Journal of Sound and Vibration 333 (2014) 4214–4231

Contents lists available at ScienceDirect

Journal of Sound and Vibration

journal homepage: www.elsevier.com/locate/jsvi

Micro-vibration model and parameter estimation method of a reaction wheel assembly

Dae-Kwan Kim *

Satellite Control System Team, Satellite Technology Research Laboratory, Korea Aerospace Research Institute, 115 Gwahagno, Yuseong-gu, Daejeon 305-333, Republic of Korea

ARTICLE INFO

Article history:
Received 18 August 2013
Received in revised form
24 February 2014
Accepted 13 April 2014
Handling Editor: L.G. Tham
Available online 10 May 2014

ABSTRACT

Reaction wheel assemblies (RWAs) are a source of disturbance in satellites, and they are regarded as the largest jitter contributor in optical payloads. In order to ensure a stringent jitter requirement, the wheel disturbance effects on spacecraft should be predicted precisely prior to launch through analytical or experimental approaches. For this purpose, the wheel disturbance should be identified and modeled accurately. In the present study, a micro-vibration model of the RWA is introduced through coupling an analytical wheel model and an empirical disturbance model; furthermore, a parameter estimation process of the coupled model from the micro-vibration disturbance data is proposed. In order to verify the modeling and estimation techniques, a micro-vibration model of a numerical RWA is established and its estimation error is validated. Then, the micro-vibration model is extended to consider an axial disturbance and a measurement offset effect. Finally, the micro-vibration model is applied to a commercial RWA and the model parameters are extracted from the disturbance test data of the RWA using the parameter estimation process. The analytical and experimental results demonstrate that the proposed micro-vibration model and parameter estimation process are effective in the dynamic disturbance modeling of RWAs.

1. Introduction

These days, space observation satellites have very precise optical instruments that are used for various purposes and delicate space-based missions. The optical payloads are very sensitive to high frequency pointing disturbances and, thus, with small amplitudes, the dynamic perturbations (micro-vibrations) on optical mirrors and detectors can cause significant effects in the image quality degradation, such as optical path length differences, blurring, and smears in the images [1,2]. In order to ensure mission success, spacecraft requirements include having extremely high pointing accuracy, stability, and sub-arcsecond level line-of-sight (LOS) jitter [3–5]. Moreover, compliance with the jitter requirements should be verified prior to launch through analytical and/or experimental approaches [6–8]. Therefore, accurate dynamic models of the disturbances should be established in order to demonstrate a good estimation of the jitter performance.

The dynamic disturbances of satellites are induced either by external sources in the space environment or by internal sources from the actuator and sensor systems onboard the spacecraft [9]. Micro-vibrations are primarily generated by the onboard mechanical moving systems including mechanically tunable optical filters, crycoolers, solar array drive

* Tel.: +82 42 870 3751; fax: +82 42 860 2898.
E-mail address: dkk@kari.re.kr

http://dx.doi.org/10.1016/j.jsv.2014.04.032
0022-460X/

mechanisms, antenna pointing mechanisms, and reaction wheel assemblies (RWAs). Among these micro-vibration disturbance sources, the disturbance produced by RWAs is generally regarded as the largest [10]. The RWA is a momentum exchange device that is used in spacecraft attitude stabilization and control, and it provides axial reaction torques and stores angular momentums through adjusting the rotational speed of the flywheel. A typical RWA, as depicted in Fig. 1, consists of a rotating flywheel suspended on ball or magnetic bearings, and is driven by an internal brushless DC motor [11,12].

The micro-vibration disturbances induced by the RWA are generally categorized into fundamental and sub and/or higher harmonic disturbances. The fundamental harmonic disturbances are considered to be the most significant micro-vibration source; they are caused by the static and dynamic imbalances of the flywheel and it produces a disturbance force and moment according to the wheel speed. The sub/higher harmonic disturbances are caused by the dynamic lubrication behavior, motor disturbance, control error (such as cogging and torque ripple), and bearing irregularities in their balls, races, and cage. This harmonic disturbance also produces a disturbance force and moment at sub/higher harmonics of the wheel speed [13]. In addition, RWAs have structural vibration modes as a result of the internal flexibility of the wheel structure. As shown in Fig. 2, there are three dominant structural modes: lateral mode, axial mode, and rocking (whirl) mode [14]. The harmonic disturbances can be amplified by these vibration modes when the harmonics cross the mode frequency. In some cases, the resonant peaks of the amplified disturbances, as measured in this study, can be significantly greater than the fundamental harmonic disturbance, which results in a significant jitter amplitude. Therefore, in order to obtain an accurate disturbance model, the dynamic flexibility of the RWAs must also be considered in the modeling process.

Over the past few decades, there have been numerous studies on RWA disturbance modeling. The disturbance modeling methods can be broadly classified into empirical models and analytical models. The empirical models use the stochastic broadband model or the geometric relationship of the wheel to establish several discrete harmonic disturbances [12,15–19]. Masterson et al. [15,16] applied a MATLAB toolbox in order to extract the disturbance coefficients of an empirical disturbance model from the RWA micro-vibration data after removing the structural resonant data. Taniwaki and Ohkami [17] developed a new model that detects low-frequency disturbances using the wheel geometric relationship and contact dynamics. Oh and Cheon [18] used an empirical model to suggest a calibration process that reduces the resonance frequency error of a measurement table. Zhao et al. [19] suggested an identification method for the amplitude coefficients of an empirical model using the energy compensation method. These empirical models are very useful in representing the RWA disturbances in discrete harmonic forms; however, they cannot capture the resonance effect between the harmonic

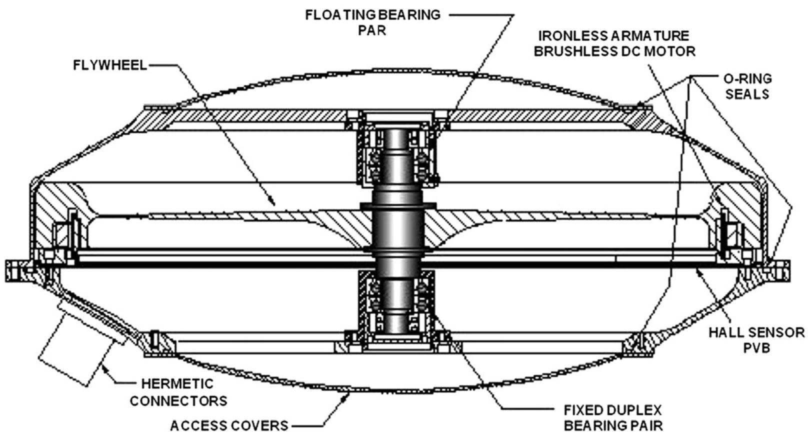

Fig. 1. Cross section of ITHACO E-type reaction [12].

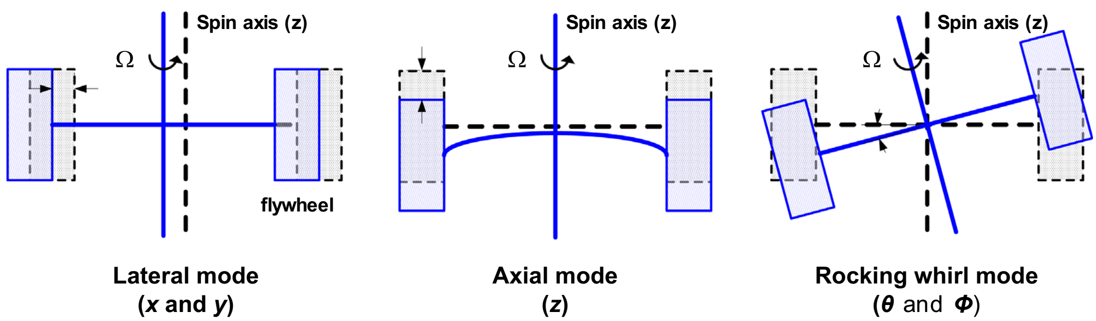

Fig. 2. Structural modes of a reaction flywheel.