per unit of time, I is an inertia matrix, ω is angular

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velocity, $\dot{\omega}$ is angular velocity per second, and H is rotation momentum.

The satellite used is a Nano parabola that has the same inertial value on each component of the coordinate so that it can be obtained using Eq. (2).

$$I_{xx} = I_{yy} = I_{zz} \tag{2}$$

Then the value that is in parentheses is zero, besides because the satellite does not receive torque from the outside and no other pusher components from the outside, then $\dot{H}_x=\dot{H}_y=\dot{H}_z=0$.

Or can be used as a form of equation globally demonstrated by the Eq. (3). $\dot{\omega}_{sat}$ is angular velocity per second of satellite, $\dot{\omega}_{rw}$ is angular velocity per second of reaction wheell, I_{rw} is an inertia of reaction wheell, and I_{sat} is an inertia of satellite.

$$I_{sat}\dot{\omega}_{sat} + I_{rw}\dot{\omega}_{rw} = 0 \tag{3}$$

B. *Fly Wheel*

Fly wheel is a wheel that used to stir the body of spacecraft into certain angle of position. In designing the flywheel, its total angular momentum should be a half of the satellite system. It is necessary so the MRW is able to move from a static state towards a steady state [10]. Corner Momentum Flywheel (h_{rw}) half of the satellite corner momentum (h_{sat}) as shown in the Eq. (4).

$$h_{rw} = \frac{1}{2}h_{sat} \tag{4}$$

To get the moment value of inertia that is designed, the author is the value of the moment of inertia obtained through the Eq. (5). Moment of inertia is a measure of the moisture of an object to rotate against its axis.

$$I_{sat} = m_{sat}R_{sat}^{2} \tag{5}$$

Finding inertia flywheel can also be done by using the Law of Eternity momentum. The Law of Eternity Momentum is one of the basic laws that exist in physical sciences. The law states that "the total Momentum of two objects before the colleges is the same after the collision". The legal equations of this momentum of eternity are demonstrated in equation (3) which in conversion becomes Eq. (6).

$$I_{rw} = \frac{-I_{sat}\,\omega_{sat}}{\omega_{rw}} \tag{6}$$

C. *DC Motor Selection*

Motor selection is an important phase that will determine the MRW performance. It produces angular acceleration on the flywheel which is able to generate torque and angular momentum that can change the orientation of the spacecraft [10]. There are many type of motor with its own performance, however, not all of them are fit with cubesat attitude control application.

DC Motor consists of 2 types, that is brushed and brushless motor. The brushless motor has more benefit to the brushed motor in control the spacecraft attitude. Brushless motori is easier to control than brushed motor based on the speed and torque, also longer-lived and have a smoother turnaround. The Brushless DC Motor (BLDC) serves as a rotary speed and torque generator that will be channelled to flywheel in order to change the satellite position. The BLDC motor used in this experiment is shown in Fig. 2.

After obtaining the specifications of the DC motors in use, can be searched the number of rounds per minute to adjust the movement and know the acceleration of the designed flywheels. The number of rounds is denoted by ω_m with the rpm(revolutions per minute) unit indicated by the equation (7).

$$\omega_m = KV.Vm \tag{7}$$

D. *Electronic Wheel Drive*

Wheel Drive Electronic (WDE) is a speed regulator of reaction wheel which control the amount of current enters into the BLDC. It will handle every motor integrated with Flywheel for one satellite axis control operation (axis). Thus, there will be at least three WDE to be able to run the satellite 3-axis stabilization operation. WDE will receive a command from OBDH to perform an attitude control operation [11].

III. DESIGN MICRO REACTION WHEEL IN CUBESAT 1U

Designing the micro reaction wheel begins with determine the needs of spacecraft properties that related to its attitude control. Table I shows the overall needs for this prototype.

Tabel.I. Satellite Specifications [12]

Current	< 3A
Voltage	< 8.4V
Dimensions	1U ($10cm^3$)
Mass	2 kg
Maximal rotation speed of satelite	5 deg/s

A. *Motor* Brushless *DC (BLDC)*

The BLDC motor used for this prototype is GOOLRC 8700KV and Fig. 2 shows the module. The specification of the BLDC motor is shown in Table II. This module has been chosen by considering its dimension and rotation performance. The specifications of the BLDC motor will affect the required flywheel dimensions, especially rpm. To look for rpm can be used equation (19) and the result is 64380 rpm.

Fig. 2. GOOLRC 8700KV Brushless Motor [13]

Tabel II. BLDC Specifications[13]

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KV Value	8700kv
Input Voltage	7.4V lipo *battery* (2S)
Max Current	3A

B. *Flywheel Design*

Flywheel design should have a precise moment of inertia, to be able to provide a momentum to the satellites. In the beginning, the maximum angular speed of the satellite have to be achieved. According to Table I, ω_{sat} is 5 deg/s or 0.0872665 rad/s. Further, the spacecraft inertia I_{sat} has to be calculated by using Eq. (5). The mass and the radius of the spacecraft is 2 kg and 0.05 m respectively. The result of the I_{sat} is 0.005. Next, the inertia Flywheel (I_{rw}) has been achieved from the Eq. (6). and the result is 0,0003830838455 gm^3.

$$I_{FW} = \frac{0.005 \cdot 0.0872665}{1139}$$

The flywheel is designed to resemble a bowl, it aims to give the BLDC as a load point to be more evenly distributed and not to overload at certain points. A knotted load at a point would result in damage to the BLDC Shaft and Bearing The consumption of the BLDC friction. And for the surface in Flywheel adjusted to BLDC surface, this aims to prevent any gaps that will result in vibration between BLDC body and Flywheel that will damage the BLDC, as well as the surface of the surface in the BLDC. The results obtained at the show in Fig. 3.

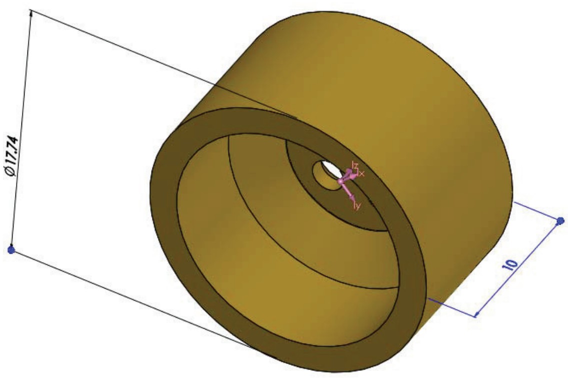
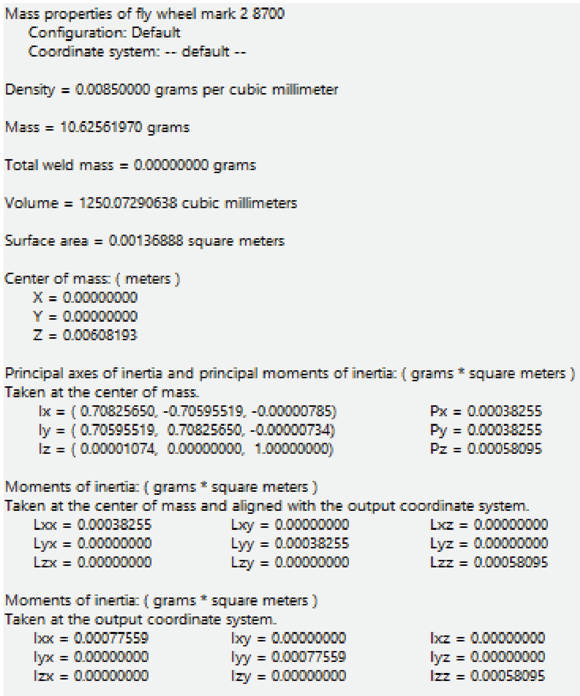


Fig. 3. Flywheel sighting designed

To obtain an I_{rw} that corresponds to the outcome of the Eq. (8). then the author performs an experiment changing the length, width, and volume of the software and acquired I_{rw} which is shown on the Fig. 4.



Mass properties of fly wheel mark 2 8700
Configuration: Default
Coordinate system: -- default --

Density = 0.00850000 grams per cubic millimeter

Mass = 10.62561970 grams

Total weld mass = 0.00000000 grams

Volume = 1250.07290638 cubic millimeters

Surface area = 0.00136888 square meters

Center of mass: (meters)
X = 0.00000000
Y = 0.00000000
Z = 0.00608193

Principal axes of inertia and principal moments of inertia: (grams * square meters)
Taken at the center of mass.

Ix = (0.70825650, -0.70595519, -0.00000785)		Px = 0.00038255
Iy = (0.70595519, 0.70825650, -0.00000734)		Py = 0.00038255
Iz = (0.00001074, 0.00000000, 1.00000000)		Pz = 0.00058095

Moments of inertia: (grams * square meters)
Taken at the center of mass and aligned with the output coordinate system.

Lxx = 0.00038255	Lxy = 0.00000000	Lxz = 0.00000000
Lyx = 0.00000000	Lyy = 0.00038255	Lyz = 0.00000000
Lzx = 0.00000000	Lzy = 0.00000000	Lzz = 0.00058095

Moments of inertia: (grams * square meters)
Taken at the output coordinate system.

Ixx = 0.00077559	Ixy = 0.00000000	Ixz = 0.00000000
Iyx = 0.00000000	Iyy = 0.00077559	Iyz = 0.00000000
Izx = 0.00000000	Izy = 0.00000000	Izz = 0.00058095

Fig. 4. Data Obtained from Simulated for Flywheel

C. *Electronic Wheel Drive (WDE) Design*

Block system of WDE is given in Fig. 5. The WDE is integrated with a BLDC motor and controls it speed. It works like Electronic Speed Control (ESC). Since there are three axis supposed to control, the WDE number is three as well.

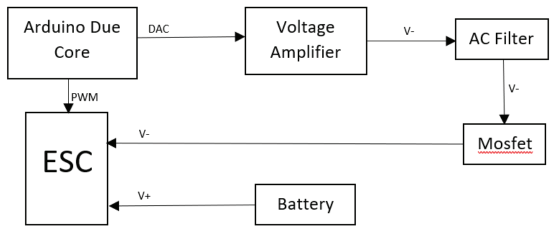


Fig. 5. Electronic Scheme of The Wheel Drive

ESC consists of MOSFET (Metal Oxide Semiconductor Field Effect Transistor) that acts as a DC voltage current faucet, so that it can adjust the tension that enters the ESC so that it will affect the round of the BLDC motor. The lower the voltage given, the more slowly the rotation of the BLDC. Inih MOSFETs are regulated by DAC (digital to Analog Converter) on Arduino Due. At Arduino Due only able to provide signal DAC 0.55-2.75 V only. The voltage that needs ESC is 3-7.4 V then in need of a circuit voltage amplifier. The output signal from DAC Arduino has noise so it gives a series of AC filters to reduce the Noise that is entered into the MOSFET.

Basically, the ESC used is ESC for a drone that rotates in one direction (rotating clockwise or counterclockwise) and has a speed starting from a high rpm. Therefore, the authors try to make the ESC so that it can rotate clockwise and counter-clockwise so that it can control the satellites even better. By using the Software KKmulticopter Flash tool.

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IV. IMPLEMENTATION AND PERFORMANCE

In the implementation on PCB coated with the polygon. On the integrated implementation of the flywheel, BLDC, and WDE in one board. In test it focus to functional, performance, and power consumption test because it first design for cubesat 1U.

A. Implementation

On the layer containing the micro reaction wheel, there are 3 flywheels, 3 BLDC, 2 batteries, and WDE as shown in the Fig. 6. Each flywheel integrates on one BLDC and each BLDC is controlled using WDE. On Fig. 6. there are 3 reaction wheel with 3 axis to adjust different orientation (roll, pitch, and yaw).

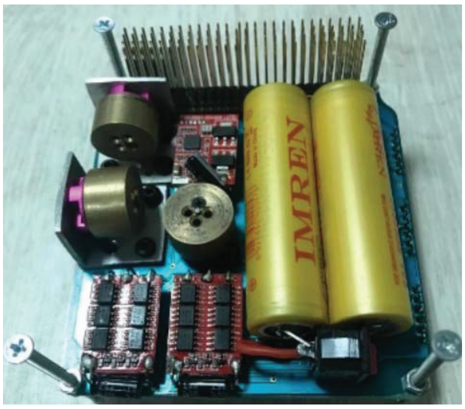

Fig. 6. Micro Reaction Wheel Board

B. Performance

The test is performed only against the 1 Micro Reaction wheel that gives the orientation of the Z-AXIS angle (yaw). Speed measurement results on Micro Reaction Wheel with clockwise rotation shown in Fig. 7. The results of the Micro Reaction Wheel speed measurement by rotating clockwise and counter-clockwise in the show in Fig. 8.

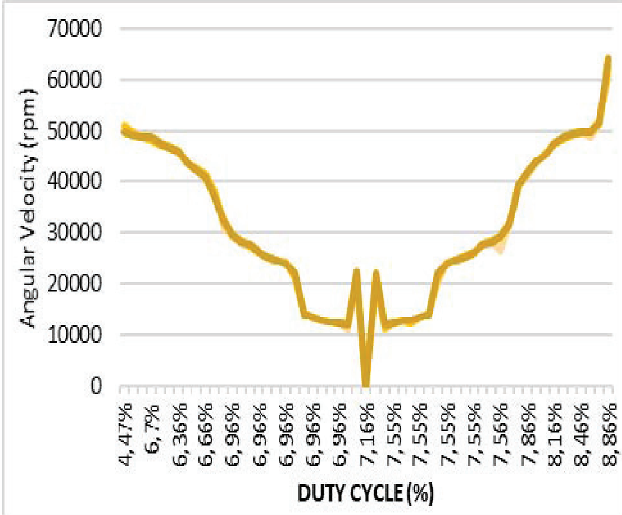

Fig. 8. Performance rotates the wheel reaction clockwise and counter-clockwise

The torque generated by the micro reaction wheel is use equation (9). In Fig. 9. can be concluded bring the torque generated by the Micro Reaction Wheel the higher the rotation speed (RPM) then the lower the torsion. The highest torque is generated at a speed of 2968 rpm.

$$\tau = I.\alpha \tag{9}$$

$$\alpha = \frac{d_\omega}{d_t} \tag{10}$$

τ is the torque generated by the Reaction Wheel. To know the torque generated by the reaction wheel it should be known inertia (*I*) first then multiplied by the acceleration angle (α) as shown in the equation (9). To know the angular acceleration can be used equations (10). d_ω is the difference between the angular velocity, while the d_t is the time difference in the Reaction wheel is needed.

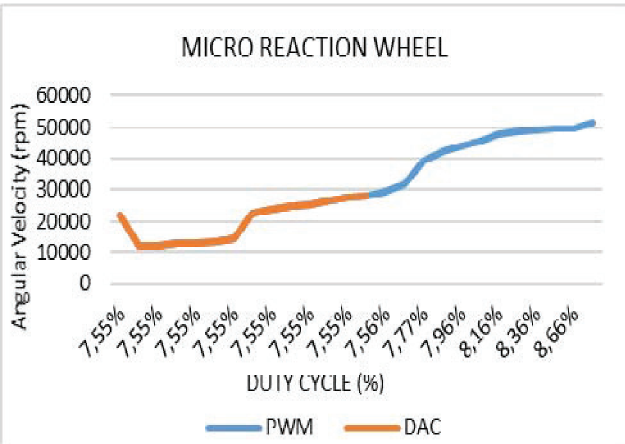

Fig. 7. BLDC Performance Rotating Reaction Wheel Clockwise

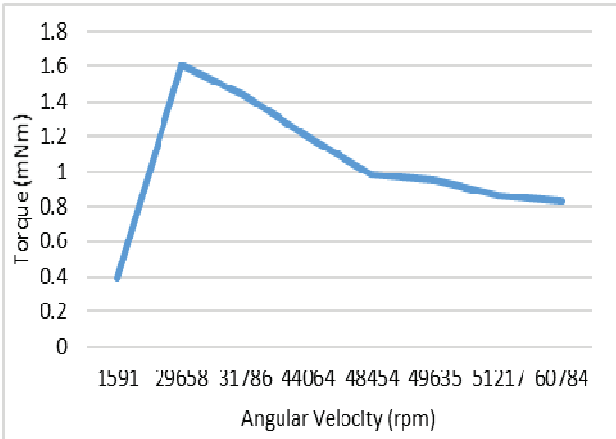

Fig. 9. Torque on a Micro Reaction Wheel

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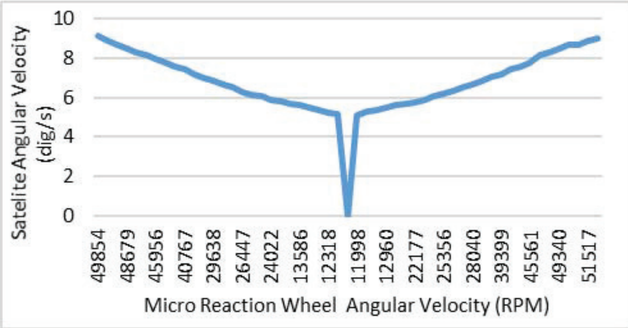

Fig. 10. Satellite Corner Speed Performance

The result of the measurements shown in Fig. 11. in the image is seen when the speed of the Micro Reaction Wheel is faster than the consumption of power that needs more and more graphics shown in Fig. 11. Indicates the consumption of power per minute compared to the speed of rotation.

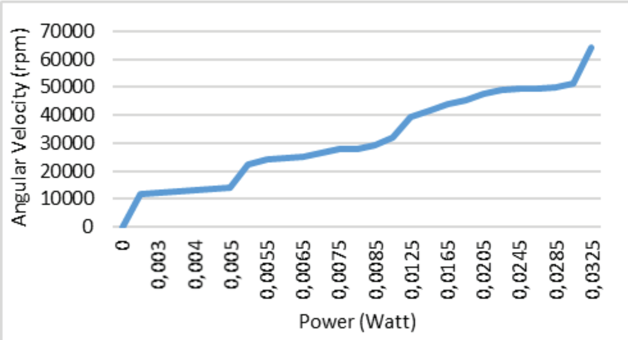

Fig. 11. Consumption Measurement Results Per minute

V. Conclusion

The Momentum generated by Flywheel can generate a 5deg/s satellite rotation speed, but with the Micro Reaction Wheel speed being different from the initial calculations. With a compact size that can be integrated into CubeSat 1U, Flywheel can move CubeSat 1U. The maximum speed of Micro Reaction Wheel is 64021 rpm with 8V voltage and 9.95% or 4.47% duty cycle. While the minimum speed of Micro Reaction Wheel is 11998 rpm with a voltage of 1, 9V and duty cycle 7.55% or 6.69%. The torque generated by the Micro Reaction Wheel is 0.74 mNm. The higher the speed used, the smaller the torque is generated. Consuming power per minute, on the Micro Reaction Wheel with a minimum speed of 11998 rpm consumes the power of about 0, 003Watt and at a maximum speed of 64021 rpm, it costs about 0.0325 watts. Consumes battery energy with the maximum speed of Micro Reaction Wheel consumes 16, 667mAh battery Energy. Micro Reaction Wheel can last more than 3 hours and no damage occurs. However, there is a temperature increase in BLDC body although it does not affect BLDC performance.

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