Mass Properties Estimation of a Satellite Simulator Based on the Integration Method

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***Abstract*—A satellite ground simulator is used to verify the performance of newly developed attitude algorithms, sensors and actuators. An air-bearing platform simulator has recently been developed at Korea Aerospace University. It has a table-top configuration capable of floating a 100kg-class platform. The estimation of the moment of inertia and mass unbalance of the platform is necessary prior to test applications. The noise of a low-grade gyro degrades the estimation performance. To reduce the effects of the gyro noise on the estimation, the integration method with averaging is applied and verified in a computer simulation to adapt the recursive least square method. With a single large 3-dimensional maneuver performed using control moment gyros (CMGs), the inertia and mass-unbalance are identified theoretically within an acceptable accuracy even in the event of CMG singularity.**

***Index Terms*—estimation, mass properties, satellite simulator, air-bearing, gyroscopes, control moment gyros**

I. INTRODUCTION

New satellite algorithms, actuators and sensors must be tested on the ground prior to launch. A ground simulator is a test platform that is used to evaluate the performance of satellite hardware equipment and software algorithms [1,2]. It is equipped with actuators and sensors that need to be tested. Mass properties, such as inertia and mass distribution, are configured to scale in a fashion similar to the target satellite. Like the satellite, the simulator parameters are identified first. Among the parameters to be identified are the moment of inertia (MOI) and mass unbalance. Although the simulator is manufactured and assembled precisely following the design, the MOI and mass distribution might not match the design values. Thus, they should be adjusted and tuned if necessary. Before test applications, the simulator parameters are identified.

The methods employed to identify a simulator's mass properties are very similar to those for a satellite, except for the existence of air-bearing support forces (torques) and the mass center deviation from the air-bearing center. Identification algorithms are mostly based on the modelling of dynamic equations and attitude data such as gyro and reference sensor data. Low-grade gyros, however, suffer from noise that hinders precise estimation. Using filers can reduce the noise effects, but this incurs costs in terms of extra data processing [3~5].

In this paper, we use the integration method to reduce the gyro noise effects [6~8]. The convectional integration method is adjusted slightly by adding an averaging technique for the application of low-cost noisy gyros. The estimation algorithm is developed for a satellite with control moment gyros, where the singularity problem occurs frequently [9]. The performance of the algorithm should thus first be verified theoretically by applying it to the simulator model with CMGs prior to the hardware application.

II. SIMULATOR CONFIGURATION

An air-bearing test platform has recently been designed at Korea Aerospace University as a satellite simulator. It is depicted in Fig.1.

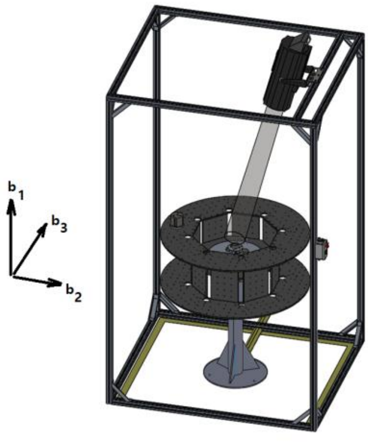

Figure 1. Simulator on an air-bearing platform

The simulator has a table-top configuration capable of floating a 100kg-class platform, the scale model for a mid-class satellite. It is maneuvered via four single-gimbal CMGs installed in a pyramid configuration, as shown in Fig.2.

Manuscript received July 23, 2018; revised March 1, 2019.

doi: 10.18178/ijmerr.8.3.418-423

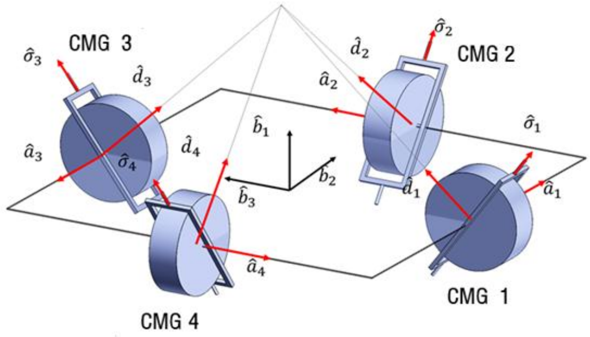

Figure 2. Control moment gyros in a pyramid configuration

Attitude is measured using reference sensors – a sun-sensor and an accelerometer – which simulate the sun vector and earth vector, respectively. The angular velocity is measured via the gyros. All sensors and actuators are not space-flight grade. Rather, they are intended for ground vehicles and are accordingly lower grade. Because the accuracy of parameter estimation depends heavily on the sensor grade, some degradation on the estimation performance shall be tolerated but minimized via the proper algorithms.

III. Dynamic Simulator Equation

A satellite equipped with four single-gimbal CMGs, as depicted in Fig. 2, is governed by the following equations.

$$\begin{aligned} \dot{q} &= \frac{1}{2}E(q)\omega \\ I\dot{\omega} + \omega^{\times} I\omega + \omega^{\times} h &= u_C + c_1^{\times} mrg \\ D\dot{\sigma} &= -u_C \end{aligned} \tag{1}$$

where q is the attitude quaternion, ω the satellite angular velocity, u_C the control torque produced by steering the CMG gimbals as $\sigma = [\sigma_1 \quad \sigma_2 \quad \sigma_3 \quad \sigma_4]$, c_1 the roll component of the direction cosine matrix $C = [c_1 \quad c_2 \quad c_3]$ of the platform with respect to the inertial frame, mrg the mass unbalance due to the center of mass of the platform apart from the center of air-bearing and h the CMG cluster momentum. The output torque matrix D is composed of output torque vectors d_i's as $D = [d_1 \quad d_2 \quad d_3 \quad d_4]$. The satellite is maneuvered via the output torque generated by steering the gimbal angle rotation σ. The required torque is calculated according to the proper feedback control law. If unbalance exists, it induces secular external torque on the platform. In this case, the feedback control law would be applied to reject the disturbance. In this study, we use the PID-type attitude stabilizing control law as

$$u = \omega^{\times} h - K_d\omega + 2K_p E^T(q)q_T + K_I \int E^T(q)\omega\, dt \tag{2}$$

where q_T is the target attitude quaternion. The gains K_i are designed in accordance with the settling time.

IV. Parameter Estimation

The parameters to be identified in the simulator are the MOI I and the mass unbalance mr where r is the position vector of the platform mass center of the total mass m from the center of the air-bearing platform. The parameter vector x to be identified is then defined as $x = [I_1 \quad I_2 \quad I_3 \quad I_{12} \quad I_{13} \quad I_{23} \quad mr_1 \quad mr_2 \quad mr_3]^T$. The dynamic equation in (1) can then be rewritten as a regression equation at time t_i, as

$$\Omega(t_i)x = y(t_i) \tag{3}$$

where $y(t_i) \triangleq -\omega^{\times} h + u$ and the regression matrix $\Omega(t_i)$ are a function of the angular velocity of the platform and the first column of the direction cosine matrix C as $\Omega(t_i) \triangleq [\Omega_1 \quad \Omega_2 \quad \Omega_3]$ where

$$\Omega_1 \triangleq \begin{bmatrix} \dot{\omega}_1 & -\omega_2\omega_3 & \omega_2\omega_3 \\ \omega_1\omega_3 & \dot{\omega}_2 & -\omega_1\omega_3 \\ -\omega_1\omega_2 & \omega_1\omega_2 & \dot{\omega}_3 \end{bmatrix}$$

$$\Omega_2 \triangleq \begin{bmatrix} \dot{\omega}_2 - \omega_1\omega_3 & \dot{\omega}_3 + \omega_1\omega_2 & -\omega_3^2 + \omega_2^2 \\ \dot{\omega}_1 + \omega_2\omega_3 & \omega_3^2 - \omega_1^2 & \dot{\omega}_3 - \omega_1\omega_2 \\ -\omega_2^2 + \omega_1^2 & \dot{\omega}_1 - \omega_2\omega_3 & \dot{\omega}_2 + \omega_1\omega_3 \end{bmatrix}$$

$$\Omega_3 \triangleq \begin{bmatrix} 0 & c_{31} & -c_{21} \\ -c_{31} & 0 & c_{11} \\ c_{21} & -c_{11} & 0 \end{bmatrix}$$

The observation equation is then obtained as

$$H_k x = y_k \tag{4}$$

where H_k and y_k are derived by accumulating at least more than three sequential $\Omega(t_i)$'s and $y(t_i)$'s as $H_k^T \triangleq [\Omega(t_i)^T \Omega(t_{i+1})^T \Omega(t_{i+2})^T]$ and $y_k^T \triangleq [y(t_i)^T \; y(t_{i+1})^T \; y(t_{i+2})^T]$.

The value of parameter x can be then estimated by the least square algorithm. The gyro noise degrades the performance and may lead to incorrect results. The acceleration terms in the Ω matrix are most affected. Trying filters or a reformed regressor matrix results in improved performance [4~8]. In this paper, we attempt to use the integration equation shown in Eq. (2) as a reformed regressor matrix, as follows.

$$\int \Omega\, dt\, x = \int y\, dt \tag{5}$$

The acceleration term $\dot{\omega}$ is then substituted as

$$\int \dot{\omega}\, dt = \omega(t) - \omega(0) \tag{6}$$

Because the gyro data includes the noises, here, the average value for ω at time t is used instead of the noisy instantaneous value.

$$\omega(t_k) = \frac{1}{n}\sum_{i=1,n} \omega(t_{k-i}) \tag{7}$$

In an assumption of no knowledge regarding the reliability data of the gyro, a batch estimation process is performed at the beginning of the estimation. The estimation is started from a nonzero angular velocity to avoid the ill-condition of the H matrix. This is subsequently followed by the usual recursive least square process, as follows.

$$\begin{aligned}\hat{x}_{k+1} &= \hat{x}_k + K_{k+1}(y_{k+1} - H_{k+1}\hat{x}_k)\\ K_{k+1} &= P_{k+1}H_{k+1}^T W_{k+1}\\ P_{k+1}^{-1} &= P_k^{-1} + H_{k+1}^T W_{k+1} H_{k+1}\end{aligned} \tag{8}$$

The goodness of the least-squares estimate can be evaluated by the error index defined in (9), which is the ratio between the residual error, that is, the total squared error, and the zero estimate [10].

$$EI \triangleq \sqrt{\frac{E^2(x^*)}{E^2(0)}} = \sqrt{\frac{y^T y - y^T H(H^T H)^{-1} H^T y}{y^T y}} \tag{9}$$

The parameter error index associated with the i-th parameter $\hat{x}_i$ is also used due to its sensitivity to the total error index in Eq. (9).

$$PEI(i) \triangleq \sqrt{E^2(x^*)(H^T H)^{-1}(i)} \tag{10}$$

A small error index indicates that the estimated value may be considered more accurate.

V. Simulations

The algorithm is applied to a simulator model, as shown in Fig. 1, which is being manufactured at KAU. The nominal parameters of the simulator are given in Table 1.

TABLE I. Model Simulation Parameteres

Items	Value
MOI I ($kg \cdot m^2$)	$diag[20 \quad 16 \quad 14]$
Unbalance mr ($kg \cdot cm$)	$[-0.1 \quad 0.1 \quad 0.05]$
Wheel momentum h_w (Nms)	$2/3$
Gyro noise σ^2	$1e^{-7}$

The platform starts a maneuver from rest as $\omega(0) = [0 \quad 0 \quad 0]$. To excite all of the axes, the initial attitude starts from the point $[\phi \quad \theta \quad \psi] = [70^\circ \quad 30^\circ \quad -30^\circ]$, which is far from the target attitude $[0^\circ \quad 0^\circ \quad 0^\circ]$. The attitude maneuver is performed in a slow mode to allow sufficient time for the estimation algorithm to converge to the real parameter values. To see the effects of the singularity in estimation, the gains are intentionally chosen to induce that singularity.

The attitude is stabilized to the origin, and as expected, the singularity is met at about 10~15 sec, as shown Figs. 3~6.

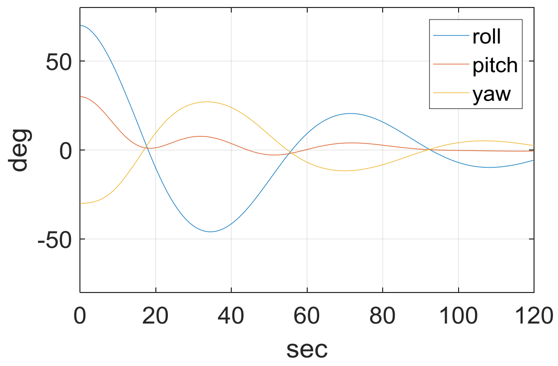

Figure 3. Attitude angles

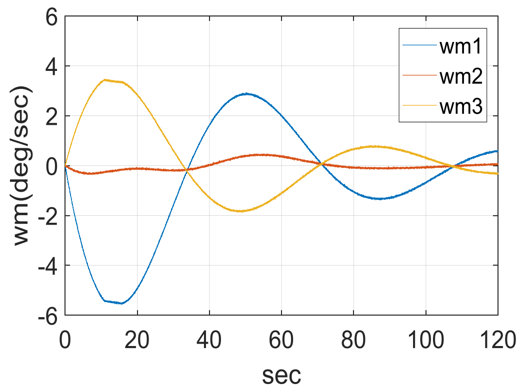

Figure 4. Angular velocity (Gyro)

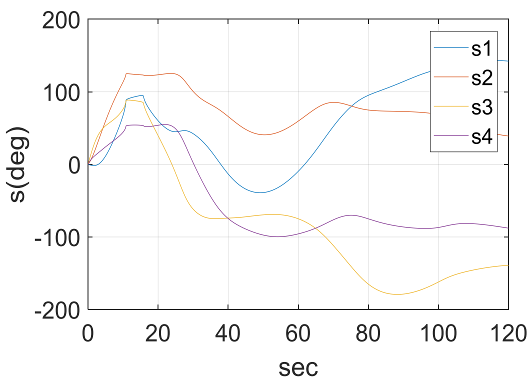

Figure 5. Gimbal angles

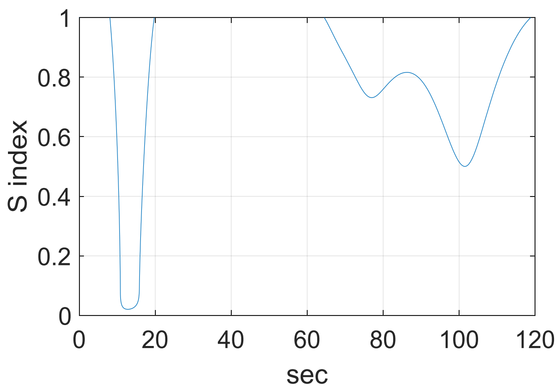

Figure 6. Singularity index

Near the singularity, the gimbal rate command is adjusted via the singular robust steering law [9], but the rate is still high, as shown Fig. 7. The generated torque subsequently differs from the required torque, as demonstrated in Figs. 8 and 9.

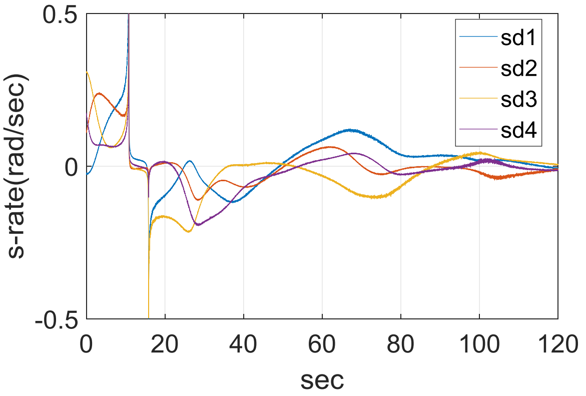

Figure 7. Gimbal rates

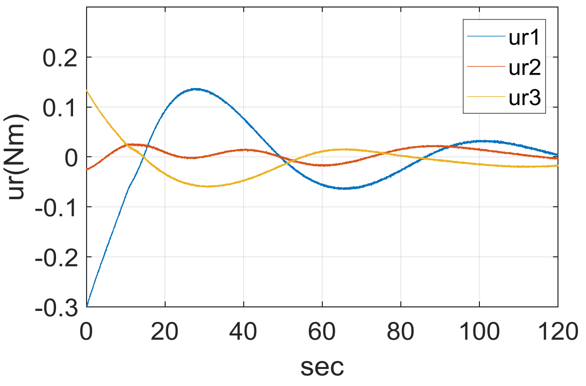

Figure 8. Required torque

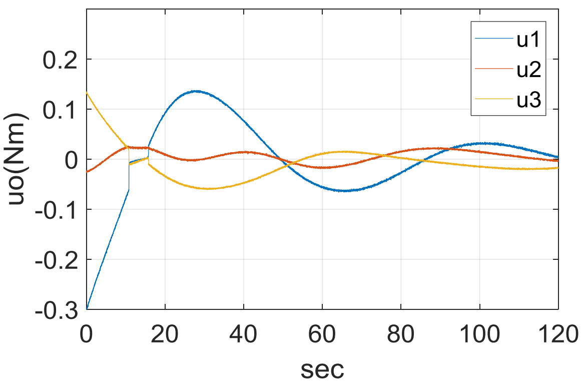

Figure 9. Output torque

Despite the singularity phenomenon, the estimation algorithms work moderately well, as shown in Figs. 10~12. By choosing the large angle maneuver with the longer settling time, the satellite angular velocity is sufficiently sustained to reduce the gyro noise influence, as shown in Fig. 4.

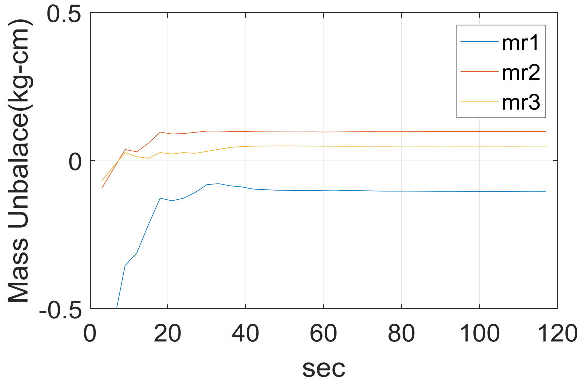

Figure 10. Estimation results of mass unbalance

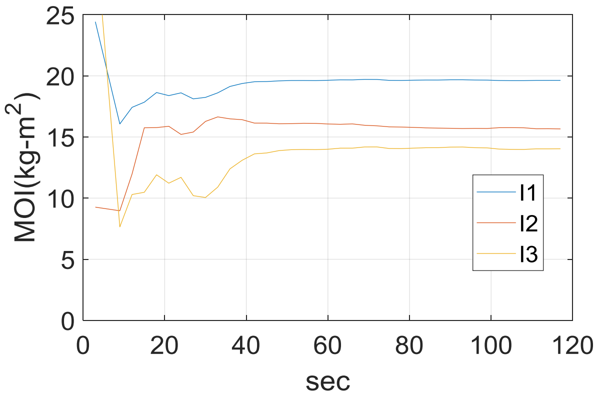

Figure 11. Estimation results of moment of inertia

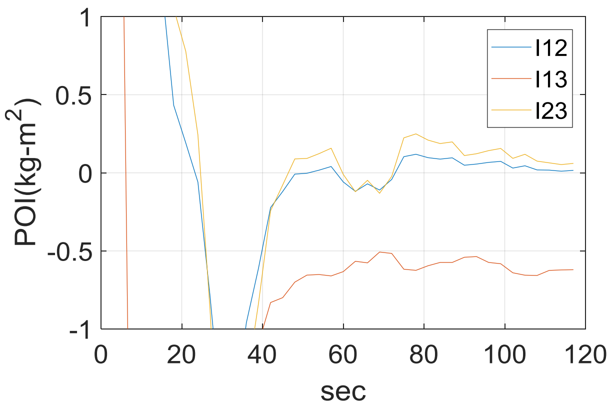

Figure 12. Estimation results of product of inertia

The goodness of the estimates are evaluated based on (9) and (10) from the simulation data, as shown in Figs. 13~16. The total error index in Fig. 13 shows a much lower value than one, indicating that the estimate is reliable. Each parameter error index defined as (10) also shows tolerable accuracy, i.e. much lower than one, at the end of the maneuver. The mass unbalance is demonstrated in Fig. 16, which reveals much higher reliability in accuracy than the MOI.

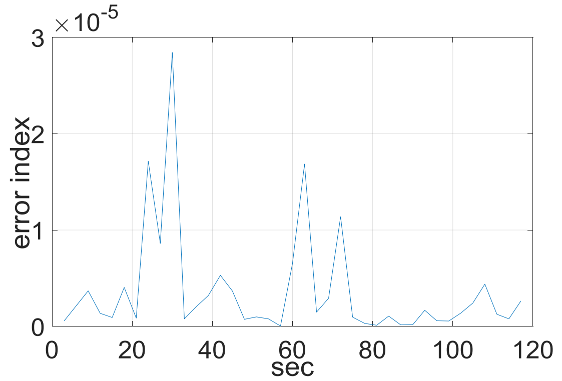

Figure 13 Total error index

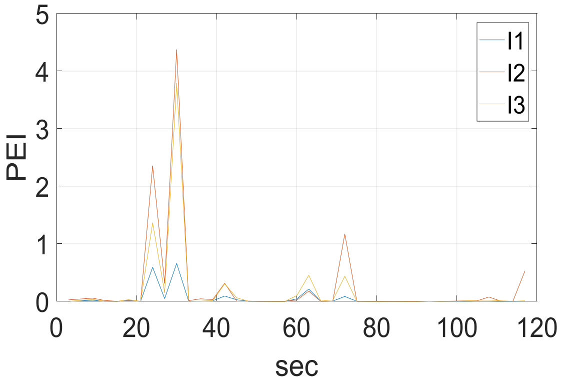

Figure 14 MOI parameter error index

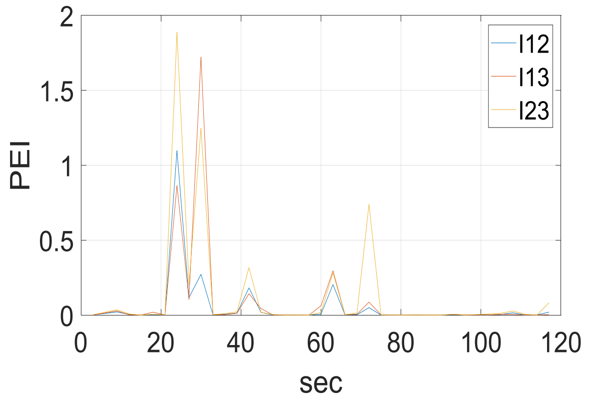

Figure 15 POI parameter error index

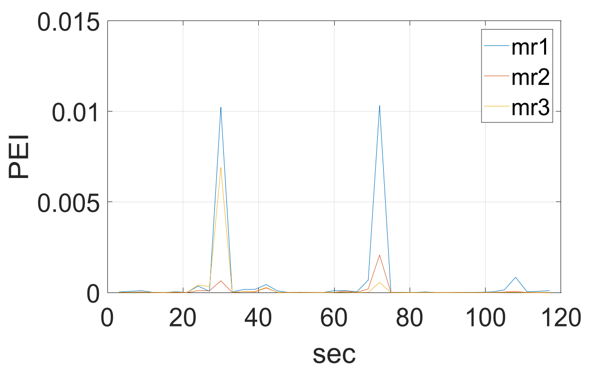

Figure 16 Mass unbalance parameter error index

If the maneuver starts from a smaller initial angle, then the effects of the gyro noise overwhelm the algorithm, and the estimation will not converge to the real values. Figs. 17 and 18 show the results when the maneuver commences from smaller angles as $\begin{bmatrix}\phi & \theta & \psi\end{bmatrix} = \begin{bmatrix}30^\circ & 10^\circ & -10^\circ\end{bmatrix}$ with the same gain conditions. The noise effects are clearly shown in Fig. 17, and the MOI estimate deviates from the real value. The importance of choosing the initial attitude condition is obviously shown for the convergence of the estimate.

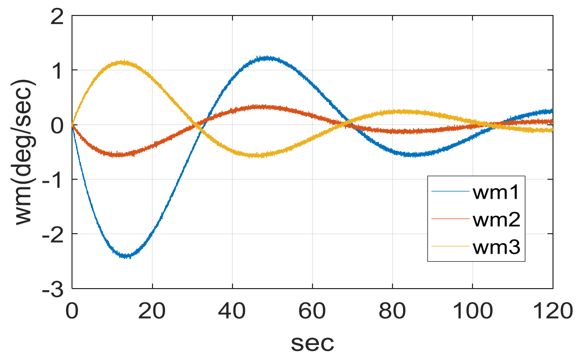

Figure 17 Angular velocity in small initial angles

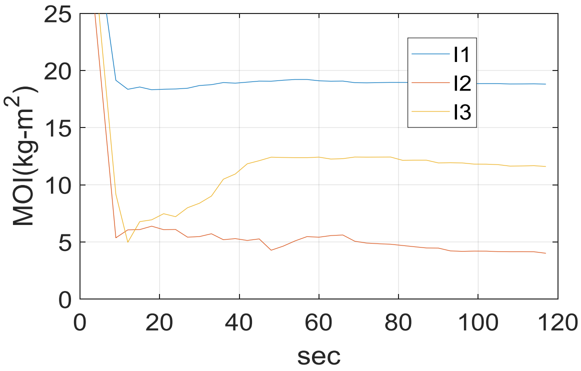

Figure 18 Moment of inertia in small initial angles

VI. Conclusions

The estimation algorithm using the suggested integration method combined with averaging diminishes the effects of gyro noise, and it facilitates the convergence to real values with acceptable accuracy. A large angle maneuver with a long settling time improves the estimation performance by exciting all three axes. Singularity does not hinder estimation performance even though the output torque generated by the robust steering law of the CMG gimbals deviates from the required torque in the singularity. The suggested algorithm is expected to work well in a real hardware simulator test in the near future.

Acknowledgment

This study was supported by a research project entitled Analysis of Control Moment Gyro Development for LEO High Agility Satellite (2017-15-009) funded by LIG Nex1 in Korea.

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