PICO-SATELLITE DETUMBLING SIMULATION USING MAGNETIC ATITUDE ACTUATOR
(SIMULASI DETUMBLING PADA SATELIT PIKO MENGGUNAKAN AKTUATOR SIKAP MAGNETIK)

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ABSTRACT

One of the methods to control Nano/pico-satellite's attitude is using magneto-torquers as attitude actuators. ITB, at the moment is planning to develop a cubesat. Therefore, the objective of the research was to investigate the performance of such attitude control system for 3U class cubesat. The research used Matlab/simulink-based satellite simulator developed by LAPAN and ITB, and B-dot control law. The advantages of the method are that the actuators are small and lighter compared to the other type of actuators, such as momentum wheels or reaction wheels. However, the disadvantages is that the torques can be created only when the actuator oriented at non-zero angle with local magnetic field. The results showed that the attitude control system could performed the detumbling operation, with the best transient time at about two orbits period. Varying the gain parameter in the controller may result into variation of transient time and even unstability.

Keywords: *Cubesat attitude control, Magnetic actuator, B-dot control, Satellite simulator*

ABSTRAK

Salah satu cara untuk mengendalikan sikap satelit nano/piko adalah dengan menggunakan magneto-torquer sebagai aktuator. Saat ini ITB tengah mewacanakan pengembangan cubesat, sehinggga tujuan dari penelitian ini adalah untuk mengevaluasi kinerja sistem kendali sikap berdasarkan medan magnet Bumi pada cubesat kelas 3U. Penelitian ini menggunakan simulator satelit berbasis MATLAB/simulink yang dikembangkan oleh LAPAN dan ITB, moda kendalinya berbasis hukum kendali b-dot. Keuntungan dari sistem kendali ini adalah ukuran dan beratnya yang kecil, dibandingkan dengan moda kendali lain, seperti momentum *wheel* atau *reaction wheel.* Sementara kerugiannya adalah hanya bisa menghasilkan torsi saat aktuator mempunyai sudut tidak nol dengan medan magnet Bumi. Hasil menunjukkan bahwa moda kendali tersebut dapat melakukan *manuver de-tumbling,* dengan waktu *transient* terbaik mendekati dua periode orbit. Juga ditunjukkan bahwa variasi waktu *transient* dan ketidakstabilan dapat diperoleh dengan memvariasikan parameter *gain* pada kontroler.

Kata kunci: *Kendali sikap cubesat, Aktuator magnetik, Kendali b-dot, Simulator satelit*

1 INTRODUCTION

Using magneto-torquers as sole attitude actuators in three-axis attitude control stability was initially proposed by Musser *et al.* (1989). The utilization of magneto-torquers in satellite is typical to dump excess angular momentum inducted by external disturbances. Other utilizations include detumbling, initial acquisition, precessing control, nutation damping, and momentum control (Markley *et al.*, 2014). The discussion in this paper focuses more on the detumbling case.

Attitude control system using magnetorquers have several advantages and disadvantages especially for near-Earth mission or satellite in Low Earth's Orbit (LEO) orbit. The advantages are the hardware is simple, lightweight compare to other types of actuator such as reaction wheels or momentum wheels, and the mass does not change over time (unlike thruster). In addition, it has smoothness of application, does not deteriorate over time, and has essentially unlimited mission, due to the absence of expendable. But this actuator only produces perpendicular torque of local magnetic field, and at any given time, the satellite is only able to control two out of its three axis while producing residual magnetic moment. The actuator also has some limitations due to the complicated dynamic nature of the Earth's magnetic field (Makovec, 2001).

The objective of this research was to investigate the performance of 3-axis magneto-torquer for attitude control system of 3U class cubesat. The investigation was done by simulating detumbling mode for the pico-satellite in LAPAN-ITB Simulink-based satellite simulator.

Before the investigation, the model of Earth's magnetic field had been implemented in the simulator developed by Triharjanto et al. (2015). The model was based on International Geomagnetic Reference Model (Thébault, 2015), which was put forth by IAGA (International Association of Geomagnetism and Aeronomy). Among others, the reference showed that the field magnitude decrease was promotionally inverted to the cube from the distance of the center of the Earth and the magnetic control torques were typical in the order of 10^{-4} Nm and 10^{-5} Nm for LEO orbit. The details of the computational implementation was published by Muksin et al (2016).

2 METHODOLOGY

2.1 Satellite-Earth Magnetic Interaction Model

According to the attitude control design guidance in Wertz (2011), it is assumed that satellite is a rigid body with homogeneus density. The satellite is cube shaped with 13x13x30 cm in dimension and 3,5 kg in weight. This satellite only has coil type magneto-torquers as the attitude actuator in three axis configuration. The coils are made of copper wire with 265 wraps for x-axis, 243 wraps for y-axis, and 279 wraps for z-axis. It is assumed that the maximum currents can be produced by the satellite is 30 mA.

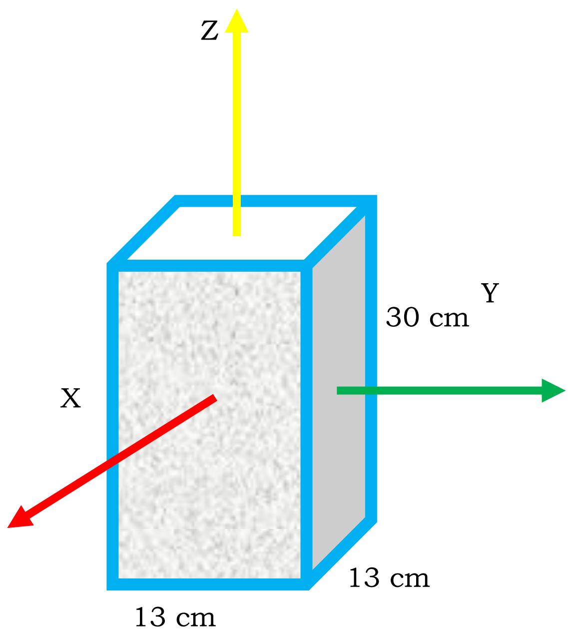


Figure 2-1: Satellite model showing coil magneto-torquers placement (blue)

To implement the model in Simulink-based simulator, we made a mathematic model of this satellite's inertia matrix. The inertia matrix was used to describe the mass distribution about center of mass. For the satellite with mass m, Wertz (2011) defined the inertia matrix as:

$$I = \int \begin{bmatrix} (x^2+z^2) & -xy & -zx \\ -xy & (z^2+x^2) & -yz \\ -zx & -yz & (x^2+y^2) \end{bmatrix} dm \qquad (2\text{-}1)$$

Using the equation, the inertia matrix (assuming the value of product inertia was 10% from the calculated value) was

$$I = \begin{bmatrix} 0.3741 & -0.005915 & 0 \\ 0 & 0.3741 & -0.01365 \\ -0.01365 & 0 & 0.1183 \end{bmatrix} kg.m^2$$

2.2 Earth's Magnetic Field Model

The Earth's magnetic field implemented in the Simulink-based satellite simulator by Muksin *et al.* (2016) was based on the updated version of IGRF-12 model. This simulator used a custom model adopted from IGRF 12th data, combined with theoretical model of spherical harmonic. The result are plotted in Figure 2-2 (axis showing latitude and longitude).

Figure 2-3 shows the simulated single orbit reading of the satellite's magnetometer. The orbit parameters used the orbit of LAPAN-A2 satellite downloaded from celestrak on April 37 2016, at 08:59 PM (Table 2-1), but the inclination angle had been modified from 6 to 97 degree.

Table 2-1. LAPAN-A2 (IO-86) TLE

1	40931U 15052B 16092.07183861 .00000704 00000-0 92160-5 0 9996
2	40931 5.9980 144.8864 0012731 105.9830 254.1966 14.76443089 27519

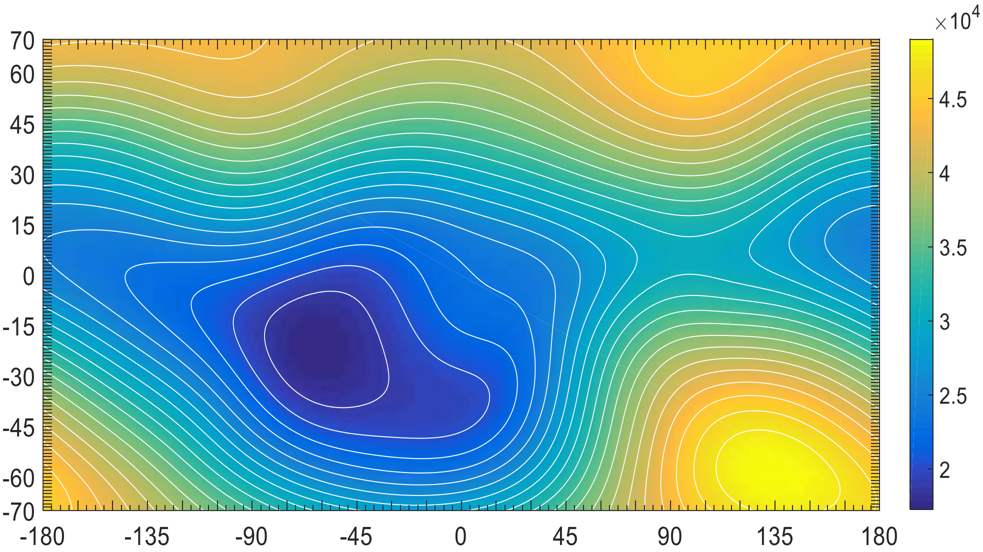


Figure 2-2: Total intensity of the Earth's geomagnetic field model in local horizon frame

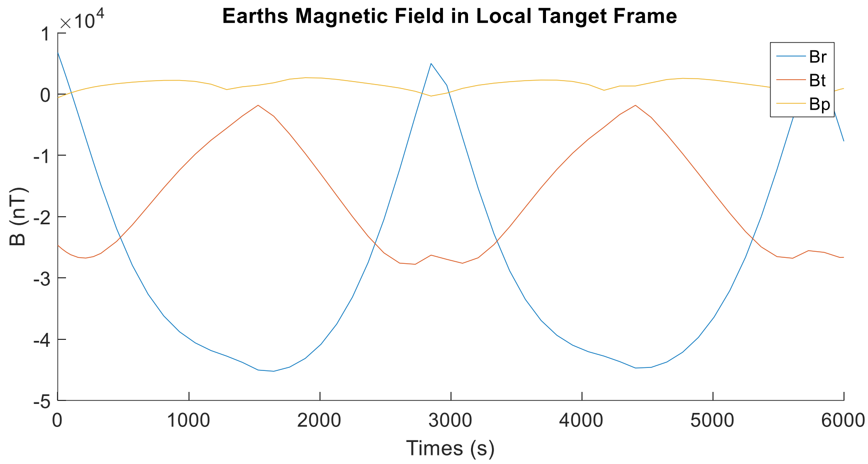


Figure 2-3: The satllite geomagnetic reading in local tangent coordinates for 1 orbit

2.3 The Attitude Control Model

Magnetic torque is a product of interaction between moment dipole generated by flowing currents through the coil, and Earth's magnetic field. This is a similar effect to compass needle that attempts to align itself with local direction of magnetic field. If a magnetic moment by spacecraft can be represented with $\vec{m}$ and the local magnetic field with $\vec{B}$, the produced torque $\vec{T}$, is (Wertz, 2011)

$$\vec{T} = \vec{m} \times \vec{B} \tag{2-2}$$

to control the attitude of the spacecraft, the electric currents $\vec{I}$ must be carefully calculated, that must be taken to generate the magnetic moment. The moment generated by magnetorquers is (Wertz, 2011)

$$\vec{m} = NIA\hat{n} \tag{2-3}$$

N is number of coil and A is cross-section area of the coil. Thus, substituting equation (2-3) into equation (2-2), will give

$$\vec{T} = NIAB(\hat{n} \times \hat{b}) \tag{2-4}$$

with $\hat{b}$ is unit vector of the local magnetic field and $\hat{n}$ is unit vector of the electro-moment dipole.

In cases using the magnetorquers as main actuator of small satellite, it can be used, among others, to de-tumble te satellite. To detumble we use B-dot control (controlling electro-magnetic dipole moment) to make an angular velocity $\vec{\omega}$, of spacecraft equal to zero or close to zero (Makovec, 2011)

$$\vec{T}_{ctrl} = \frac{k}{\|\vec{B}\|}(\vec{\omega} \times \vec{b}) \qquad (2\text{-}5)$$

with $\vec{b} = \vec{B} / \|\vec{B}\|$, k is positive scalar gain. The gain is used to estimate how much torque must be acted to achieve the detumbling mode and the value of this gain can be estimated. The equation above gives

$$\vec{T}_{ctrl} = k(\vec{\omega} \times \vec{b}) \times \vec{b} = -k(I_3 - \vec{b}\vec{b}^T)\vec{\omega} \qquad (2\text{-}6)$$

Where we can see the control torque is clearly perpendicular to local magnetic vector $\vec{b}$. To prove the stability of this control law considering the following candidate Lyapunov function (Makovec, 2011)

$$\vec{V} = \frac{1}{2}\vec{\omega}^T I \vec{\omega} \qquad (2\text{-}7)$$

with I is an inertia matrix, using dynamic and kinematic equation in Wertz (2011)

$$I\dot{\vec{\omega}} = -[\vec{\omega}\times]I\vec{\omega} + \vec{T} \qquad (2\text{-}8)$$

and previous equation, will get

$$\dot{\vec{V}} = -k\vec{\omega}^T(I_3 - \vec{b}\vec{b}^T)\vec{\omega} \qquad (2\text{-}9)$$

with $(I_3 - \vec{b}\vec{b}^T)$ is eigenvalues that always be 0, 1, and, 1. Using these equation will give (Makovec, 2011)

$$\dot{\vec{B}} = A\dot{\vec{R}} - \vec{\omega} \times \vec{B} \qquad (2\text{-}10)$$

where $\dot{\vec{R}}$ is geomagnetic vector depends on spacecraft orbital's position. Assuming, or initial stage of detumbling, $\dot{\vec{R}} \ll \dot{\vec{B}}$, we can approximate that

$$\vec{m} = -\frac{k}{\|\vec{B}\|}\dot{\vec{B}} \qquad (2\text{-}11)$$

this equation is well-known as B-dot control and the gain value can be estimated using

$$k = \frac{4\pi}{T_{orb}}(1 + \sin i)I_{\min} \qquad (2\text{-}12)$$

in this case, the gain value that is used is a fix single gain value, not an adaptive gain value or PID (proportional-integral-derivative).

T_{orb} : Orbital period, seconds
i : Inclination angle, degree
I_{mi} : Minimum value of principal inertia moment

3 THE SATELLITE SIMULATOR

The simulator was built using MATLAB (a programming language developed by MathWorks) and Simulink (a block diagram environment for multi-domain simulation and Model-Based Design), with the graphic user interface (GUI) given in figure 3-1. The main input (satellite parameter and initial condition) of the simulator given in Satellite Parameter is INPUT block and all output is given in OUTPUT block. With this simulator we can visualize the orbit and attitude of the satellite in 2D graph or 3D animation.

Before we make a scheme of B-dot controller, the first thing to do is to convert the Earth's magnetic field model in local horizon frame to body reference frame as magnetometer. Using coordinate transformation, if R_l^b represents matrix transformation from local horizon to body reference frame, the transformation coordinate given by

$$\vec{B}_b = R_l^b \vec{B}_l \qquad (2\text{-}13)$$

with $\vec{B}_l$ is Earth's magnetic field in local horizon frame and $\vec{B}_b$ is field in body reference frame. The schematic implementation B-dot control is shown in Figure 3-2, and the Simulink implementation in Figure 3-3.

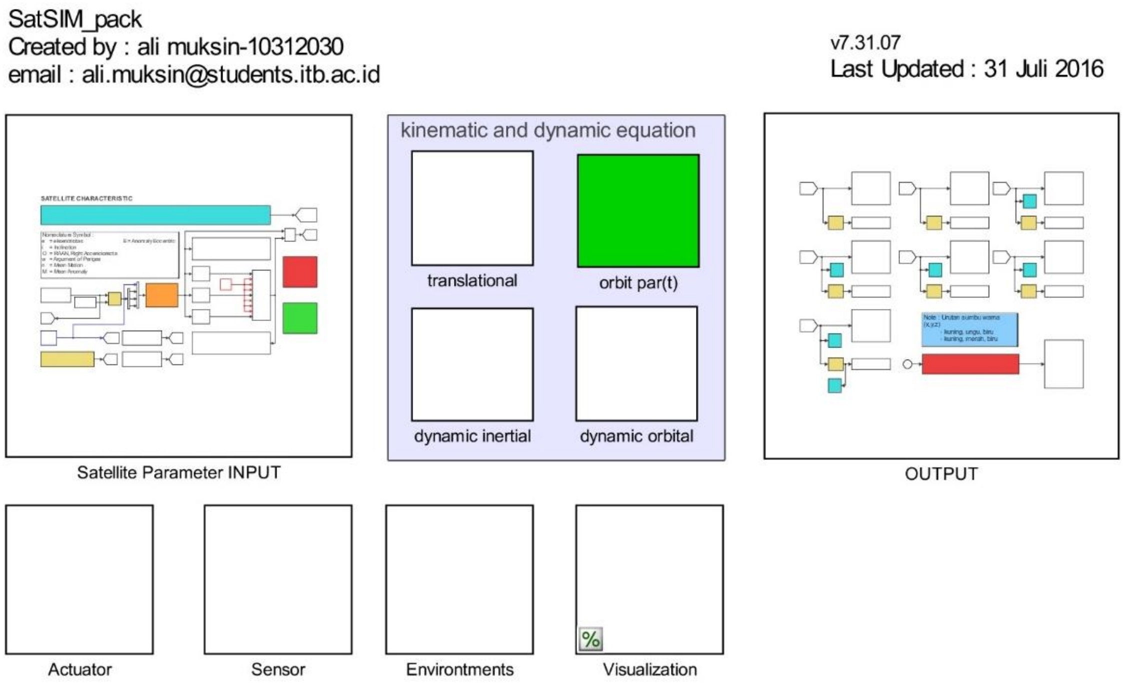


Figure 3-1: GUI of satellite simulator base on MATLAB Simulink

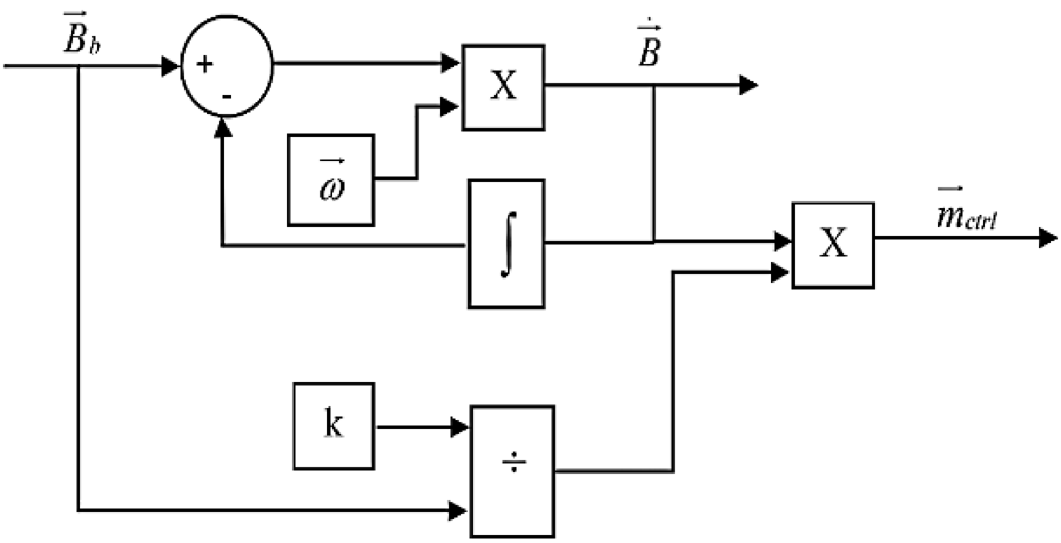
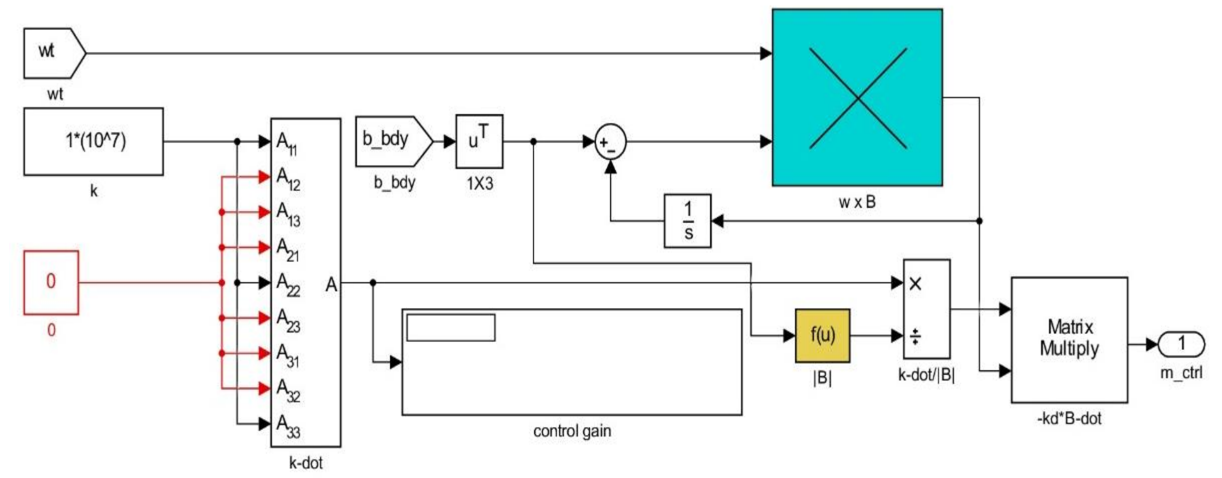


Figure 3-2: B-dot control scheme



$$k = \frac{4\pi}{T_{\text{orb}}}(1 + \sin \xi_m)\, J_{\text{min}}$$

Figure 3-3: Implementation of B-dot control in the satellite simulator

3 RESULTS AND DISCUSSIONS

These are the results of simulation for detumbling mode with different gain value (k) for t=15000s, with the initial angular velocity of spacecraft is $\omega_0 = [0.03 \;\; -0.02 \;\; 0.01]$ rad/s and initial rotation angle is $[\psi \;\; \theta \;\; \phi] = [0 \;\; 0 \;\; 0]$ degree, with θ is rotation about roll axis, ψ is rotation about pitch axis, and ϕ is rotation about yaw axis.

Figure 3-1 (angular velocity plot) shows that the time needed to stop the satellite rotation is ~1600s, which is nearly <1 orbit periods. In rotation angle plot shows that during such time the satellite has rotated 4 times in x-axis (roll) and 3 times in z-axis (yaw). Full rotation cannot happen in y-axis (pitch), because at the initial condition the satellite's position located at the equator and the field in down direction that effect on pitch rotation is not too strong compare to another component in other direction. After detumbling mode, we can see from magnetic torque plot (the torque is result of interacting between the Earth's geomagnetic field and dipole moment by magnetorquers), the system unable to lock the attitude or completely stop the rotation of the satellite. It is because when the satellite toward the Earth's magnetic pole, the field increases and affects the angular velocity due to the gain value is large. Even so, b-dot still reduces the angular velocity.

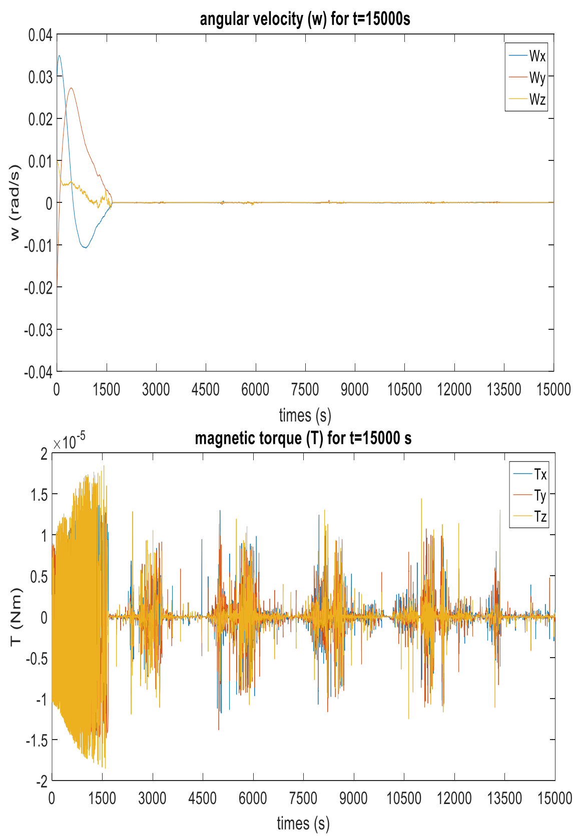


Figure 3-1: Attitude control parameters for $k = 5.0617 \times 10^4$ without perturbations

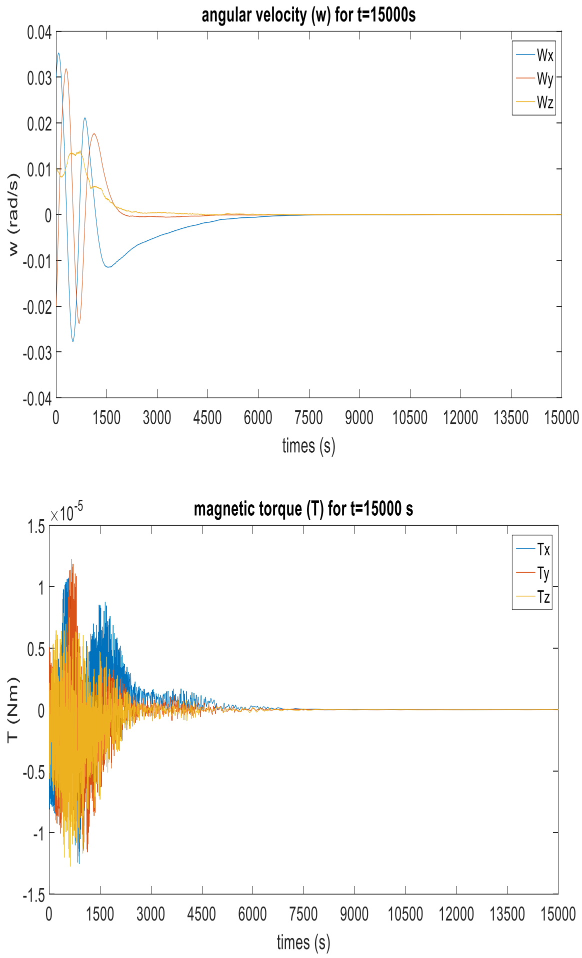


Figure 3-2: Time history of attitude parameter for $k = 1\times10^{1}$ without perturbations

Figure 4-2 (angular velocity plot) shows that the time need to stop the satellite rotation is ~12000*s*, which is nearly >1 orbit periods. In rotation angle plot shows that during such time the satellite has rotated 3 times in *x*-axis (roll) and 4 times in *z*-axis (yaw). Full rotation cannot happen in *y*-axis (pitch), because at the initial condition the satellite's position located at the equator and the field in down direction that effect on pitch rotation is not too strong comparing to another component in other direction. After detumbling mode, the system was managed to lock the attitude or completely stop the rotation of the satellite (see magnetic torque plot). And it can be concluded that b-dot successfully achieve detumbling mode with this fix or constant gain value.

Figure 4-3 (angular velocity plot) shows the system fail to reach its goal of stopping the satellite rotation. In this case, the rate explodes near the pole (around ~10000*s*) and the system or b-dot cannot recover or reduce the angular velocity, the spacecraft spins about *z*-axis or yaw. It is because when the value of gain (*k*) is too large, it means that the magnetorquers is too sensitive and can cause instability after detumbling mode is achieved. This indicates that the system performing at the limit of its capability at this gain value.

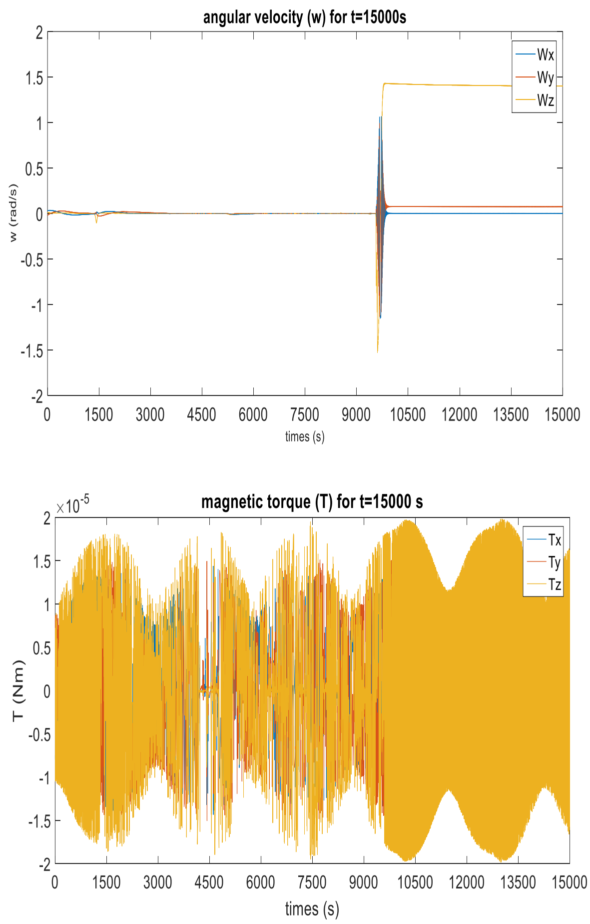


Figure 4-3: Time history of attitude parameter for $k = 1\times10^{7}$ without perturbations

The gain value in this case is depending on the mass moment of inertia of the spacecraft and should be recalculated for different configurations. For this simulator, the gain value used is a fix single gain value. The only consequence of having too low gain set is the settling time proportional increase (Guerrant, 2005) or otherwise. But the maximum stable gain did not guarantee that detumbling mode can be achieved fastest due to when the gain with the fastest settling time (the gain value is large) has a stability limit. And the different configurations of the gain value give a different perfomance (Leomanni, 2012).

4 CONCLUSIONS

From the results, we can conclude that gain value k has important rule to define how long to achieve detumbling mode and define the sensitivity of the model of magnetorquers. If gain value k is large, the time to achieve detumbling mode is shorter, but if gain value is too large, after detumbling mode, bias moment still exists that causes disruptions while the satellite attitude control mechanism in effect. To avoid the torques with infinite (∞) value, when the value of the gain k is too large, the currents are limited to a maximum of 30 mA or 0.030 A. In this paper the best and smoothest result was for gain k=1x10^1. In this simulator, for k>1x10^6 the system could not achieve detumbling mode and it was the limit of the gain value for this simulator. The instability occurred when k=1x107 for $t = \pm 1000s$ and the system failed to reach detumbling. Another factor that influenced how long it took to reach detumbling mode was the satellite model (matrix inertia moment). The model would give a variety of gain values to get the best result. If we had used a different satellite model, then the order of gain value to reach de-tumbling mode would have been different too.

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