Investigation of reaction wheel disturbance with Air Floating Disturbance Detector

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Abstract
To comprehend a reaction wheel disturbance character is important for yielding the reliability of reaction wheel and evaluating the stability of spacecraft. Therefore, this paper introduces a new method to measure the micro and low-frequency disturbance, and leads the principle of this system and presents the experimental results.

空気浮上式擾乱測定装置を用いたリアクションホイール発生擾乱に関する研究
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摘要
リアクションホイールの擾乱特性を解析することは、RW の品質保証や衛星の姿勢安定度を評価するために重要である。しかし、従来の方法では低周波数帯域の擾乱については十分な精度で測定することが困難になりつつある。そこで本研究では、低周波数帯域の並進力及びトルクの測定に有効なエアテーブル式低周波微小擾乱測定装置を整備した。本論文では、本装置の測定原理・精度、及び RW の擾乱測定結果について述べる。

1. Introduction

Recently, for realization of the various and complicated missions, observation satellites are required extremely high pointing accuracy[1]. However, reaction wheel, which is used as actuator of attitude control system (ACS), can be a major disturbance source [2,3]. Therefore, to meet the requirement, it is important to measure the disturbance and evaluate the disturbance characteristic of reaction wheel. Furthermore, the next generation satellite, such as advanced land observation satellite will be required controlling the disturbance in a low frequency as compared to current satellites, and the acceptable amplitude of disturbance will become lower level. As a result, the currently available measurement device is not useful for this micro disturbance in low frequency. Consequently, disturbance-measuring system, called “Air Floating Disturbance Detector with linear slide”, has been developed since 1999 [4]. However, this device can measure only disturbance force. Therefore, this paper introduces a new measuring system, called “Air Floating Disturbance Detector with Air Table”, to measure not only disturbance force but also torque in low frequency. Next, experimental results with this device are shown. Finally, the dynamic model of reaction wheel, using the theory of Hertzian contact is shown.

2. Air Floating Disturbance Detector

2.1. Measurement principle and framework

Fig.1, 2 show an outside and a framework of “Air Floating Disturbance Detector with Air Table”, respectively. In this device, reaction wheel is fixed to the flat plate called “Air table”. The bottom face of the table is supported by an air pad, and floated by compressed air. As a result, “Air table” has three degrees-of-freedom. Moreover the displacement caused by the disturbance force and torque is measured with the four high-resolution laser sensors. Therefore, the disturbance force and torque can be calculated from the displacement off-line.

Fig.1 Outside of device
2.2. Measurement accuracy of disturbance

In measurement device, springs are attached, because the displacement is not out of range of laser sensors. Therefore, floating part is assumed to the second-order-system and the transfer functions from disturbance force and torque to displacement are written as follows,

\[
\frac{X_i(s)}{F_i(s)} = \frac{1}{ms^2 + c_i s + k_i} \tag{1}
\]

\[
\frac{\theta_i(s)}{T(s)} = \frac{1}{I_i s^2 + c_i s + k_i} \tag{2}
\]

where, \(X_i\) is displacement, \(F_i\) is disturbance force, \(T\) is disturbance torque, \(m\) is mass of floating part, \(I\) is inertia moment of floating part, \(k_i\) is spring constant, \(c_i\) is viscosity, subscript \(i=1\) means direction of x-axis, \(i=2\) means y-axis and \(i=3\) means z-axis. However spring constant and viscosity are determined from experiment of free decay. Fig.3 shows experimental and numerical result of free decay of floating part and table 1 shows characteristics of floating part.

Next, for calculating the measurement limit, equation (1) and (2) are Laplace transformed as follows.

\[
F_i = X_i \sqrt{\left(k_i - m\omega^2\right)^2 + \left(c_i\omega\right)^2} \tag{3}
\]

\[
T = \theta_i \sqrt{\left(k_i - I\omega^2\right)^2 + \left(c_i\omega\right)^2} \tag{4}
\]

Measurement limit is calculated from equation (3), (4) and resolution of laser sensor (translation: 0.1 \(\mu m\), rotation: 0.01 \(\mu m\)). Fig.4 and 5 show the measurement limit of each frequency and the required level of disturbance in next generation satellites. In Fig. 4 and 5, it is confirmed that the performances of this device satisfy the required level. Moreover, traditional sensor, (example: force and torque sensor) can measure the disturbance with resolution of 0.01N and 0.01 Nm. Therefore, “Air Floating Disturbance Detector with Air Table” can available to measure the micro disturbance in low frequency.

2.3. Sensitivity analysis

To confirm the accuracy of measurement, sensitivity analysis is carried out with self-produced reaction wheel, which has large mass imbalance intentionally. Sensitivity analysis is useful to confirm whether this device can measure the amplitude of
disturbance with accuracy or not, and confirm the lower limit of frequency which this device can measure. Fig.6 shows self-produced reaction wheel, which has large mass imbalance intentionally. Self-produced reaction wheel consist of brush less DC motor, rotor, and bearing. The mass imbalance can be adjusted by adding the arbitrary mass on the rotor. Sensitivity analysis is carried out with two types of mass imbalance. Experimental result is shown in Fig.7. In experiment, Self-produced reaction wheel is rotated at constant speed (3-5000 rpm) and displacement caused by disturbance is measured. As a result, in this low-frequency range, it is confirmed that “Air Floating Disturbance Detector with Air Table” has a high sensitivity to disturbance.

3. Experimental Work

3.1. Characteristic of Reaction Wheel

Table 2 shows the characteristic of reaction wheel, which is used in this study. This reaction wheel is the engineering model and the same model mounted on Engineering Test Satellite-VI (ETS-VI) and Communications and Broadcasting Engineering Test Satellite (COMETS). The cross section view of reaction wheel is shown in Fig.8.

3.2. Experimental Result of Disturbance Measurement

Using “Air Floating Disturbance Detector with Air Table”, a series of tests are conducted to measure the disturbance. Disturbance force and torque are measured when the reaction wheel is rotated at a constant speed (60-600rpm). Experimental result is shown in Fig.9 and 10. In Fig.9, there are three disturbance peaks in the frequency domain. One of the peaks has the same frequency as the rotor spin frequency, the next peak has the frequency as the rotor spin frequency multiplied by 0.6 and last peak has the frequency as the rotor spin frequency multiplied by 1.6. The first peak results from static imbalances. Static imbalance is the offset of the center of gravity of the rotor from the rotation axis, represented by a small mass at a radius. Therefore, static imbalance produces a sinusoidal force from a fixed reference, and the amplitude is proportional to the wheel speed squared [21]. The second peak results from cage of the ball bearing [4]. The cage has a mass imbalance and rotate at 0.6 multiplied by wheel speed. The third peak results from sizing error of the ball in the bearing. The period of revolution is calculated by,

\[
f = \left(1 + \frac{\cos \alpha}{d_{w}/D}\right) \frac{\omega}{2} = 0.5948\omega \tag{5}
\]
two ball bearings, a brushless DC motor and a housing. The outer race of the bearing unit supports the wheel rotor, and the inner race is fixed to the base plate. Therefore, we assume that a rotor and an outer race of a bearing unit form a single rigid body, which have six degrees-of-freedom, and it is received the contact force from the twenty-four balls contacting the inner and outer race. To calculate the contact force, we applied the theory of Hertzian contact [5] to the bearing unit. This theory is based on the next assumptions: (i) the contact area becomes elliptical and much smaller than the contacting surface area. (ii) the force acting on the contact area is vertical to that area. (iii) the deformations are within the range of elastic deformation. Fig.11 shows that the contact ellipse between the ball and the two races. As a result, the bearing unit is approximated to the non-linear spring. Moreover, we modeled that the wheel rotor and the cage of bearing have mass imbalances and the ball of bearing has a sizing error. The numerical model of this study is written as follows:

\[
\begin{bmatrix}
  A_{11} & A_{12} \\
  A_{21} & A_{22}
\end{bmatrix}
\begin{bmatrix}
  \omega_r
  \omega_w
\end{bmatrix}
+ 
\begin{bmatrix}
  b_1 \\
  b_2 + b_{vor}
\end{bmatrix} = \begin{bmatrix}
  f_{aw}
\end{bmatrix}
\]  

(6)

where

\[
A_{11} = I_w
\]
\[
A_{12} = -m_w (\vec{v}_{\omega w})^T
\]
\[
A_{21} = -m_w \vec{v}_{\omega w}
\]
\[
A_{22} = m_w U_3
\]
\[
b_1 = \omega_r \omega_w I_w + m_w \vec{v}_{\omega w} \omega_r \omega_w + m_w \vec{v}_{\omega w} \dot{\omega}_w \dot{v}_{\omega w}
\]
\[
b_2 = m_w \omega_r \omega_w (\vec{v}_{\omega w} + \dot{\omega}_w \dot{v}_{\omega w})
\]

4.2. Simulation results

Fig.12 shows the waterfall plot of simulation result when the reaction wheel is rotated at a constant speed. In this figure, three kinds of peaks are confirmed. They result from mass imbalance of wheel and cage, and the sizing error of the ball in the bearing, respectively. As a result, it is confirmed that the experimental result was almost same as the simulation result.
Fig 12 Simulation result (disturbance force)

5. Conclusion

We have developed disturbance detector, which is called “Air Floating Disturbance Detector with Air Table”, and experimented to measure the micro disturbance of RW in low frequency. As a result, three disturbance sources are determined, due to mass imbalance of wheel and cage, and sizing error of the ball in the bearing. Moreover, we have developed the dynamic model of the ball bearing within the reaction wheel. For the modeling the ball bearing, we have applied the theory of Hertzian contact. The simulation result shows a good coincidence to the experimental result. Therefore, we can conclude that the proposed model has high fidelity.

Acknowledgment

This work is supported in part by Grant in Aid for the 21st century center of Excellence for “System Design: Paradigm Shift from Intelligence to Life” from Ministry of Education, Culture, Sport, and Technology in Japan.

References


