

Satellite actuator balancing based on the disturbance measurement table data

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Abstract. Reaction wheel is one of primary actuators for satellite attitude control. Since it uses electrical power supplied by the solar panels and thus consumes no invaluable fuel of satellite, it has been used as primary actuator. However, rotation of reaction wheel induces torque and force disturbances which degrade the satellite attitude stability quality. The disturbances are mainly due to static and dynamic imbalances of the wheel. These imbalances shall be reduced on the stage of manufacturing. In this paper a method for the imbalance reduction of the wheel is suggested. Torque/force measurement table is used to measure the disturbances of the reaction wheel and the measured data are used for the identification of location and magnitude of the imbalances. The corrections of the imbalances are performed by adding proper counter masses on the wheel. Through iterative balancing steps, the static and dynamic imbalances are remarkably reduced.

Key words

reaction wheel, disturbance, imbalance, balancing, measurement table

1. Introduction

Reaction wheels have been used as primary attitude control actuators for a variety of spacecraft. Slew or reorientation maneuvers are executed by exchanging their angular momentum with the spacecraft body. Since the wheels are actuated by electric energy generated by satellite solar panel, they can operate with no cost during life time.[1] The change of wheel speed provides the spacecraft with maneuvering capability: torque. However, the vibrational force and torque disturbances are inherent in this type of rotating actuators. The disturbances are mainly due to the non-uniform mass distribution within the flywheel, as called the static and dynamic imbalances. The static imbalance generates a disturbance force, and results into the moment of force about satellite center of mass. The dynamic imbalance induces the torque directly on the satellite body. These disturbances affect the attitude stability quality of the spacecraft, and cannot guarantee the precision pointing.[2]-[4] For this reasons, the reduction of the imbalances of the rotating flywheel is necessary on the stage of wheel manufacturing [5]-[6].

On the reduction of static and dynamic imbalances, the magnitude and phase location of imbalances shall be identified first. It can be done by observing the vibration motion of rotating wheel. In this paper, we suggest a method

on which the disturbance force and torque are measured by a measurement table and the static and dynamic imbalance are identified from the measured data. The suggested identification method is applied on the reaction wheel which is developed by Spacecraft Control Laboratory (SCL) in Korea Aerospace University (KAU) for a small satellite program in KOREA. The imbalances are then reduced either by subtracting or adding a counter mass opposite to the location to the imbalance.

In the next section, the torque/force measurement table system and the reaction wheel developed in SCL are introduced. In the section III, the disturbances and their characteristics including the test results are presented and analyzed. In the section IV, a disturbance identification method is introduced, and the results after balancing the static and dynamic imbalances are shown.

2. Force and Torque Measurement Table

Measurements of disturbance torque and force are carried out using the torque/force measurement table developed in SCL of KAU as in Fig.1. When the reaction wheel runs on the table, it exerts torque and force on the top of the table.[7]-[8] The forces measured on the four 3D load-cells are transformed to the torques and forces equivalent to the disturbance generated on each wheel axis direction. A test reaction wheel of SRE-192 series, is located on the table top. The brief specifications are listed in Table 1. This wheel is developed by SCL/KAU for a small satellite program. It can be equipped on 100-500kg class satellite.



Fig.1 SCL reaction wheel on the measurement table

Table I Specifications of SRW-192 Series.

Items	Value
Nominal wheel speed	3000 rpm
Maximum torque	
- @ 0 rpm	0.3 Nm
- @ nominal speed	0.05 Nm
Angular momentum @ nominal speed	1.9 Nms
Physical envelope of housing	
- Diameter	< 200 mm
- Heights	< 110 mm
- Total mass	< 3.5 kg
Imbalance	
- Static	< 1 g.cm
- Dynamic	< 10 g.cm ²
Control mode	- Torque control - Speed control

3. Disturbances of the Reaction Wheel

A. Imbalances on the Reaction Wheel

The mass imbalances on the reaction wheel are the main sources of the wheel disturbances. When the well-balanced reaction wheel runs at a constant speed, the disturbance is not generated albeit theoretically. However, in case that the imbalances exist in the wheel, torque and force disturbances are produced by dynamic and static imbalance respectively.

The static imbalance is caused by the offset of the center of mass of the flywheel from the axis of rotation. It is most easily modeled as a small imbalance mass m_s located at a radius r_s departed from the wheel spin axis as shown in Fig. 2. Similarly, the dynamic imbalance is modeled as two imbalance masses m_d 's which are located at a radius r_d from the spin axis and departed h_d each other along the z -axis as in Fig.3. Since the disturbances are periodically fluctuating due to the wheel rotation, they are normally represented as the combination of harmonic periodic functions. The frequency of each harmonic is proportional to the wheel speed and the magnitude to the square of the wheel speed.[9]-[11] The theoretical models of disturbance forces and torques are then presented as (1):

$$\begin{aligned}
 F_j &= \sum_i^n F_{ji} \Omega^2 \sin(h_i \Omega t + \alpha_{Fji}) \\
 T_j &= \sum_i^n T_{ji} \Omega^2 \sin(h_i \Omega t + \alpha_{Tji}) \\
 h_i &= \frac{\omega_i}{\Omega}
 \end{aligned} \quad (1)$$

where F_j and T_j are the disturbance forces and torques on the j -axis direction, respectively, F_{ji} and T_{ji} the i -th harmonic parameter, h_i the harmonic number, Ω the wheel speed, α_{ji} the i -th harmonic phase angle, and ω_i the i -th disturbance frequency. In (1), the disturbance force and torque corresponding to the first harmonic are most dominant in the imbalances and thus expressed as (2),

$$\begin{aligned}
 F_j &= m_s r_s \Omega^2 \sin(h_1 \Omega t + \alpha_{Fj1}) = U_s \Omega^2 \sin(\Omega t + \alpha_{Fj1}) \\
 T_j &= m_d r_d h_d \Omega^2 \sin(h_1 \Omega t + \alpha_{Tj1}) = U_d \Omega^2 \sin(\Omega t + \alpha_{Tj1})
 \end{aligned} \quad (2)$$

where U_s is called the static imbalance of $g\text{-cm}$ in SI unit, and U_d the dynamic imbalance of $g\text{-cm}^2$.

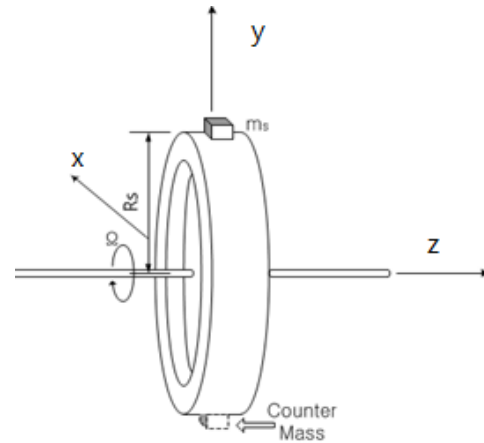


Fig. 2 Static Imbalance Model

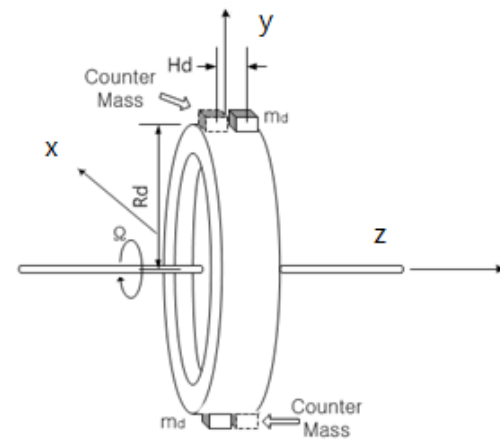


Fig. 3 Dynamic Imbalance Model

B. Force and Torque Disturbance Before Balancing

In order to measure the disturbances, the reaction wheel is set on the torque/force measurement table as in Fig. 1. The x and y -axis forces and torques are radial directional as shown in Figs.2 and 3. The reaction wheel is tested on the rundown mode. On the rundown test, the wheel speed is decreased from the maximum speed to zero rpm with the motor driver circuit open. On each wheel speed span, the power spectrum density plot is obtained through FFT of the measured force and torque disturbance data. By accumulating the PSD plots on the whole speed span, we can then get 3D waterfall plot about wheel speed and frequency as Fig.4. Only the x -axis disturbance data is displayed because the wheel is symmetric about the spin axis. It is found in Fig. 4 that the harmonic vibrations are in the multiples of the rotation frequency: ridges radiated from the origin. The dominant component of the harmonics is the first one as expected, which is produced by the imbalance at the wheel rotation frequency. The higher harmonic components are generated by other disturbance sources like bearing, retainer, and motor driver, etc.

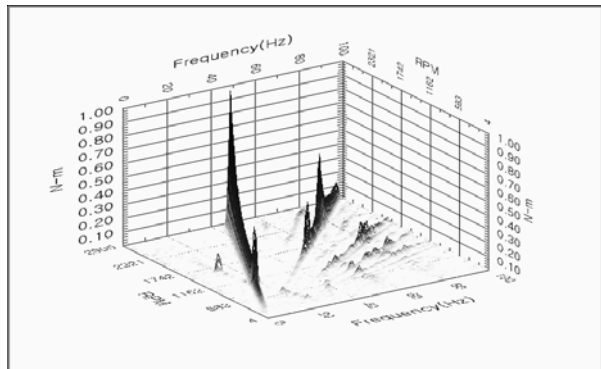
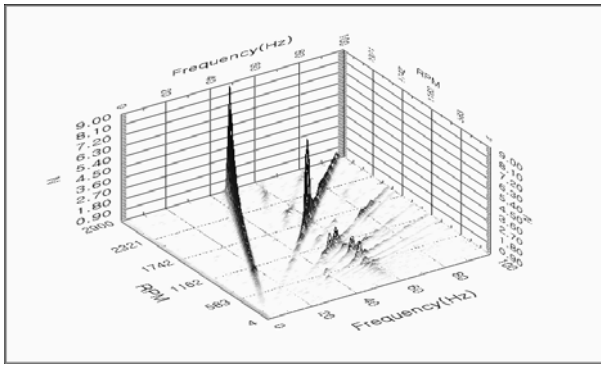


Fig. 4 Force and Torque Disturbance PSD Waterfall Plots

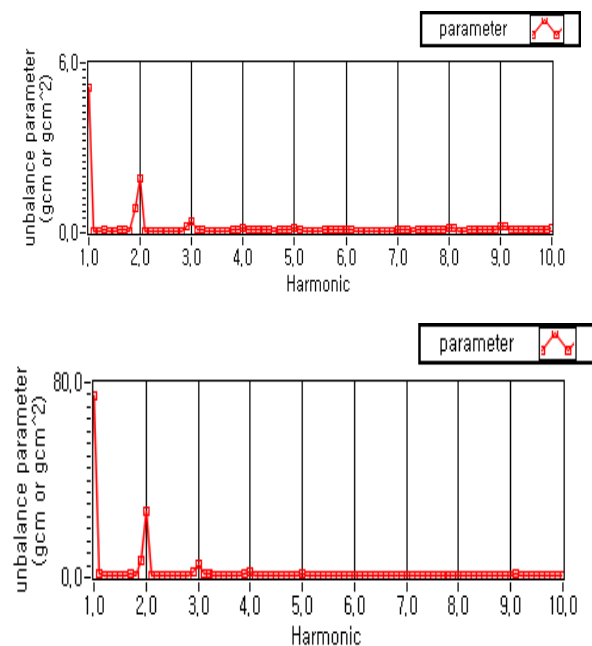


Fig. 5 Static and Dynamic Imbalances on each harmonic

4. Disturbance Reduction

A. Disturbance Identification and Correction

To reduce the wheel imbalance disturbances, the location and magnitude of the imbalances shall be first identified. The identification method has not clearly shown in literatures.[2]-[10] Cheon et al suggested a method for the magnitude identification based on the measured

PSD.[11] We suggest a new method in this paper to identify the phase location of imbalances based on the measured data.

First, the magnitude of imbalance can be extracted from the peak of PSD in each harmonic as previously shown in Fig.5. The location of imbalance is identified with the phase difference detection as represented in Fig. 6. Let a z-phase detector be positioned at the location of the known phase angle θ_1 from the measurement table x-axis. Assume the imbalance mass m_s (or equivalent torque imbalance mass m_d : actual torque masses are located perpendicular) is located at the point of unknown phase θ_2 departed from the reference trigger location. As the wheel rotates, the z-phase detector is triggered when the reference trigger on the wheel passes by the detector as in Fig.7. If the disturbance has the peak value in x-axis direction at θ_3 after the triggering moment, the phase θ_3 is related to the phase angle α_{j1} in (1)

as $\alpha_{j1} = \theta_3 - \frac{\pi}{2}$. The phase θ_2 is then identified as $\theta_2 = \theta_1 - \theta_3$. Therefore, we get finally both the magnitude and phase angle of disturbance force and torque.

After the location of the imbalance is identified, the counter mass of magnitude m_s (or m_d in dynamic case) is added on the opposite side of the imbalance to compensate the imbalance mass: balancing.

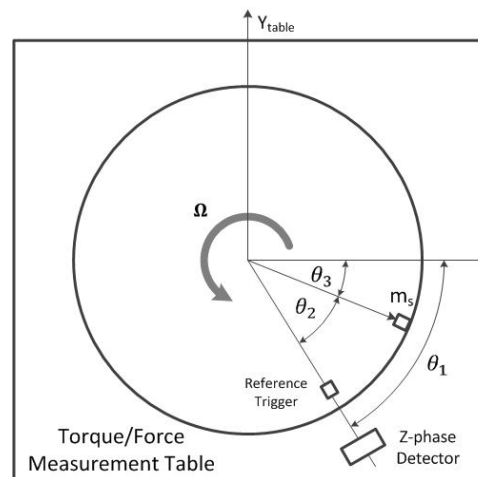


Fig. 6 Imbalance phase identification concept

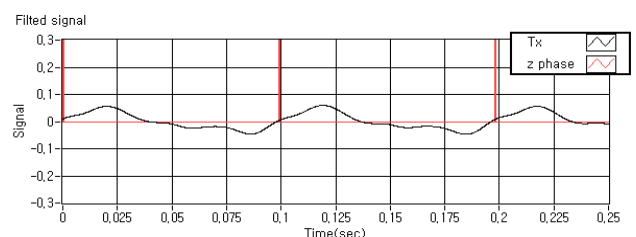
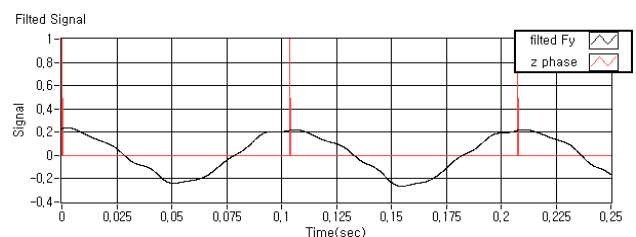


Fig. 7 Phase difference between disturbance peaks and z-signal

B. Force and Torque Disturbance After Balancing

Through some iteration of the imbalance identification and counter weighting, the disturbance forces due to the static imbalance can be effectively reduced. The results are shown in Figs. 8 and 9. The primary peak in the disturbance plot Fig.8 are almost diminished after balancing.(Compare with Fig.4) The imbalance values of the first harmonic are also greatly decreased as shown in Fig.9 compared with Fig.5.

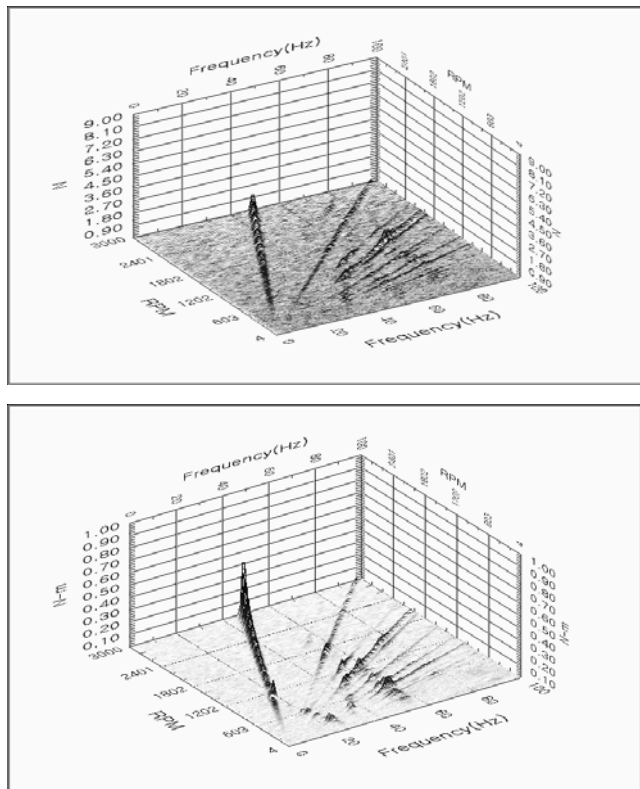


Fig. 8 Disturbance PSD Waterfall Plots after balancing

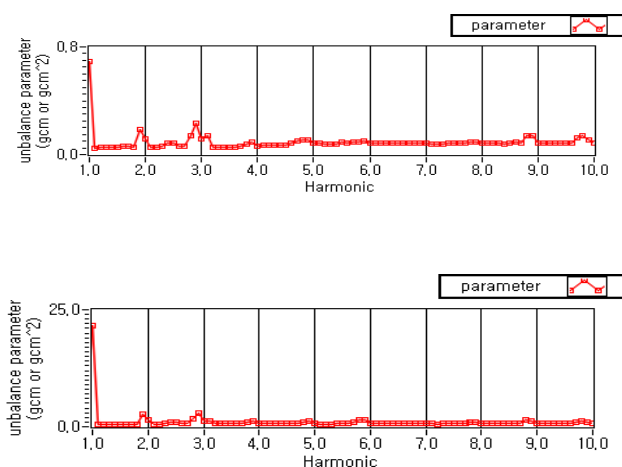


Fig. 9 Imbalances on each harmonic after balancing

5. Conclusion

Disturbance force and torque of the reaction wheel is measured during rundown tests on the torque/force measurement table developed by SCL on KAU. The suggested identification for the phase and magnitude of the imbalances based on the measurement table data works well. The counter weighing reduces the static and dynamic disturbance effectively.

Acknowledgement

This work was supported partly by Global Surveillance Research Center (GSRC) program funded by the Defense Acquisition Program Administration (DAPA) and Agency for Defense Development (ADD), and partly by the National Space Laboratory Program (NSL-2011-0029878) of National Research Foundation (NRF) funded by the Ministry of Education, Science and Technology (MEST of Korea).

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