Torque and Force Measurement of a Prototype HAU Reaction Wheel and the Effect of Disturbance on the Attitude Stability of Spacecraft

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A Prototype reaction wheel, named the Hankuk Aviation University (HAU) reaction wheel, has been developed for KAISTSAT satellite series. Torque and force disturbances are inherent in reaction wheels, and thus the force and torque characteristics should be examined for every newly developed reaction wheel. The torque and force disturbance noises in the prototype HAU reaction wheel are measured with a torque-measuring table developed for the present study. A new measuring procedure based on a simple principle is applied for the measurements. The frequency characteristics of the torque and force noises are analyzed by examining the power spectral density. The effect of the torque noise on the attitude stability is also examined through numerical simulations with a single-axis attitude model. The noise-induced attitude error and jitter are found to be well below the specified error limits for the KAISTSAT satellite series.

Key Words : Spacecraft Attitude Stability, Reaction Wheel, Torque Disturbance, Torque Measurement, Attitude Error

1. Introduction

Reaction wheels have been used as primary attitude control actuators for a wide variety of spacecrafts. A slew or attitude reorientation maneuver can be executed by employing a set of reaction wheels. They absorb cyclic torques and temporarily store momentum from the body during maneuvers. Reaction wheels are well suited because they allow continuous and smooth control with comparatively low disturbing torques. However, disturbances arising in the reaction wheels can have strong influence on the quality of the attitude control. So efforts must be made to minimize their influence.

Disturbance noise is inherent in reaction wheels. Torque and force disturbance noises can originate from the wheel mass imbalance, bearing and retainer vibration, damper rocking, and motor torque ripple, etc. (Sidi, 1997; Wertz, 1978). A DC motor produces harmonic disturbances that are functions of the rotor's angular velocity. The disturbances due to both the static and dynamic imbalances are mainly produced by non-uniform mass distribution within the flywheel, and can be the most significant source of the disturbance from a reaction wheel that affects the spacecraft. The reaction wheel shows resonant behavior at certain frequencies. The resonant frequencies are determined by the interaction of the wheel harmonics with wheel flexibility. In ball bearing wheels, another important noise source is the relative motion between the bearing and retainer.

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Although the reaction torque disturbance level is generally as low as a few milli-Newton-meter, its effect on the attitude stability can be significant. The disturbances are often amplified by the control system and may result in unacceptable attitude error and jitter. Therefore, it is necessary to investigate the characteristics of the torque and force disturbances of a reaction wheel that has been newly developed. A prototype reaction wheel, named the HAU reaction wheel, has been recently developed for KAISTSAT satellite series (Kwon, et al, 2000). We needed to measure the torque and force disturbances of the wheel prior to finalizing the design of the newly developed reaction wheel.

Although the reaction wheel is primarily designed to produce a clean axial torque in response to a command, the transverse torque and various disturbance forces usually accompany the axial torque as by-products. Since they all influence the attitude stability of the spacecraft, we need to measure them before the stability analysis. Measurement of the three dimensional torque and force vectors usually entails very expensive devices (Oliver, 1998; Doeblin, 1990; Bosgra and Prins, 1980). One example is the six-axis Kistler force/torque measurement table, in which the force and torque generated by the reaction wheel are measured by several load cells. Very expensive three-dimensional load cells are installed to measure the three-dimensional torques and forces simultaneously.

In this study, the torque and force disturbances of the prototype HAU reaction wheel are measured and the effect of the torque disturbances on the attitude stability is examined with numerical simulations. At first, the performances of the prototype HAU reaction wheel including the test results are presented in Sec. 2. The torque and force disturbances are measured with a torque-measuring table that has been developed by our laboratory (Oh and Kwon, 2000; Oh, 1999). The principle of disturbance noise measurement is introduced in Sec. 3. The frequency characteristics of the torque and force disturbances are analyzed from the power spectral density. In the following section, the effect of the torque disturbances on the attitude stability is examined with numerical simulations using the single-axis attitude model. The disturbances-induced attitude error and jitter are compared with the error requirements for the KAISTSAT satellite series (Kim, et al, 1999).

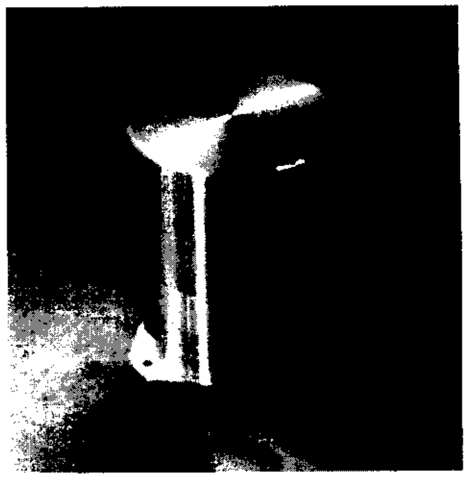


Fig. 1 Prototype HAU reaction wheel

2. Prototype HAU Reaction Wheel Design

The prototype HAU reaction wheel set is composed of a wheel and driving motor, a servo driver, a speed detector, and the communication interface, etc. Figure 1 shows the outer view of the reaction wheel. Although the current prototype has been developed for the KAISTSAT-4, the performance requirements were established based on KAISTSAT-3 satellite mission analysis. Design, manufacturing, and test were performed at the Spacecraft Dynamics and Control Laboratory in HAU. Table 1 summarizes the design specifications of the prototype reaction wheel.

The most important performance characteristic of the reaction wheel is the response to a speed or torque command. In speed control mode, the response time-constant and speed maintainability are important. The approximate time constant of the HAU reaction wheel is found to be approximately 0.5 sec. Fast response to the sinusoidal input command is necessary and the reaction wheel shows good response to a sine-wave speed command input, as shown in Fig. 2.

Table 1 Reaction wheel performance specifications

Performances	-Brushless DC Motor and Driver -Rated Speed: 3000 rpm -Nominal Angular Momentum: 0.1 N-m-sec -Rated Torque: 30mN-m -Rated Power Consumption 10 W -Power Voltage: 24 V -4 Quadrant Speed or Torque Control Mode
Operating Environments	--10~60℃
Speed Detector	-Resolution: ±1.46 rpm
Outer Configuration	-Air-tighted Vacuum Sealing -Diameter: 80mm -Height: 102 mm -Weight<1.3 kg
Communication Interface	-Digital RS 422/242

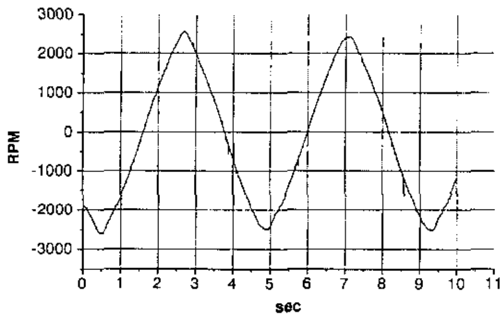


Fig. 2 Response to a sine-wave speed command input

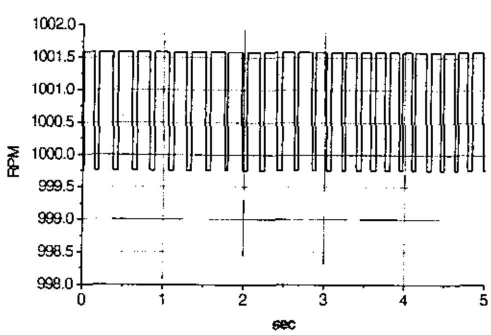


Fig. 3 Response to 1000 rpm speed command input

Maintaining a constant speed is one of the most

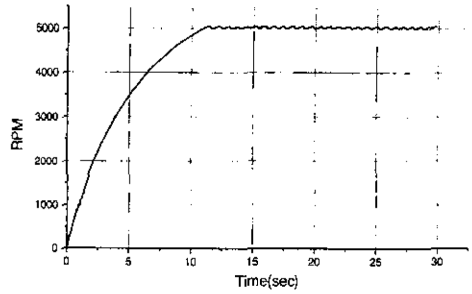


Fig. 4 Response to a constant torque command input

important characteristics of the reaction wheel. Figure 3 shows the response to 1000 rpm speed command. The response seems oscillatory, but this behavior is due to the speed detector's resolution limit. The peak-to-peak magnitude of the fluctuation in the response is only slightly larger than the resolution of the wheel speed detector.

In the torque control mode, fast response to a torque command is required. Figure 4 shows the response to a constant torque command. The response is linear at low operating speeds. Increasing nonlinear behavior of the speed response at higher rpm is due to the torque saturation of the driving motor and the friction in the rotating wheel.

3. Torque and Force Disturbance Measurement

The primary function of the reaction wheel is to produce a clean axial torque in response to a command. But the transverse torque and various disturbance forces usually accompany the axial torque as by-products. Such disturbances in torque and force originate from the wheel mass imbalance, bearing and retainer vibration, damper rocking, and motor torque ripple, etc. The force and torque disturbances have three-dimensional components. The transverse torque as well as the axial torque disturbance is the most crucial to attitude stability of the spacecraft since they act as perturbing sources to attitude control problem. The force disturbance itself is not a torque, but it nonetheless affects the attitude stability indirectly by applying a moment about the

Fig. 5 Torque and force measurement test view

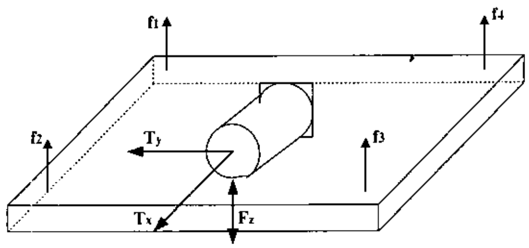


Fig. 6 HAU reaction wheel coordinates definition

center of mass of the spacecraft. The torque and force disturbances are thus undesirable as they can affect the spacecraft pointing jitter. Efforts have been undertaken to minimize them, but they cannot be completely removed. Therefore, the measurements of torque and force are necessary prior to the stability analysis of the spacecraft.

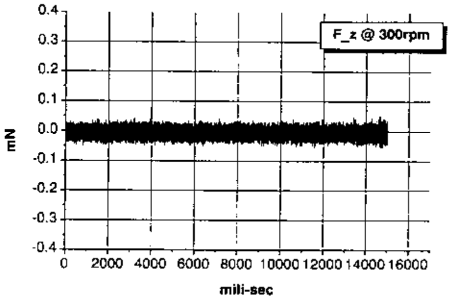
The torque can be measured either indirectly by monitoring speed fluctuation of the wheel (Bosgra and Prins, 1982) or directly by measuring torque using a torque-measuring device (Oliver, 1998; Doeblin, 1990; Bosgra and Prins, 1982). The accuracy of the speed fluctuation monitoring method, however, is limited by the resolution of the speed detector. The speed detector installed on the HAU reaction wheel has a resolution of 1.46 rpm. The resolution is good enough for the control purpose, but is not good enough for measuring high frequency torque disturbance. Therefore, the indirect measuring method is abandoned for the torque measurement. Instead, the direct torque and force measuring method is adopted in this study. In this section, a procedure for measuring the torque and force disturbances in the HAU reaction wheel is described.

Measurement of the three dimensional torque and force vectors usually entails very expensive devices (Oliver, 1998; Doeblin, 1990; Bosgra and Prins, 1982). However, the torque and force disturbances in the HAU reaction wheel are measured through a relatively simple and inexpensive device, which was manufactured in our laboratory at HAU (Oh and Kwon, 2000). The torque-measuring device is composed of three functional modules, i.e., the torque-measuring table module, signal processing module, and data acquisition module.

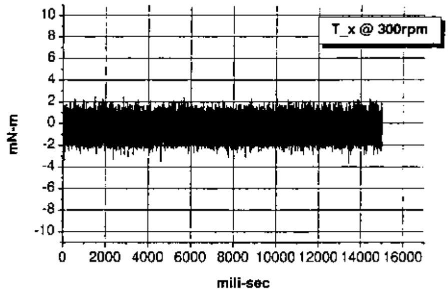
When the reaction wheel runs on the table, it applies forces and torques on the top of the table. If the wheel is an ideal device and there is no gravity, then it will produce the axial torque only. In this case, when the wheel is running at the constant speed, it shall produce no torque at all. But in the real world, there exist many torque and force disturbance sources, and the wheel produces disturbances even at a constant wheel speed.

The torque and force disturbance each has three components along three orthogonal axes, respectively. Kistler type measuring table can measure all six disturbances simultaneously using four multi-axis measuring load-cells (Oliver, 1998). Ibid type table uses six bi-directional load-cells to measure the forces and torques (Doeblin, 1990). However, for the HAU reaction wheel, we devised a torque and force measuring table that can measure two-axis torque and one-axis force simultaneously. Since the table uses only four uni-directional load-calls, the manufacturing cost is relatively low. Figure 5 depicts the overview of the torque-measuring test. Figure 6 shows the coordinate definition of the torque table and the wheel.

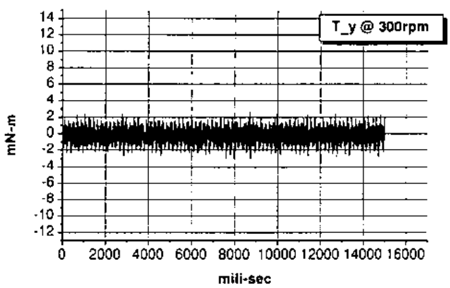
The torque and force disturbances of the reaction wheel each have three-dimensional components. But two force-components F_y and F_x, apply to the transverse direction of each load-cell and they cannot be measured with this table. Torque T_z cannot be measured for similar reason. When torques and force are applied simultaneously on the top of the table, they exert forces on the table suspensions. Then, by measuring four



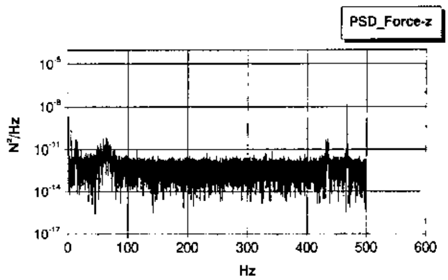
(a) Transverse force F_z



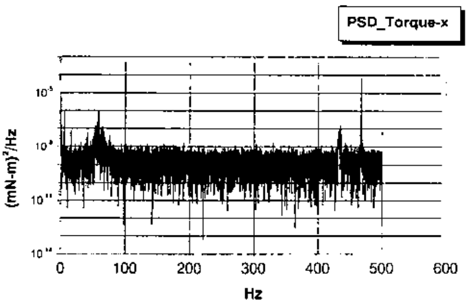
(b) Axial torque T_x



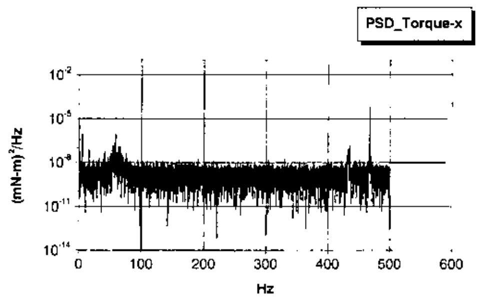
(c) Transverse torque T_y



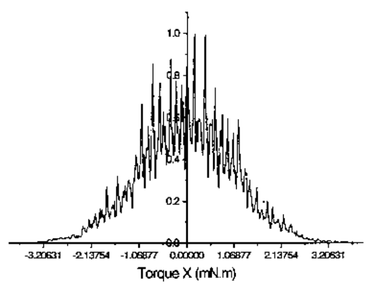
(d) Power spectrum density of transverse force F_z



(e) Power spectrum density of axial torque T_x



(f) Power spectrum density of transverse torque T_y



(g) Probability density function of torque T_x

Fig. 7 Force and torque noise of HAU reaction wheel on 300 rpm

load-cell forces exerted on the table suspensions, the resultant torques and forces can be obtained by suitable data processing. Finally, two axis torques and one axis force can be obtained, i.e., the axial torque T_x, the transverse torque T_y, and the transverse force F_z. The force actuating point can also be determined, and then the information can be used for the analysis of the effect of the force-actuating point on the spacecraft stability.

Figure 7 shows the measurement results. While

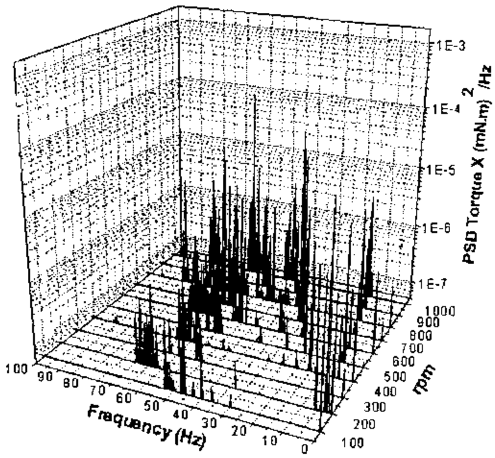


Fig. 8 Waterfall plot of PSD of torque T_x

the reaction wheel was running at the operating speed of 300 rpm, the force and torque were measured as shown in Figs. 7(a), (b), and (c). Since another transverse torque T_z has the same characteristics as T_y due to the symmetric configuration of the wheel, measurement of T_z was omitted.

Figures 7(d), (e), and (f) show the Power Spectrum Density (PSD) functions of F_z, T_x, and T_y, respectively. We can see that the most dominant spectrum is located at the operating speed and its harmonic multiples, as expected. The observed peak near 60 Hz in the spectrum is due to the resonance of the torque measuring table, and is similar to the phenomenon shown in other torque measuring devices (Oliver, 1998). By raising the resonance frequency of the table to fall outside of the operating bandwidth, the peak can be removed from the PSD diagram. Figure 7(g) shows the probability density graph of T_x. The standard deviation σ is 1.069 mNm. Figure 8 shows a waterfall plot of the power spectrum density functions corresponding to other wheel speeds. We can see that the peak spectrum streams are located at each rotation speed.

4. Attitude Error and Stability Analyses

The wheel torque irregularities significantly affect the spacecraft stability. For the purpose of studying the effect of torque disturbance on the spacecraft attitude error and jitter, a simple pitch angle model of small satellite equipped with a reaction wheel is first considered as follows(Sidi, 1997).

Table 2 Model spacecraft data

	Initial Condition
Moments of Inertia	diag (7.1, 5.84, 8.16)kg·m^2
Angular Rate	$[0\ -0.0010399\ 0]^T$ deg/sec
Control Gains	$K_D=1.472$, $K_P=0.115$

$$I_2\ddot{\theta}+3n^2(I_3-I_1)\sin\theta\cos\theta=u+T_x, \quad (1)$$

Here, u denotes the reaction wheel control torque and T_x the axial wheel torque noise.

When the initial roll and yaw attitude angle and the angular rate are zero, then the roll and yaw equations are completely decoupled from the pitch equation. Thus, we can use a simple equation such as Eq. (1) for the analysis of pitch motion. Moreover, since the gravity gradient torque is negligibly small in small-sized satellites, the plant dynamics can be further simplified and the control system can be depicted as shown in Fig. 9. Here, the spacecraft state observation and estimation process are ignored, and a simple Proportional-Derivative control law is used for control u. The model spacecraft parameters are described in Table 2. The controller gains are selected so that the critical damping response is obtained within the torque capacity of the reaction wheel. The transfer function between the torque disturbance input and the attitude output is then written as

$$\frac{\theta(s)}{T_x(s)}=\frac{1/I_2}{s^2+(K_D/I_2)s+(K_P/I_2)}\left(\frac{\omega_c}{s+\omega_c}\right) \quad (2)$$

We assume here that the torque disturbance is band-limited by frequency ω_c. To determine the effect of torque disturbance on the spacecraft attitude, the torque disturbance measured with the torque-measuring table as shown in Fig. 7(b) is applied to the above spacecraft model and simulated. The torque disturbance data of the wheel running at the speed of 300 rpm is chosen as input because the data were not affected by the

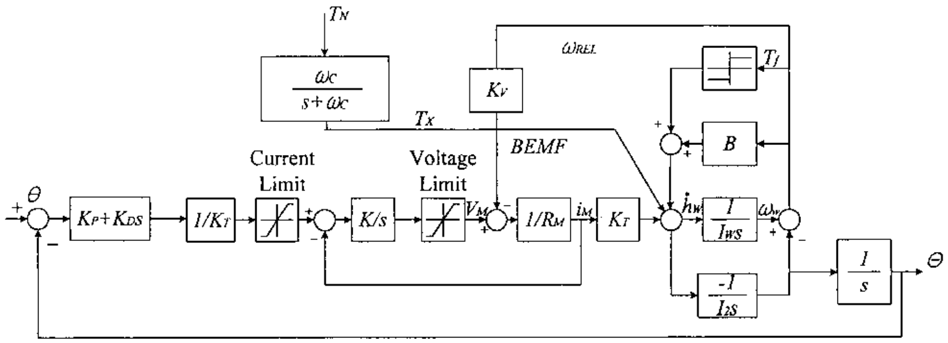
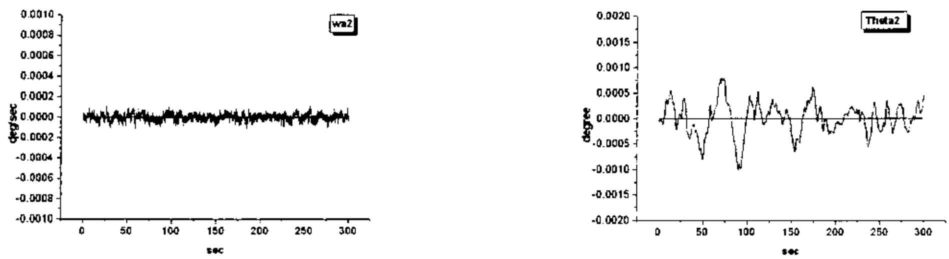


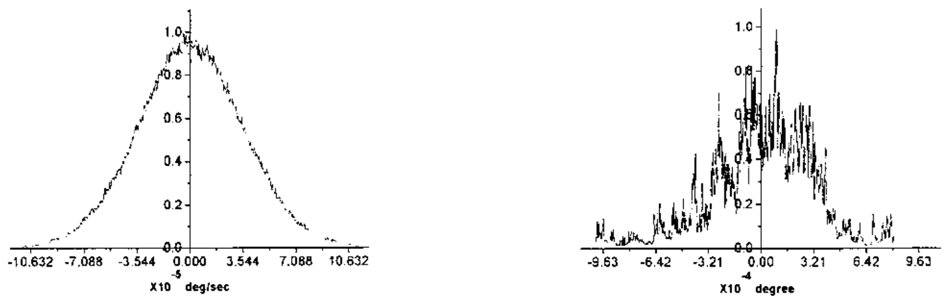
Fig. 9 Attitude control systems with reaction wheel in torque control mode



(a) Attitude rate response

(b) Attitude angle error response

Fig. 10 Attitude responses to torque disturbance



(a) Pitch rate

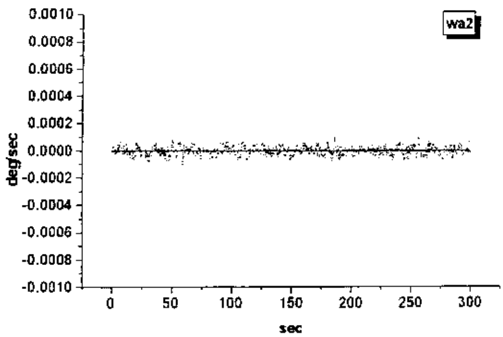
(b) Pitch angle

Fig. 11 Probability distribution curves

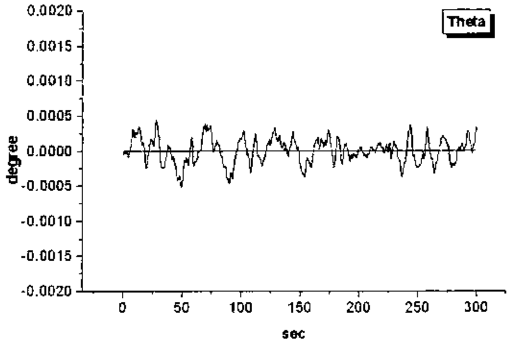
table resonance (Oliver, 1998; Oh and Kwon, 2000).

The output attitude responses are plotted in Fig. 10. Figures 10(a) and (b) show the responses of the pitch angular rate and the pitch angle, respectively. The maximum attitude angle deviation is less than 0. 001 degree, which is well below the specified attitude error limit 0.04 degree of KAISTSAT-4 (Kim, et al, 1999). The angular velocity is also well below the requirements of the satellite. Probability distribution function curves of the pitch angular rate and the pitch angle responses are shown in Fig. 11.

Although we have considered only the response of the spacecraft to the disturbances of the wheel at 300 rpm, we can get the similar conclusions for the other wheel speeds. The spectral density function at the maximum disturbance wheel speed of 4000 rpm was similar to the one at 300rpm. The peak disturbance value at 4000 rpm was almost



(a) Pitch rate



(b) Pitch angle

Fig. 12 Attitude responses to torque disturbance with $K_D=1.472$, $K_P=0.23$

twice as large as that of 300 rpm. Therefore, we can expect that the attitude error at the maximum wheel speed to be within the specified attitude error limit. However, in order to determine whether a given reaction wheel set satisfies the attitude requirements of the target satellite, much more detailed three-dimensional error analyses are needed including in-depth statistical analysis. That is out of scope of the present study, and remains as a future research topic.

When the torque disturbance noise is assumed to be a white noise with amplitude W, then the variance of the pitch attitude angle can be obtained as (Sidi, 1997)

$$\sigma^2=\frac{W}{4I_2^2\zeta\omega_n^3} \tag{3}$$

We can see that the variance is inversely proportional to $\zeta\omega_n^3$. In order to determine the effect of the system gain selection, we tried another control gains of $K_D=1.4795$ and $K_P=0.23$ to increase the system bandwidth ω_B to be approximately 0.2184. The simulation results are shown in Fig. 12, where we can observe the reduced attitude error due to increased bandwidth. Thus, it can be assured that the effect of the wheel torque irregularities on the spacecraft stability can be reduced by properly selecting the attitude control gains.

5. Conclusions

Torque and force disturbances in the prototype HAU reaction wheel were measured with a torque-measuring table. Simple but efficient measuring principle was devised. The power spectral density graphs of the torque disturbances showed a typical characteristic of the reaction wheel, i.e., the disturbance had a peak value at the operating speed frequency and its harmonics. The disturbances at other frequencies were found to be negligible. The effect of the torque disturbances on the attitude error and jitter were determined through numerical simulations using a single-axis attitude model. The error and jitter induced by disturbances were found to be well below the required limit for KAISTSAT series spacecraft. It was also shown that the variance of the attitude error and stability depends on the system control bandwidth. For more detailed three-dimensional attitude analysis, more in-depth statistical simulations are planned in near future.

Acknowledgements

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