Attitude Control of Bias Momentum Micro Satellite Using Magnetic and Gravity Gradient Torque

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Abstract— **Earth pointing satellites commonly use bias momentum for attitude control. It provides gyroscopic stability against the external disturbance torque. Typically, the bias momentum satellite use momentum wheel and thruster for actuator and star tracker or pairs of horizon and a sun sensor to determine the direction of angular momentum. This paper proposes an effective technique to control the angular momentum of Lapan-Tubsat satellite using wheels and magnetic coil for actuator and overcome the limitations of the spacecraft that has no on-board horizon sensor and magnetometer that usually used to measure the magnetic field. The determination of angular momentum direction use video camera instead a horizon sensor even though it is available once per 24 hours of ground station contact. This idea is effective if only the disturbance torque and the angular momentum has been characterized and established. After the video camera gives attitude information the satellite operator tries to control the direction of angular momentum by over or under-compensate the disturbance torque using magnetic coil. On Lapan-Tubsat, the disturbance torque level is in the order of 10^{-5} Nm, i.e. 10% of the maximum coil torque.**

Keywords—magnetic torque, gravity gradient torque, bias momentum, micro satellite

I. INTRODUCTION

Micro satellites are now starting to implement for some advanced missions such as astronomy and remote sensing that require high accuracy of attitude control. In general, the method which is often used for standard-sized satellite attitude control does not apply to small satellites due to constraints on power consumption, space requirements, and mass. In addition, small satellites are more susceptible to the attitude disturbance than a standard-sized satellite because of low moment of inertia. While disturbance torque is neglected in the standard-sized satellites, it is dominant in small satellites [1].

For an effective attitude control method, a micro satellite utilizes the angular momentum where the satellite rotates around one axis to obtain gyroscopic stability. A simple technique to take advantage of the angular momentum in the attitude control is by rotating the whole body of the spacecraft around one axis. This method is known as the bias momentum and it was first applied to the geostationary communications satellite Syncom 2 in 1963 [2]. Although this method provides the stability that is passively attached to a spacecraft, it has limitation on the design and mission applications. The majority of the mission that one part from the satellite should point to the Earth such as remote sensing cameras cannot be fulfilled by a simple rotation method as well as Syncom 2. Then many methods are introduced into momentum exchange technique by utilizing a device that can rotate in the spacecraft such as a momentum or reaction wheel.

The satellite that implements bias momentum for attitude control usually carried momentum wheels and thruster or torquer for actuators and star sensor or pairs of horizon and sun sensor for attitude determination. In the seventh year of its operation, Lapan-Tubsat implements the bias momentum method since it is a simple technique to control the attitude. The idea of this experiment is how to use the video camera and solar panels instead horizon sensor or star sensor for attitude determination. Actually, the spacecraft carried star sensor for fine attitude determination but it got failure in the second year of its operation. Furthermore, the video camera is available only once per 24 hours when the spacecraft is in contact with the ground station. Nevertheless, it could determine the drift of angular momentum direction. To control the drift of angular momentum, the external disturbance torque of the spacecraft should be well determined. Once the disturbance torque is characterized, the magnetic coil torque will compensate it so the drift of angular momentum direction is controlled in the low-level during 24 hours.

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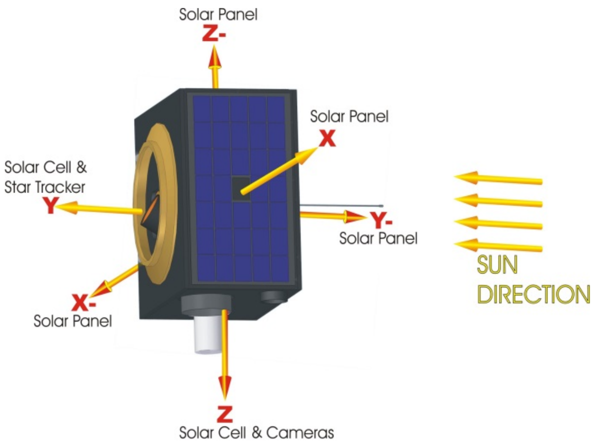
II. Lapan-Tubsat Attitude Control System

The attitude control that described in this paper use Lapan-Tubsat satellite which is categorized as micro satellites. For controlling the spacecraft that has weight 57 kg and 450 mm x 450 mm x 270 mm dimension, the spacecraft employs 3 reaction wheels and 3 magnetic coils that are placed in orthogonal axis as actuator. The attitude determination is supported by 3 gyros, 1 star tracker, 4 solar panels and 2 solar cells as sun sensors. Later, the star sensor is no longer available due to failure because of latch-up. The configuration of attitude control system is shown on Fig. 1.



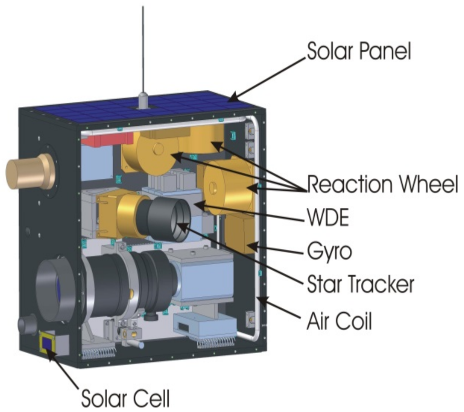


Fig. 1. Configuration of Lapan-Tubsat's attitude control system

The attitude mode of Lapan-Tubsat consists of operation and hibernation mode. Operation mode will be done while the spacecraft is in contact with the ground station to collect the video by nadir pointing maneuver or interactively controlled by the operator. As soon as the spacecraft has finished in taking the pictures, it will enter hibernation mode.

Hibernation mode is more than 90% of spacecraft duty cycle. During hibernation mode the angular momentum is maintained in y axis which is perpendicular to the orbital plane. Here the reaction wheel on y axis is set to absorb the angular momentum. Lapan-Tubsat employed video camera and solar panels to determine the direction of angular momentum and use magnetic coil to control it. The magnetic coil will drive the direction of angular momentum by over or under-compensate the disturbance torque. This concept is applied to Lapan-Tubsat since the satellite does not have on board horizon sensor and magnetometer that usually used in the other satellite to measure the magnetic field.

III. Methodology

The first step to control the satellite attitude is determining the characteristics of the external disturbance torque. In this step, the disturbance torque is measured in the zero momentum condition by calculating the change of angular momentum through three satellite gyros. The change of angular momentum is equivalent to the torque experienced by the satellite. The sources of external disturbance torque can be gravity gradient, solar pressure, and magnetic field. Nevertheless, the dominant disturbance torque in low orbit micro satellites is the magnetic torque. On Lapan- Tubsat, the devices that potentially generate magnetic torque disturbance are batteries due to Nickel content and the wheels that employ permanent magnet.

The next step is generating the angular momentum up to 80% of the maximum angular momentum that can be stored by the wheel to get the desired gyroscopic stiffness. As soon as the angular momentum reached 80% of its maximum capacity, the process continued with controlling the direction of angular momentum to be perpendicular to the orbital plane. As shown in the Fig. 2, the angular momentum should be maintained in right ascension and declination direction. To control the direction of angular momentum, the system uses magnetic torque to obtain the precession on right ascension and gravity gradient torque to make declination precession. The precession of angular momentum vector is evaluated by video camera for the element of right ascension and by solar panels for the element of declination. In the next sections, the details of the two control step are presented.

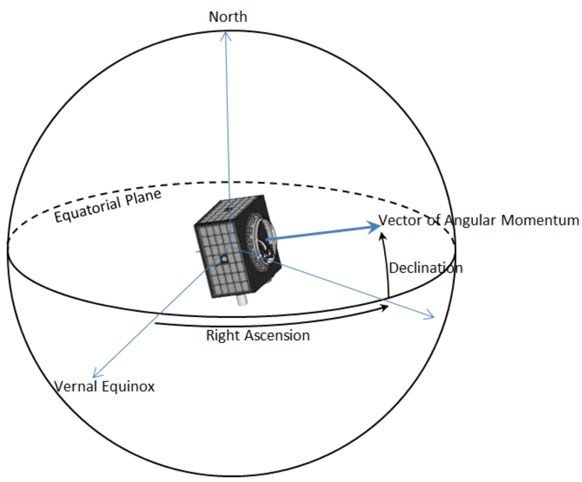


Fig. 2. Angular Momentum Vector

IV. DISTURBANCE TORQUE CHARACTERIZATION

At an altitude of 630 km the sources of external disturbance torque can be gravity gradient, solar pressure, and magnetic field. According to the coordinate that showed on

Fig.1, the torque caused by the gravity gradient and solar pressure can be calculated using the following equation:

- Gravity gradient gives torque:

$$\tau_{gg} = \frac{3\mu}{2R^3}\left|I_{yy} - I_{xx}\right|\sin(2\theta) \tag{1}$$

where μ: Earth gravitation constant = 3.986 x 10^{14} $m^3.s^{-2}$
R: Orbit radius (m)
θ: Maximum deviation of spacecraft vertical axis from local vertical
I_{xx}: Moment inertia on x axis
I_{yy}: Moment inertia on y axis

- Solar pressure gives torque:

$$\tau_{sp} = C_{sp} A_{sp} \ell \tag{2}$$

where C_{sp} : solar pressure constant = 0.5 x 10^{-5} N/m^2
A_{sp} : solar panel area (m^2)
ℓ : lever arm of solar panel (m)

The parameters that used in the calculation of the torque are shown in the Table I.

The disturbance torque that caused by magnetic field depends on activity of devices that emit a magnetic dipole. There are two devices that potentially produce the magnetic torque. Those are the batteries due to the Nickel content and the wheels that can produce a radial dipole when they are not rotating. Therefore, there are three steps to measure the magnetic torque of Lapan-Tubsat satellite. The first step is measuring the external torque when the satellite in zero momentum and switch off all the wheels. The second step is measuring the torque when all the wheels are active. The third step is measuring the torque when all the wheels are switched off and one of the magnetic coils is set with maximum current.

TABLE I. PARAMETERS FOR CALCULATING THE TORQUE

Parameters	Value	Unit
Spacecraft's Moment of Inertia:		
I_{xx}	1.386	kg.m^2
I_{yy}	2.062	kg.m^2
I_{zz}	1.441	kg.m^2
I_{xy}	0.035	kg.m^2
I_{xz}	0.063	kg.m^2
I_{yz}	-0.003	kg.m^2
Wheel's Moment of Inertia	0.00088	kg.m^2
Orbit Radius	7 x 10^6	m
Solar Panel Area	0.2	m^2
Lever Arm of Solar Panel	0.05	m

Measuring external torque is easier when the spacecraft's momentum was almost zero. The external torque will be equivalent to the changing of angular momentum that is evaluated by gyro reading in each orthogonal axis. The gyros reading for free tumbling condition are shown on Fig. 3.

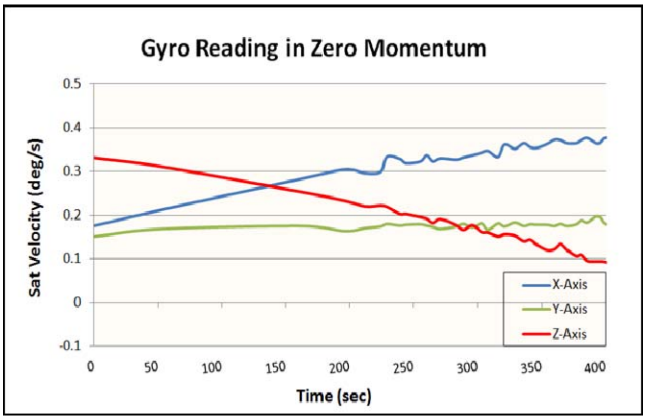


Fig. 3. Gyro Reading during Free Tumbling Condition

According the first measurement, it shows the angular velocity of the satellite in the x, y, and z axis has been changed 0.201 °/s, 0.03 °/s, and 0.239 °/s respectively in the 400 seconds. These rates of change are equivalent to an external torque 1.956 x 10^{-5} Nm. Meanwhile, based on the calculation, the maximum theoretical value of gravity gradient torque and solar pressure are 1.17 x 10^{-6} Nm and 0.5 x 10^{-7} Nm respectively. This value is very small compared to the total external torque on the satellite. This fact confirms that the most likely sources of the torque are the devices that generate a magnetic field. Fig. 3 also show the angular velocity on y axis almost stable. It indicates that the source of the external torque is on the y axis. The external torque can be easily compensated by using magnetic coil torque on the y axis so that the resultant of the torque become zero.

The second measurement is taken when all the wheels are rotating. As previous explanations, there are two source of magnetic dipole on the spacecraft i.e. wheels and batteries. The objective of this measurement is to know the magnetic torque that produced by batteries only. The wheels can produce a radial dipole when they are not rotating. The direction of the wheel dipoles is random on a plane perpendicular to the axis of rotation. So far it is not clear which of the dipoles are stronger, the wheels or the batteries. To know the influence of the devices clearly, then this measurement was conducted. This test command zero rate in all 3 satellite axes and collects as many wheel speed data as possible. The main difference from the previous test is that the wheels are now continuously rotating so that all the wheel dipoles are averaged and the torque should be influence of the battery dipole only. The measurement results can be seen in Fig. 4.

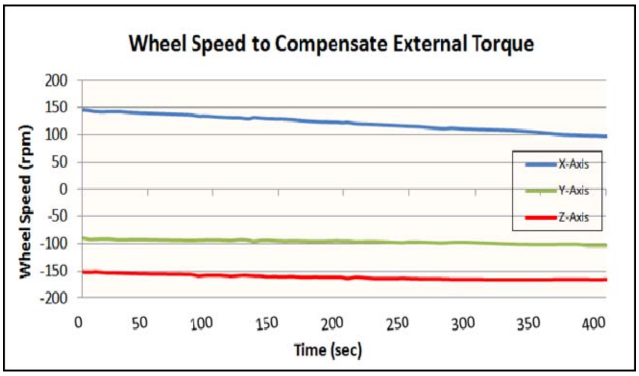


Fig. 4. Wheel Speed for External Torque Compensation

According the second measurement as shown in Fig. 4, the changes of wheel speed on the *x*, *y*, and *z* axis are 46.8 rpm, 14.6 rpm and 13.9 rpm respectively in the 394 seconds. The changes of wheel speed are equivalent to a torque of 1.193 x 10^{-5} Nm due to the effect of the battery only. The maximum torque is a bit lower in comparison with 1.956 x 10^{-5} Nm which is caused by wheels and batteries.

To compare the entire test with the knowing source of magnetic dipole, the third measurement should be done. As the third test, the spacecraft would be measured in free tumbling mode but at this time it was provoked by the influence of a known magnetic dipole by switching on the y coil to its maximum current (242 mA) without time limitation. The satellite angular rate was read by gyro as in the first test as shown in the Fig. 5.

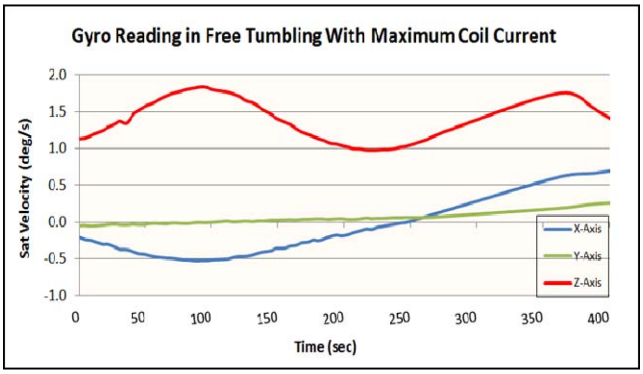


Fig. 5. Gyro Reading during Free Tumbling Condition with the Maximum Current Setting on Y Coil

The third measurement result showed that the angular velocity on the *y* axis is almost stable, while the angular velocity in the *x* and *z* axes are always changing. Fig. 5 shows the changes of angular velocity in the *x*, *y*, and *z* are 0.423 °/s, 0.052 °/s, and 0.861 °/s respectively in the 128 seconds which is equivalent to 1.88 x 10^{-4} Nm of torque. If the result of this measurement is compared with the first measurement, the external torque on the first measurement was about 10% of the maximum torque generated by *y* coil. It means the magnetic coil only uses 10% of its maximum capacity to compensate the disturbance torque or even less. It depends whether the wheel rotors are rotating or not. If the wheel rotors are stopping, the influence torque also depends on the actual end position of the wheel rotors.

In the next sections, the details of controlling the angular momentum are presented.

V. CONTROLLING THE ANGULAR MOMENTUM

Lapan-Tubsat use magnetic coil and reaction wheel as actuator which is fixed on each orthogonal axis x, y, and z. It generates the angular momentum through the following steps:

- Stopping the satellite rotation of all axes so that the satellite is in a stationary condition.
- Enables ones of the coil that produces the biggest torque with maximum currents.

The maneuver is performed each time the satellite passes a telemetry, tracking and command (TT&C) relay ground station located on Spitsbergen, Norway, i.e. every 1.5 hours. Fig. 6 shows the process of raising the satellite angular momentum up to 80% of the wheel maximum storage capacity which is equivalent with 4000 rpm of wheel speed or 0.37 Nms.

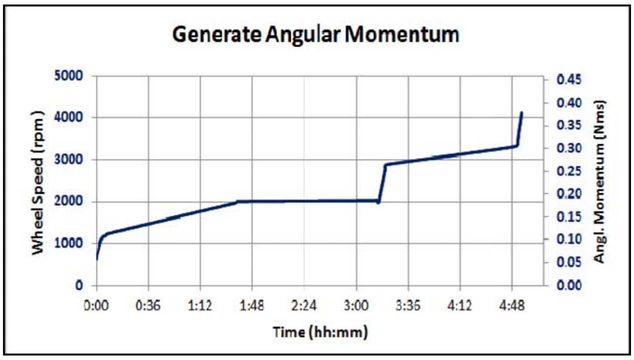


Fig. 6. Angular Momentum Generation

Once the angular momentum reaches 80% of its maximum capacity, the wheel on the *y* axis is used to absorb all the momentum. The next strategy is to speed up the *y* wheel 800 rpm higher than the total momentum of the spacecraft so that the spacecraft rotates 2 °/s in the opposite direction. To damp the nutation, the control loop of the wheel in the *x* axis was activated. This strategy is effective for averaging the residual torques of the *x* and *z* direction.

What remains to be compensated is the constant disturbance torque of the satellite and the *z* axis wheel in the *y* axis direction. This torque produces a precession cone around the average magnetic dipole vector of the Earth that can be detected by the solar panels and compensated by the *y* magnetic coil bias current. Regarding the previous measurement when the wheels are rotated, the maximum torque is 1.193 x 10^{-5} Nm or about 6.3% of the maximum coil torque (1.88 x 10^{-4} Nm) with maximum current setting 242 mA. Therefore, the current of the *y* coil has to be setting 15 mA to compensate the disturbance torque.

The angular momentum which coincides with the *y* axis direction has to be pointed at a desired direction that is perpendicular to the orbital plane. To control the angular momentum in the right ascension direction the current setting of the *y* coil is a toggled between 14 mA, 15 mA and 16 mA. By over or under-compensation of the disturbance torque, it converts the disturbance torque into a control torque. Since this torque seems to be very stable, it is able to be compensated for a level of 10^{-7} Nm that resulting in a residual drift rate of the right ascension of better than 1°/day. Evaluation of the angular momentum in the direction of the right ascension is done by transmitting a real time video camera to the main ground station in Bogor, Indonesia once per 24 hour.

The right ascension drift will be shown on the horizon flatness in the capturing video. If the right ascension of angular momentum is perpendicular to the orbit, the horizon will be perfectly flat. But if the right ascension is drifting off the desired position, the camera video will cut the horizon in the left or right side of the ground track so the horizon that capturing by camera seems inclined. Since the angular radius of the horizon from 630 km altitude is about 65°, the relation between the right ascension drift (RA_{drift}) in degree unit and the horizon flatness (θ_h) will approximately follow:

$$RA_{drift} = 65 \sin(\theta_h) \quad (3)$$

The drift of right ascension will tilt the angular momentum axis from local horizon. Therefore, it will generate the gravity gradient torque where the maximum deviation of spacecraft vertical axis from local vertical is equal to the right ascension drift. This gravity gradient torque will create drifting on declination of angular momentum. However, during one orbit there are periods when the momentum vector is inclined out of plane and periods where the inclination is in plane and does not contribute to the precession on declination. In average the net effect is only a half of the period so the angular momentum that generated by gravity gradient torque during 24 hours should be multiplied by factor of ½. By knowing the initial angular momentum and the angular momentum that generated by gravity gradient torque, the declination drift per day can be estimated as shown in Table II. The estimation of declination drift rate of table II takes assumption that the initial angular momentum is 0.37 Nms.

TABLE II. DRIFT OF RIGHT ASCENSION (RA) AND DECLINATION (DE)

Horizon visualization	Horizon Flatness (°)	RA_{drift} (°)	τ_{gg} (Nm)	Estimation of DE drift rate (°/day)
	4.97	5.63	2.3 x 10^{-7}	1.55
	0.41	0.47	1.9 x 10^{-8}	0.13
	-5.37	-6.08	-2.5 x 10^{-7}	-1.67

In the attitude control experiment, the declination of the momentum vector was evaluated directly using the sun angle on the *y*-minus side solar panel. This simple estimation is only valid as long as the sun direction is more or less perpendicular to the orbit. This situation will change since the orbit of the satellite is not maintained as sun synchronous anymore so in the future the sun angle will show a mixture of right ascension and declination. The other solution to this problem is to analyze the horizontal movement towards the little targets on video which is proportional to the declination angle. Perhaps in the next experiment the estimation of declination drift on Table II can be compared with the drift of the target movement in the captured video.

VI. CONCLUSION

The bias momentum method has been successfully implemented on Lapan-Tubsat satellite. The basis of the success for the momentum bias control of Lapan-Tubsat is a very efficient hibernation mode when the spacecraft compensate disturbance torques on *x* and *z* axis by a slow rotation or by running the *y* and *x* axis wheels continuously. What remains to be compensated is the constant disturbance torque of the satellite and the *z* axis wheel in *y* axis direction. This torque can be detected by video camera or the solar panels and compensated by the *y* axis magnetic coil bias current of 15 mA.

Since this torque seems to be very stable, it is able to be compensated so the residual drift rate of the right ascension is better than 1°/day. By over or under-compensation of the disturbance torque, the disturbance torque is converted into a control torque. What remains is the drift rate of the declination that is not produced by magnetic effects but by gravity gradients. Again the disturbance torque can be converted into a control torque by introducing a small bias angle to the right ascension. The only control parameter for both control loops is the bias current of the y axis coil that is toggled between 14mA, 15mA, or 16 mA in the one day interval.

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