Attitude Control Strategy for HAUSAT-2 with Pitch Bias Momentum System

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ABSTRACT: The HAUSAT-2 is a 25kg class micro/nanosatellite which is being developed by graduate students at the Space System Research Laboratory(SSRL). This paper addresses a newly proposed strategy for detumbling the HAUSAT-2 and starting up a momentum wheel, and also studies performance validation and application ranges of such method through simulation. B-dot logic is generally used for controlling the initial tip-off rate. However, it has the disadvantage of taking a relatively long time to control the initial tip-off rate. To solve this problem, this paper suggests a new detumbling control method to be able to adapt to micro/nanosatellite with the pitch bias momentum system, and has shown simulation results. Proposed detumbling method was able to control the angular rate within 20 minutes which is a significant reduction compared to conventional methods. In addition, the momentum wheel initial start-up must be done under stable conditions, and conventional pitch spin-stabilized initial wheel start-up method is commonly used. The performance of the method is compared and verified through simulation. The overall result shows much faster control time compared to the conventional methods, and achievement of the nominal wheel speed and 3-axes stabilization while maintaining stability.

INTRODUCTION

The bias momentum method is one of the satellite attitude control methods that has the advantage of delivering a high attitude control performance (0.1°~0.5° in all three axes) with only one actuator.[1-6] This method is also used on the majority of currently operating communication satellites for attitude stabilization. The bias momentum method achieves attitude stabilization by attaching a momentum wheel that incorporates an angular momentum inside a satellite. The angular momentum generated by the spinning of the wheel creates a gyroscopic stiffness that provides the stabilizing effect on the satellite attitude. The angular momentum of the momentum wheel also generates torque through gyroscopic coupling perpendicular to the wheel axis. A three-axis stabilization is achieved using these torques. The representative of the bias momentum is the pitch bias momentum method where the spin axis of the momentum wheel points perpendicular to the orbit normal (pitch direction). The satellite pitch error is controlled by changing the wheel speed, and the nutation of roll/yaw is controlled by magnetic torquers. Therefore, the pitch bias momentum method uses one momentum wheel, together with magnetic torquers, to achieve three-axis control.

Satellites separate from the launch vehicle with a high initial angular rate, or tip-off rate. The initial angular rate must be controlled to within the required range before satellite three-axis stabilization, and this is called the detumbling control or initial attitude acquisition. For detumbling control, B-dot controller using magnetic torquers is generally implemented.[4,7,8] B-dot controller utilizes only the earth's magnetic field and does not require other attitude determination sensors, orbit parameters, or attitude information. Accordingly, the controller can be made simple and highly reliable. However, the disadvantage of the magnetic torquers is that detumbling takes relatively long time due to the low torque level. In order to shorten the detumbling time of B-dot controller that uses three-axis magnetic torquers, this paper suggests a new detumbling method for micro/nanosatellites using pitch bias momentum method, and verifies the performance of the new method through simulation. Unlike the previously used methods, the proposed detumbling method uses both magnetic torquers and a momentum wheel concurrently. In addition, a new detumbling controller with momentum wheel is proposed that can increase performance over the previous B-dot controller that uses only magnetic torquers.

Satellites using pitch bias momentum method has a momentum wheel spinning at a constant speed, at a nominal rpm, for attitude stabilization. However, the wheel inside the satellite is at rest until before the separation from the launch vehicle occurs, and needs to be sped up to the nominal rpm after the separation. It is called momentum wheel start-up. While the momentum wheel is spinning, it creates an angular momentum within the satellite. If the wheel is suddenly brought up to the nominal rpm, the satellite attitude becomes unstable due to the rapid increase in angular momentum from the initial angular momentum caused by wheel speed-up. Therefore, the momentum wheel start-up must be carried out under stable conditions to avoid the unstable satellite attitude. For wheel start-up of small satellites, various researches into achieving this goal for small satellites have been done.[5,7-9] Previous researches required the satellites to be pitch spin-stabilized(Y-Thomson mode) before the momentum wheel initial start-up.[5] However, if the detumbling method proposed in this paper is used, the previous wheel start-up method cannot be implemented any more. This paper proposes a method for speeding up the momentum wheel to the nominal rpm while maintaining stability. The performance has also been compared to other methods and verified through simulations.

SATELLITE ATTITUDE CONTROL AND EARTH'S MAGNETIC FIELD MODEL

The satellite used in attitude control simulation of this paper is HAUSAT-2 currently being developed by SSRL(Space System Research Lab.) of Hankuk Aviation University. HAUSAT-2 is a 25kg class micro/nanosatellite with a sun-synchronous mission orbit of 650km altitude. It uses pitch bias momentum method for attitude stabilization. HAUSAT-2's moment of inertia is $I = diag\{0.3078 \;\; 0.2865 \;\; 0.2747\}\, kg \cdot m^2$. HAUSAT-2 has a momentum wheel and magnetic torquers as attitude control actuators. Momentum wheel has angular momentum of $h_W = 0.09\; Nm \cdot s$, nominal wheel speed of 2500 rpm, and consumes power of 2 W(watt) at a nominal speed. One magnetic torquer generating $M_{max} = 2Am^2$ of maximum magnetic dipole, consuming 1 W of power, is installed in each axis. In case of an environmental model, a tenth order IGRF(International Geomagnetic Reference Field) 2005 Earth's magnetic field model was utilized.[6,10]

DETUMBLING CONTROL

The worst initial tip-off rate of satellites separating from the launch vehicle is known to be 0.1 rad/s(1 rpm) in each axis.[7,8,11] Therefore, the detumbling controller must be able to control the fast initial angular rate of 0.1 rad/s in three axes down to a level where the 3-axes stabilization controller is able to stabilize the satellite. In this paper, this level was assumed to be 0.003 rad/s. As mentioned above, B-dot controller has been generally used to control the initial angular rate. Magnetic dipole moment in each axis generated by B-dot controller is described by the following Eq. (1).[4]

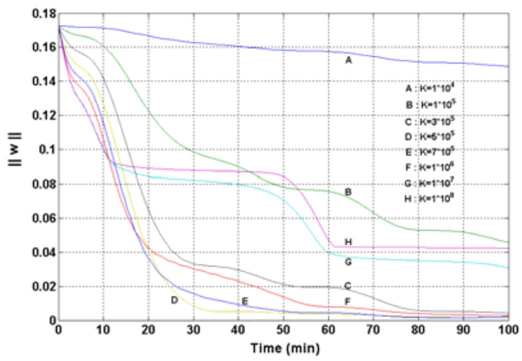
$$\underline{M} = -K\dot{\underline{B}} \quad , \quad (K > 0) \qquad (1)$$

where, K is the control gain constant. $\dot{\underline{B}}$ is the differentiated earth's magnetic field vector $\underline{B}$ in each axis and the output of the magnetometer installed in the satellite can be calculated as shown in Eq. (2).

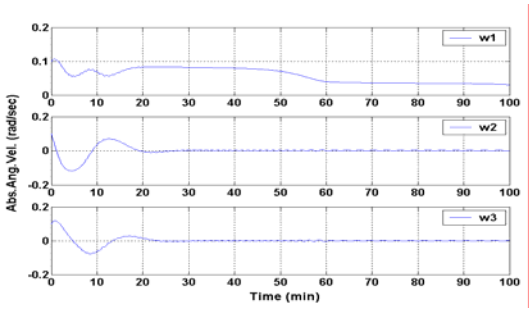
$$\dot{\underline{B}} = \frac{\underline{B}(t) - \underline{B}(t-T)}{T} \qquad (2)$$

where T is sampling time.

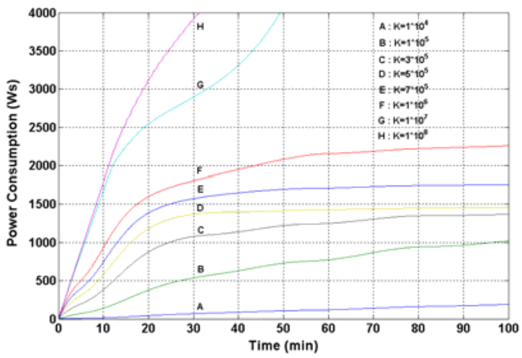
First, the trend in angular rate change according to the gain K was simulated in order to find the optimum gain K. The optimum gain K was chosen considering detumbling time and actuator power consumption from the simulation results. The simulated detumbling process assumed the satellite initial angular rate to be 0.1 rad/s in each axis, and was carried out until the values fell below 0.003 rad/s for all axes. Figure 1(a) represents the angular rate trend according to gain K. As shown in Figure 1(a), control torque is quite small for small control gain of $K \le 1\times10^5$ and as a result, detumbling takes a long time. On the other hand, as shown in Figures 1(a) and 1(b), large control gain of $K \ge 1\times10^7$ results in quick angular rate control about two axes, but shows a slow response in the third axis control. This remaining axis is aligned almost parallel to the earth's magnetic field vector. For this reason, angular rate about the axis aligned with the Earth's magnetic field vector is quite difficult to control. $1\times10^5 < K < 1\times10^7$ show a satisfactory detumbling control result. The gain K in this range illustrates that the angular rate is reduced to the desire level within one orbit, however, power consumption results of Figure 1(c) also needed to be considered for optimum control gain. Therefore, $K = 5\times10^5$ was chosen as the gain value to be used by B-dot controllers in this study.



(a) Angular Rate



(b) Angular Rate at $K = 1\times10^7$,



(c) Power Consumption

Figure 1. Angular Rate and Power Consumption Trends According to Control Gain K

The B-dot controller performance according to the initial angular rate has been verified using the chosen gain $K = 5\times10^5$. As mentioned before, the worst case initial angular rate after separation is 0.1 rad/s for each axis. The simulation was performed for varying initial angular rate from ±0.1 rad/s to ±0.07 rad/s for each axis. Figure 2 presents the simulation results. As can be seen from Figure 2, the required detumbling time varies a bit for different initial angular rates but generally takes approximately 70 minutes to stabilize.

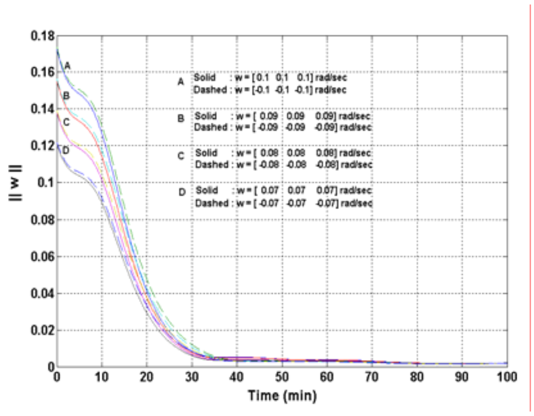


Figure 2. B-dot Controller Performance According to Initial Angular Rate Change

A New Detumbling Control Method

Despite the advantages of B-dot controller mentioned above, the method takes relatively a long time to control angular rate due to the low torque level of magnetic torquers. In order to improve on this disadvantage of the B-dot controller that rely only on the magnetic torquers, this paper proposes a new detumbling method that uses both magnetic torquers and a momentum wheel.

The design process of the momentum wheel controller for detumbling control is as follows; First, the general controller for controlling angular rate can be easily designed as described by Eq. (3).

$$T_W = -K_W \cdot \underline{\omega} \quad (3)$$

where, K_W is the control gain and $\underline{\omega}$ is the satellite's angular rate vector. T_W is the control torque generated by actuator. Therefore, in case of the momentum wheel, the above controller can be used for detumbling controller. However, one thing to note is that the wheel controller of Eq. (3) requires angular rate information. This means that, unlike B-dot controller where only the earth's magnetic field measurements are needed, the wheel controller requires a sensor or a gyro that can measure the angular rate. To overcome this disadvantage, a controller that uses only the earth's magnetic field values is proposed. The control torque $\underline{T}_M$ generated by magnetic torquers during detumbling is shown in Eq. (4).

$$\underline{T}_M = \underline{M} \times \underline{B} \tag{4}$$

Substituting the B-dot controller $\underline{M}$ from Eq. (1), the following Eq. (5) is obtained.

$$\underline{T}_M = \underline{M} \times \underline{B} = -K\dot{\underline{B}} \times \underline{B} \tag{5}$$

Pitch axis control torque has to come from the momentum wheel. If the second column of $\dot{\underline{B}} \times \underline{B}$ matrix is taken, the wheel controller can be designed as shown in Eq. (6), and it can also be shown clearly that the satellite angular rate can be controlled with this controller.

$$T_W = T_{M2} = K_W \cdot (B_3\dot{B}_1 - B_1\dot{B}_3) \tag{6}$$

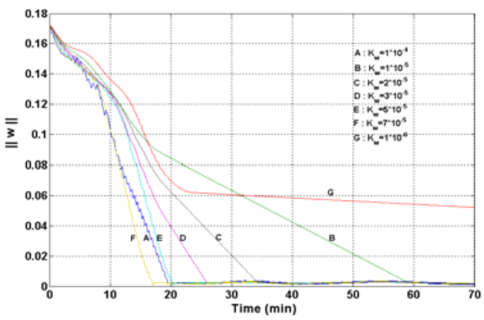
where, T_W is the momentum wheel control torque, and K_W is the control gain. B_1, B_3, $\dot{B}_1$, and $\dot{B}_3$ represent the earth's magnetic field values in roll and yaw axes, and their differentiated values, respectively. However, if Eq. (6) is used as a momentum wheel controller, the amount of control torque is determined by the earth's magnetic field's rate of change. Therefore, when the change in the earth's magnetic field is large (when the initial satellite angular rate is large), the required momentum wheel control torque can exceed the maximum wheel capacity, and reach a saturation point. On the other hand, uncontrollability can also result if the required torque is too small such that the wheel hardware performance cannot execute the given command accurately. In order to remedy these shortfalls, the controller described by Eq. (6) is modified such that an executable constant torque is generated, when applied to an actual controller, as described by Eq. (7). In this paper, this modified controller is termed the momentum wheel detumbling controller.

$$T_W = K_W \cdot \mathrm{sgn}(B_3\dot{B}_1 - B_1\dot{B}_3) \qquad \mathrm{sgn}(A) = \begin{Bmatrix} +1 : A \geq 0 \\ -1 : A < 0 \end{Bmatrix} \tag{7}$$

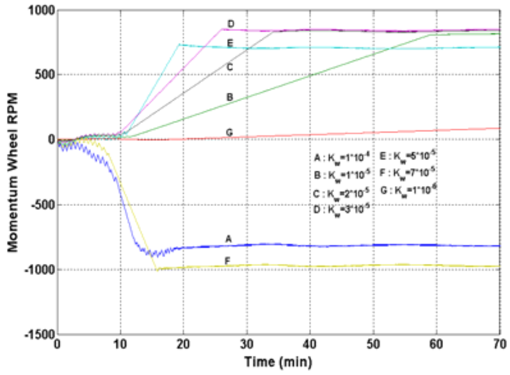
In the case of the proposed method, the initial angular rate in roll and yaw axes will be controlled only by the magnetic torquer in pitch axis as shown in Eq. (8).

$$M_2 = -K\dot{B}_2 \quad , \quad (M_1, M_3 = 0) \tag{8}$$

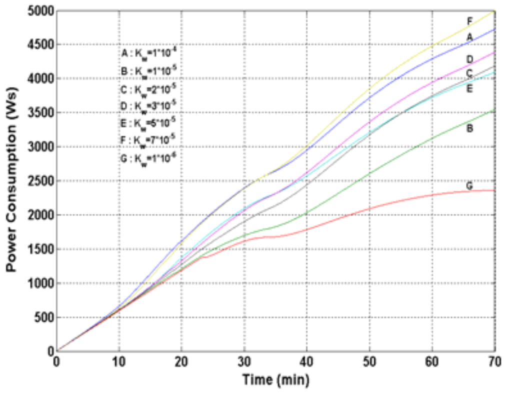
Angular rate change trend according to K_W has been simulated in order to find the optimum control gain K_W for the momentum wheel detumbling controller of Eq. (7). The optimum control gain K_W was chosen through simulation, taking into account wheel conditions, detumbling time, and actuator power consumption. For simulation conditions, the initial angular rate was set to 0.1 rad/s for each axis as was the case for the previous B-dot controller. The simulation was carried out until the angular rate has fallen below 0.003 rad/sec in all three axes. Also, the control gain of the pitch axis magnetic torquer was set to $K = 3\times10^7$. Figure 3 shows the angular rate trend according to the control gain K_W. As can be seen from Figures 3(a) and 3(b), the satellite angular rate stabilizes in about 20 minutes for relatively large control gain of $K_W = 1\times10^{-4}$, but the wheel speed changes in a unstable manner. On the other hand, the wheel speed changes in a stable manner for a small control gain of $K_W = 1\times10^{-6}$ but the pitch axis angular rate changes quite slowly. $1\times10^{-6} < K_W < 1\times10^{-4}$ show a good response(control time of less than 60 minutes) considering the wheel speed change and detumbling time. A Significant time reduction was achieved when control gain K_W is slightly increased from $K_W = 1\times10^{-5}$ by taking into consideration momentum wheel speed and power consumption of Figure 3(c). Therefore, the control gain of $K_W = 5\times10^{-5}$ was chosen for the momentum wheel detumbling controller in this study.



(a) Angular Rate



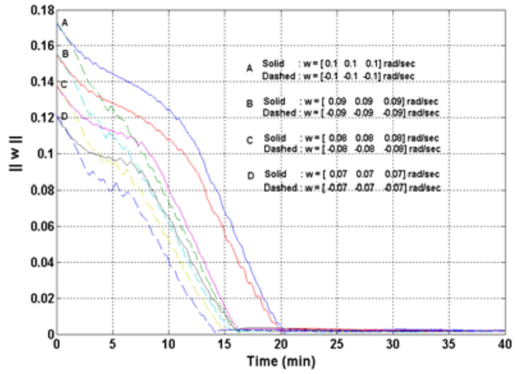
(b) Momentum Wheel RPM



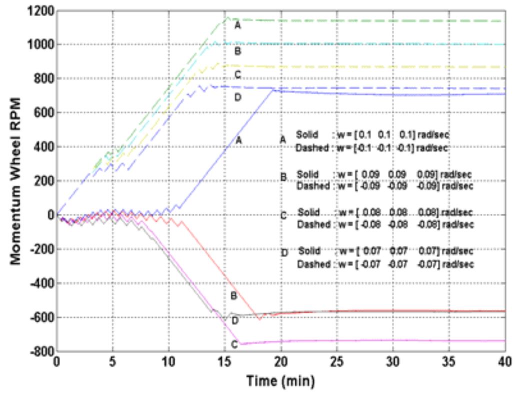
(c) Power Consumption

Figure 3. Angular Rate, Momentum Wheel RPM and Power Consumption Trends According to Control Gain K_W

The momentum wheel detumbling controller performance according to the initial angular rate has been verified using the chosen gain $K_W = 5\times10^{-5}$. In this simulation, the initial angular rate was also varied from ±0.1 rad/s to ±0.07 rad/s for each axis. Figure 4 shows the results of the simulation. As shown in Figure 4(a), all initial angular rates stabilize within 20 minutes. Compared to performance of the B-dot controller using only the magnetic torquers in Figure 2, this result shows a detumbling time reduction of approximately 50 minutes corresponding to half orbit. In Figure 4(b), it can also be seen that the momentum wheel speed is increased to an arbitrary rpm at the last simulated hour.



(a) Angular Rate



(b) Momentum Wheel RPM

Figure 4. Performance of Momentum Wheel Detumbling Controller According to Initial Angular Rate Change

MOMENTUM WHEEL INITIAL START-UP

The satellite attitude becomes unstable if the momentum wheel suddenly speeds up to the nominal rpm from rest. Therefore the momentum wheel initial start-up must be done under stable conditions, and various researches into achieving this goal for small satellites have been done.[5,7-9] The common factor in previously studied wheel initial start-up methods is that it requires the satellite to be spin-stabilized before the start-up of the momentum wheel. However, the previous pitch spin-stabilized initial start-up method cannot be used if the detumbling controller proposed by this paper is implemented. This paper proposes a method for bringing up the momentum wheel speed to nominal rpm while maintaining stability, and compared and verified the performance of the method through simulations.

The previous general wheel start-up method follows the following 4 steps.

Step 1 : Detumbling control using B-dot controller.

Step 2 : Pitch spin-stabilization (Y-Thomson Spin) to an arbitrary angular rate

Step 3 : Momentum wheel speed-up at a constant angular acceleration (open-loop)

Step 4: 3-axes attitude stabilization

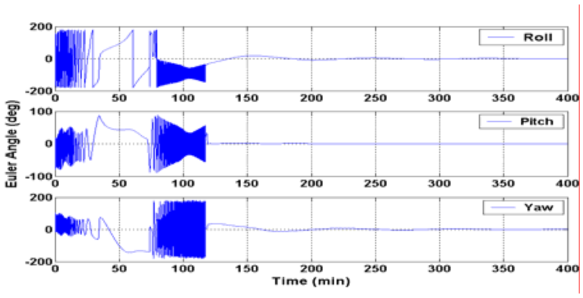
Existing method performance verification simulation scenario is as follows. B-dot controller was used for detumbling control with initial angular rate of 0.1 rad/s and stability condition of less than 0.003 rad/s for each axis. Once the angular rate is stabilized to within the set range, pitch stabilization is carried out. In this step, the magnetic torquer controller as described by Eq. (9) is used for pitch spin stabilization7).

$$M_1 = K_s(\omega_2 - \omega_{2-Target})\text{sgn}(B_3) \quad (9)$$

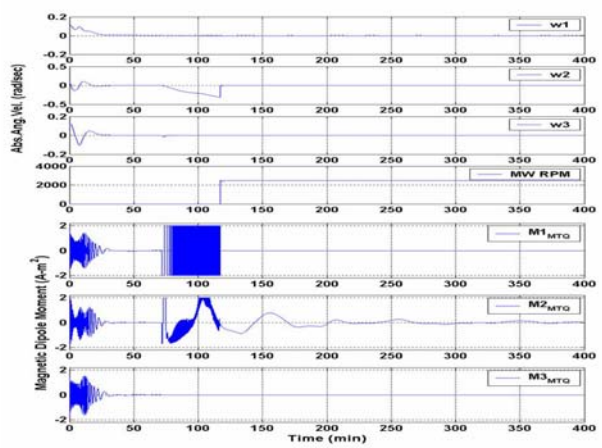
where, K_S is the control gain, and the value used in simulation is $K_s = 3\times10^7$. ω_2 is the pitch angular rate in orbit coordinate reference, and $\omega_{2-Target}$ is the target satellite angular rate. $\omega_{2-Target}$ used in simulation was set to 0.31 rad/s taking into consideration the momentum wheel angular rate of 0.09 Nms at the nominal rpm. In this step, the satellite is spinning at 0.31 rad/s about the pitch axis while the other axes are stabilized to below 0.003 rad/s. Once the satellite is pitch spin-stabilized, the momentum wheel speed is increased at a constant rate of 0.01 Nms in an open-loop fashion. Finally, when the wheel's momentum reaches 0.09Nms at its nominal 2500 rpm, the satellite carries out its 3-axes stabilization process. For 3-axes stabilization, magnetic torquers use a B-dot controller described by Eq. (1), and the momentum wheel uses a PD controller expressed by Eq. (10).[3,6]

$$T_{MW} = -K_p \cdot \theta - K_d \cdot \dot{\theta} \quad (10)$$

where, K_p and K_d is PD controller gain. Values used in the simulation are $K_p = 9.1708\times10^{-4}$ and $K_d = 2.292\times10^{-2}$. θ and $\dot{\theta}$ is pitch axis attitude and its rate of change. Figure 5 shows the results of the process described above. As Figure 5 shows, the satellite angular rate stabilizes to the specified range after about 73 minutes from the start of detumbling control, and then the pitch spin controller is activated. The satellite pitch axis angular rate reaches 0.31 rad/s after about 110 minutes and the wheel momentum is increased at a constant rate of 0.01 Nms in an open-loop fashion. After 112 minutes, nominal wheel speed of 2500 rpm is reached, and the 3-axes stabilization starts. The time it takes to achieve 3-axes stabilization is about 250 minutes.



(a) Attitude



(b) Angular Rate, Wheel RPM and Magnetic Dipole Moment

Figure 5. Conventional Momentum Wheel Start-up Method

A New Method for Wheel Initial Start-up

As mentioned before, if the detumbling controller proposed by this paper is utilized, then the conventional wheel initial start-up method that requires pitch spin stabilization cannot be used. Therefore, this paper proposes a 3-step process for the wheel initial start-up and achieving 3-axes attitude stabilization.

Step 1: Detumbling control using momentum wheel and B-dot controller

Step 2 : Wheel speed-up using momentum dump controller

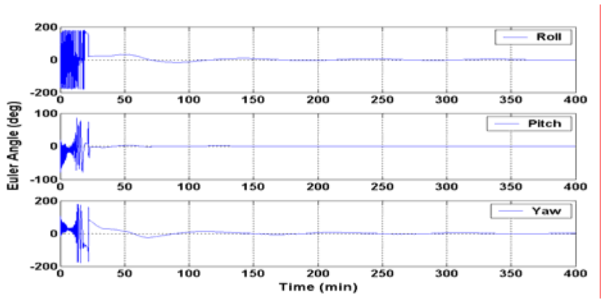
Step 3: 3-axes attitude stabilization

In the performance verification simulations, the same values for the satellite initial angular rate and the angular rate stabilization condition were used. First, detumbling control is done using the proposed momentum wheel detumbling controller as described by Eq. (7) and the B-dot controller. Then, the wheel is brought up to the nominal 2500 rpm using magnetic torquers for momentum dumping as described by Eq. (11).[4]

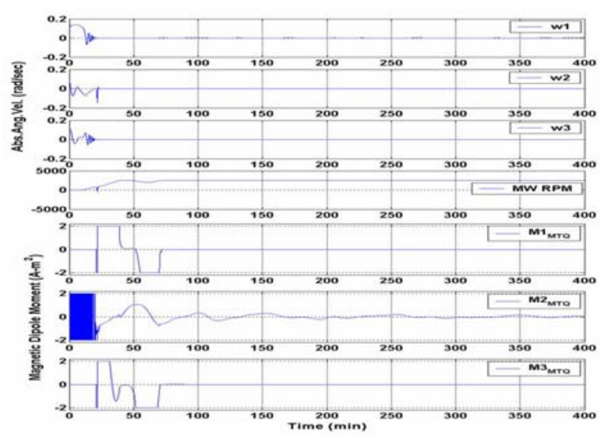
$$M_1 = -K_{WS} \cdot B_3 \cdot (h_W - h_{W-Target})$$
$$M_3 = K_{WS} \cdot B_1 \cdot (h_W - h_{W-Target}) \qquad (11)$$

where, K_{WS} is the control gain and the value used for simulation is $K_{WS} = 3 \times 10^7$. h_W is the angular momentum of the wheel and $h_{W-Target}$ is the control target wheel angular momentum. Magnetic torquer controller of Eq. (11) controls the wheel momentum to $h_{W-Target}$, and according to the specifications of the momentum wheel installed on HAUSAT-2, this value was set to $h_{W-Target} = 0.09\ Nm \cdot s$ in this paper. Lastly, 3-axes attitude stabilization is carried out once the wheel reaches its nominal speed determined by $h_{W-Target}$, where PD controller described by Eq. (10) is utilized.

Figure 6 presents the simulation results of the proposed wheel initial start-up process. As can be seen from Figure 6, the satellite angular rate falls below the specified stability level with the wheel spinning at about 800 rpm approximately 20 minutes after the start of detumbling control. Momentum dumping control starts at this point and the wheel reaches its nominal speed of 2500 rpm after about 78 minutes. 3-axes attitude stabilization starts once the nominal wheel speed is reached, and the total simulated time for overall stabilization is about 150 minutes. As the results show, the total time required for stabilization is shorter compared to conventional methods, and detumbling control, wheel nominal speed achievement, and 3-axes stabilization are all carried out while maintaining stability.



(a) Attitude



(b) Angular Rate, Wheel RPM and Magnetic Dipole Moment

Figure 6. Proposed Momentum Wheel Start-up Method

CONCLUSIONS

Micro/nanosatellite's detumbling control and momentum wheel initial start-up using pitch bias momentum method has been studied. In case of the detumbling control, a significant improvement was shown over the slow response of the conventional B-dot controller that uses magnetic torquers when the momentum wheel detumbling controller proposed in this paper was implemented. Proposed detumbling method was able to control the angular rate within 20 minutes which is a considerable reduction compared to conventional methods. In the case of momentum wheel start-up, the proposed method also provides a suitable wheel initial star-up method, and the performance was compared and verified through simulations. The overall results show faster control time compared to the general methods, and achievement of the nominal wheel speed and 3-axes stabilization while maintaining stability. It was proved that the detumbling controller and wheel initial start-up method proposed in this study can be effectively applied to micro/nanosatellites using pitch bias momentum method.

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