Quarter orbit maneuver using magnetorquer to maintain spacecraft angular momentum

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Abstract. LAPAN-Tubsat, angular momentum is maintained by using magnetorquer in right ascension direction and gravity gradient in declination direction. Declination correction using gravity gradient in LAPAN-Tubsat only produce 1.5 °/day corrections for 5° gravity gradient. Must be noted that gravity gradient achieved by tilting the satellite, or require off-nadir attitude, this condition is not ideal for imaging mission. This paper introduces new method for angular momentum vector correction in declination direction by using magnetorquer. In this method certain coil current in y direction is set to produce magnetic torque. From previous research certain y coil current for one orbit will effectively change angular momentum's right ascension. In this research y coil current is only set for a quarter orbits, hence torque resultant will only affect angular momentum's declination. LAPAN-A3 satellite, 7° declination correction can be achieved by setting y coil current 30 mA for a quarter orbits or 23.5 minutes. Furthermore, by varying y coil current direction for each quarter orbit, 28° declination correction can be achieved in one full orbit. From this research can be seen that the new method is more efficient than the gravity gradient and also have advantage where the spacecraft will always in near nadir pointing.

1. Introduction
Indonesia has already had three satellites in orbit, LAPAN-Tubsat [1], LAPAN-A2 [2] and LAPAN-A3 [3]. LAPAN-Tubsat and LAPAN-A3 have polar orbit, while LAPAN-A2 has equatorial orbit [4-6]. In all of three LAPAN satellites, momentum bias is used for attitude control. In momentum biased attitude control, certain angular momentum is generated so the spacecraft will naturally spinning to gain stability and then one wheel is used to absorb the angular momentum [7,8]. One key factor for momentum biased attitude control is the direction of angular momentum vector. In momentum bias, the direction of angular momentum vector must always perpendicular to the orbital plane.

Figure 1 shows angular momentum vector in celestial coordinate. Right ascension and declination are used to describe the direction of angular momentum vector. Due to angular momentum the spacecraft will spin in direction of the biggest moment inertia, which in LAPAN-Tubsat is in y axis of body coordinate (as seen in Figure 1). By observe the ybody orientation, the direction of angular momentum vector can also be observed. To maintain the direction of angular momentum vector, LAPAN-Tubsat use magnetorquer and effect of gravity gradient [9]. To move the right ascension of angular momentum vector, certain coil current in ybody is used to generate torque in zbody when in equator. Meanwhile, to move the declination of angular momentum vector, gravity gradient is used to generate torque in xbody when in equator. Gravity gradient is achieved by tilting the satellite so one side of the satellite is nearer to earth and get more gravitational force than the other side.
Figure 1. Vector of angular momentum in earth centered inertial frame (Blue) and spacecraft body frame (Red).

Although angular momentum vector maintenance by using gravity gradient already proven in LAPAN-Tubsat this method has some weaknesses. First, this method required off-nadir attitude to produce gravity gradient torque. For earth imaging operation, off-nadir operation is not ideal since off-nadir operation can reduce imaging quality [10]. Second, gravity gradient torque is very small, for 5° gravity gradient in 1 day only produce around 1.5° angular momentum vector movement in declination direction [9].

In this research a new method to maintain spacecraft angular momentum vector by using only magnetorquer is developed. By using only magnetorquer, spacecraft’s attitude can always nadir pointing. A numerical model for three-axis stability with magnetorquers as actuator has been developed since long time ago [11]. Review from the old numerical model already available in some research [12]. Some simulation works for spacecraft detumbling and stabilization using three-axis magnetorquers also has been done [13-16]. A simulation of three-axis magnetorquer has already demonstrated the capability for rate control of spacecraft [17]. Inertial pointing using only magnetorquers already been simulated [18]. From [19,20] attitude control by using magnetorquer is most effective for high inclination orbit. Based on all previous research, LAPAN-A3 will be used to characterize the effectiveness of magnetorquer as the only actuator for spacecraft angular momentum vector maintenance.

2. Methodology
This research can be divided into two steps. First step is analytical study to understand earth magnetic field characteristic and see the possibility for moving angular momentum vector in declination direction using magnetic torque. Second step is implementation and observation of analytical study result to real case in LAPAN-A3 satellite. From observation result an empirical equation that show relation between magnetorquer and spacecraft angular momentum vector movement in declination direction. In future, the equation can be used for LAPAN-A3 momentum vector maintenance.

3. Analytical Study
From the law of angular momentum conservation, the angular momentum will remain the same unless there is external torque applied. In this study, torque from earth magnetic field will be used to change the angular momentum vector. Equation (1) shows torque resulted from earth magnetic field.

$$\tau = mxB$$ (1)
Where \( \tau \) is magnetic torque vector, \( m \) is satellite dipole and \( B \) is earth magnetic field vector. In LAPAN-A3 air coil is used as magnetorquer, where the dipole can be calculated as follow,

\[
m = nI \mathcal{S}
\]

Where \( n \) is number of the loop, \( I \) is coil current and \( \mathcal{S} \) is the area of the loop. From equation (1) can be seen that torque direction is perpendicular to satellite dipole and earth magnetic field. Figure 1 show earth centered inertial (ECI) frame and celestial coordinate. Right ascension zero is coincide with \( x \) axis of ECI frame. From the picture, in order to move the angular momentum’s declination, torque in \( z_{ECI} \) is needed. For easier understanding cylindrical coordinate version of ECI will be used, such as shown in Figure 2, where \( \hat{z} \) is coincide with \( z_{ECI} \).

![Figure 2. Cylindrical coordinate system.](image)

Expanding equation (1) for cylindrical coordinate resulted,

\[
\begin{bmatrix}
\tau_r \\
\tau_\theta \\
\tau_z
\end{bmatrix} =
\begin{bmatrix}
m_r \\
m_\theta \\
m_z
\end{bmatrix} x
\begin{bmatrix}
B_r \\
B_\theta \\
B_z
\end{bmatrix}
\]

For torque in \( \hat{z} \) only,

\[
\tau_z = (m_r B_\theta - m_\theta B_r) \hat{z}
\]

Figure 3 shows earth magnetic dipole model. In earth magnetic dipole model, there is no earth magnetic field in tangential direction \( B_\theta \), so the only way to generates torque in \( \hat{z} \) is by using spacecraft dipole in tangential direction \( m_\theta \) to gain torque from \( B_r \). While \( B_r \) is approached by,

\[
B_r = -\frac{3}{2} \frac{B_0}{R^3} \sin(2\lambda)
\]

where \( B_0 \) is mean magnetic field at equator on earth surface, \( R \) is distance from earth center divided by earth radius, and \( \lambda \) is latitude.
Figure 3. Earth magnetic field dipole model.

For a spacecraft with 90° inclination, the orbit will in the same plane with earth magnetic field line. For a momentum biased spacecraft, the $y_{body}$ will coincide with normal vector of the orbit. In case of momentum biased spacecraft with 90° inclination, the $y_{body}$ will be in $\hat{\theta}$ direction. In this case to move the angular momentum vector declination can be easily achieved by generate spacecraft dipole in $y_{body}$. According to equation (2) spacecraft dipole in $y_{body}$ can be generated by giving certain current to the $y$ coil. For spacecraft with lower inclination or when the $y_{body}$ not perfectly coincide with the orbit normal vector the result of $y$ coil current will not as effective as the case before, but still can move the angular momentum vector.

From equation (5) can be calculated that the value of $B_{r}$ will be zero when above equator ($\lambda = 0^\circ$) and pole ($\lambda = 90^\circ$ or $\lambda = -90^\circ$). The direction of $B_{r}$ will be in opposite direction when crossing equator or pole. By applying constant $y$ coil current, resulted torque in $\hat{z}$ can be divided into four regions which are separated by equator and pole, shown in Figure 4. For each quarter the resultant torque in $\hat{z}$ will increase or decrease spacecraft angular momentum declination.

According to the result of analytical study above, a method can be proposed by setting certain $y$ coil current for a quarter orbit to change the angular momentum vector in declination direction. In the next part an experimental method will be done by variating $y$ coil current of LAPAN-A3 satellite for some quarter orbit. Effect on angular momentum vector declination will be observed to see the effectivity of the proposed method.
4. Observation Result
In this part quarter orbit maneuver using \( y \) coil current for LAPAN-A3 are observed. The method using here are by observing the effect of \( y \) coil current to the angular momentum vector movement in declination direction. LAPAN-A3 is already in momentum biased and has 97° inclination. Due to a 97° orbit inclination, direction \( y \) coil will not perfectly perpendicular to \( B_r \) so the resulted torque in \( \hat{z} \) will not maximum. Earth magnetic field are not uniform as magnetic dipole model, the variation will cause uncertainty in torque resulted by this method.

Figure 5 show effect on angular momentum vector declination for maneuvers by applying \( y \) coil current -29 mA, while Figure 6 show for \( y \) coil current 31 mA. For both current setting maneuver, the effect to angular momentum vector declination are mirroring to 0° latitude. For maneuver using \( y \) coil current -29 mA, the declination is increasing in negative latitude and increasing for positive latitude. In opposite, for maneuver using \( y \) coil 31 mA, the declination is increasing in positive latitude and decreasing in negative latitude.

\[
\frac{dDE}{dt} = \frac{d\lambda}{dt} \frac{dD\lambda}{d\lambda}
\]

Gradient of change in declination to latitude for each maneuver are calculated using linear regression to see effect of \( y \) coil current. Spacecraft can move ascending \((d\lambda/dt > 0)\) or descending \((d\lambda/dt > 0)\) in latitude. Change in declination in a time period is,
declination will increase. Table 1 shows change of declination for \( y \) coil current -29 mA in each quarter. For \( y \) coil current 31 mA the effect will be the inverse.

**Table 1.** Effect of \( y \) coil current -29 mA to declination for each Quarter.

|          | descending | ascending |
|----------|------------|-----------|
| positive\( \) latitude | quarter 2 | quarter 1 |
|         | Increase   | decrease  |
| negative\( \) latitude | quarter 3 | quarter 4 |
|         | decrease   | increase  |

Another \( y \) coil current is applied for each quarter. Figure 7 show change of declination for a quarter orbit period (23.5 minutes) for each quarter. From the figure can be seen that quarter 1 and quarter 3 have same characteristic, while quarter 2 have same characteristic as quarter 4. Linear regressions are used to conduct relation between \( y \) coil current and declination change for a quarter orbit. There are two linear regressions; first one is for quarter 1 and quarter 2 where \( y \) coil current has positive relation whit change of declination, while the second one is for quarter 3 and quarter 4 where \( y \) coil current has negative relation with change of declination.

![Figure 7. \( y \) Coil current to change of angular momentum vector declination.](image)

From Figure 7, regression 1 applied for quarter 1 and quarter 3,

\[
\Delta DE = 0.2355I_y + 0.2038
\]  

(7)

while regression 2 applied for quarter 2 and 4,

\[
\Delta DE = -0.2490I_y + 0.3133
\]  

(8)

where \( I_y \) is \( y \) coil current in mA.
By using equation (7) or equation (8), maneuver for moving angular momentum vector in declination direction can be calculated. The maneuver can used one quarter orbit or combine more than one quarter orbit. When combination of quarter orbit is used in sequence to gain more declination change, direction of y coil current must be altered for each quarter orbits or the effect will neglect each other.

5. Conclusion
A new method for moving spacecraft angular momentum vector by using magnetorquer only is already conducted in this research and already applied for LAPAN-A3. The method is by applying certain y coil current for a quarter orbit period to gain a magnetic torque that can move spacecraft angular momentum vector in declination direction. By using this method, angular momentum vector direction can be moved around 7° for a quarter orbit (23.5°). Furthermore, by varying the direction of y coil current for one orbit, angular momentum vector can be moved around 28°. Compared to old gravity gradient method, this method is more effective.

This method can be applied for an equatorial orbit such as LAPAN-A2 satellite, although can be not as effective as for a high inclination orbit. For future, based on this research and previous research, an automatic angular momentum vector control by using magnetorquer as actuator will constructed. The control system will be implemented for the next LAPAN satellite.

Acknowledgements
The authors would like to thank to head of LAPAN satellite technologi center, Mr Mujtahid for the support and all LAPAN Satellite operator for help in data collection.

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