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Nonlinear electromechanical modelling and dynamical behavior analysis of a satellite reaction wheel

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ABSTRACT

The present research addresses the satellite reaction wheel (RW) nonlinear electromechanical coupling dynamics including dynamic eccentricity of brushless dc (BLDC) motor and gyroscopic effects, as well as dry friction of shaft-bearing joints (relative small slip) and bearing friction. In contrast to other studies, the rotational velocity of the flywheel is considered to be controllable, so it is possible to study the reaction wheel dynamical behavior in acceleration stages. The RW is modeled as a three-phases BLDC motor as well as flywheel with unbalances on a rigid shaft and flexible bearings. Improved Lagrangian dynamics for electromechanical systems is used to obtain the mathematical model of the system. The developed model can properly describe electromechanical nonlinear coupled dynamical behavior of the satellite RW. Numerical simulations show the effectiveness of the presented approach.

1. Introduction

Micro-vibrations have important effects on satellites instruments with high stability requirements. One of the largest disturbance sources onboard the spacecraft are reaction wheel and momentum wheel assemblies [1]. The micro-vibration produced by these actuators is transmitted through the satellite and excite the satellite structure or elements of the sensitive instrument, influencing its performance [2]. Typical sources of micro-vibration from a RWA can be categorized into three groups [3]:1) Flywheel mass imbalances 2) bearing irregularities and 3) motor irregularities.

A large number of studies have been conducted on reaction wheel induced micro-vibration. These studies started by research on satellite micro-vibration and its control approximately in the early 1970's mainly driven by the HST project [4,5] and then continued in four major categories: a) modeling analytically the disturbances of RWA [6–14] b) measuring the disturbances of RWA and using it to predict some parameters of the analytical model [10–19] c) modeling the interaction of reaction wheel and satellite dynamics [20–24] and 4) attenuating the RWA disturbances using passive and active controllers [24–27].

Masterson (1999) has presented the analytical and empirical disturbance models for RWA which considered that the mass imbalances are the most significant source of the disturbances [10]. Elias and Miller (2001), also Elias, et al. (2003) have proposed a coupled RWA disturbance analysis method using dynamic mass measurement techniques [20,21]. Taniwaki and Ohkami (2003) have developed a method to measure lower frequency disturbances induced by RWA/MWA, which are traditionally difficult to detect [19]. Zhang, et al. (2013) have proposed a cost-effective measurement system consisting of a seismic mass and two high sensitive accelerometers which has been used to test the micro-vibrations produced by a cantilevered R/MWAs [11]. Le, et al. (2014) have measured the Bradford reaction wheel disturbances on micro-vibration facility at ESTEC to detect ball bearing imperfections in reaction wheel. They also have presented a full disturbance model for Moog Bradford by combining empirical and theoretical models. In this model, the bearing stiffness is formulated as a function of ball pass frequency and the flexibility of the supporting structural items such as the reaction wheels housing are included [14,15].

Due to introduction of the electromechanical coupling system, RWs are more complex and may present different micro-vibration characteristics. To the best of our knowledge, there has not been any research in the area of reaction wheel electromechanical coupling mathematical modeling and what has been reported is limited to mechanical analytic models or micro-vibration measurement and subsequently analytical-experimental models. In fact, a reaction wheel is an electromechanical device. It is important to model the effects of electromechanical interaction in the dynamic of the system because space missions are very expensive and all components must be studied and modeled completely

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considering all effective parameters before launching. Also it make a good sight to detect some faults of the system by monitoring some parameters such as currents flowing of stator windings when it is used in space and thereby made appropriate decisions. Additionally, it provides some good data for satellite ADCS control algorithms to increase its efficiency and mission safety. The rotational velocity of RWA is variable and depends on the torque should be produced. In all of the above mentioned works, the RWA is modeled at a constant spin speed of flywheel. Then it is important to study the RWA behavior along the acceleration/declaration process.

In this paper, we consider the flywheel imbalances, structural modes, gyroscopic effects and dynamic eccentricity of rotor (shaft with motor magnet poles) as motor irregularity simultaneously to model the mid-span configured RWA micro-vibrations and then analyze the influence of each source on the characteristic of micro-vibrations. As well as because of the rotating speed of the flywheel is controlled by Pulse Width Modulation (PWM) method, we can study the behavior of RWA in acceleration/declaration process. This model is capable to add by some faults (such as noisy rotating speed, acceleration time of rotating speed, internal friction, ball bearing friction) to study those effects on reaction wheel dynamic.

2. Dynamic model

Reaction wheel assemblies are part of the satellite attitude determination and control system (ADCS). A typical reaction wheel consists of a flywheel mounted on a shaft which suspended by bearings and driven by a brushless direct current (DC) motor. The whole assembly is then covered by the housing.

As shown in Fig. 1, the mechanical configuration of a RWA can be either mid-span or cantilevered configured. RWAs usually have a nominally zero speed (or several hundred rpm to avoid stiction problems near zero speed) and can spin in either direction, as well as provide control torque in both directions along the rotational axis.

Fig. 2 shows the model of RWA considered in this paper. The RWA is modeled as a balanced flywheel with mass, M, rotating on a rigid shaft. Linear springs and dampers at an axial distance, d_k and d_c, are added to model the shaft and bearing flexibility. The BLDC motor is placed at one end of the shaft. The flywheel static and dynamic imbalances are modeled with lumped masses, m_s and m_d, that are positioned strategically on the wheel.

Fig. 3 shows the BLDC motor which has ten rotor magnet poles, 30 slots and three stator phases. The rotor with permanent magnets has mass, m_{rot}, and is supported by the rigid shaft. The stator, which is supported by the RWA housing, includes many poles holding stator coils formed by wire winding.

The three motor phases are connected in a Y-connection topology as shown in Fig. 4. This type of connection is the most commonly implemented motor drive and connects all of the windings to a central point which called neutral point and power is applied to the remaining end of each winding. Each phase winding is composed of a resistive component with the resistance, r_a, and an inductive component with self-inductance, L_a.

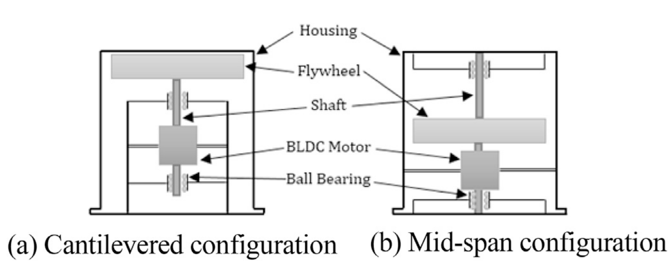

Fig. 1. Typical reaction wheel configurations.

The equations of motion of the full system are derived using energy method in two general stages. The first stage is included the dynamics of mechanical part of the system and the second is the dynamics of BLDC motor considering interaction between two mentioned parts.

To achieve the kinetic energy in first stage, we calculate it for balanced flywheel, flywheel with static and dynamic imbalance, and then apply superposition principle. Euler angles are used to define the rigid body rotations of the flywheel and related on coordinate frame to another. The wheel is free to rotate about three different axes as shown in Fig. 5. The first rotation, φ, is about the Y-axis of the ground fixed, inertial frame, XYZ, and defines the intermediate reference frame, $a\,b\,c$. The next rotation, θ, which is about the a-axis, defines the rocking frame, $x'y'z'$, which is rotating in both φ and θ with respect to ground. The final rotation, ψ, is about the z'-axis. This rotation represents the spinning of the wheel and defines the final, body-fixed frame, xyz.

As discussed above, the wheel has three rotational and two translational degrees of freedom, $\theta,\ \varphi, \psi$ and x, y, respectively. The angular and translational velocity of the wheel in $x'y'z'$ frame is:

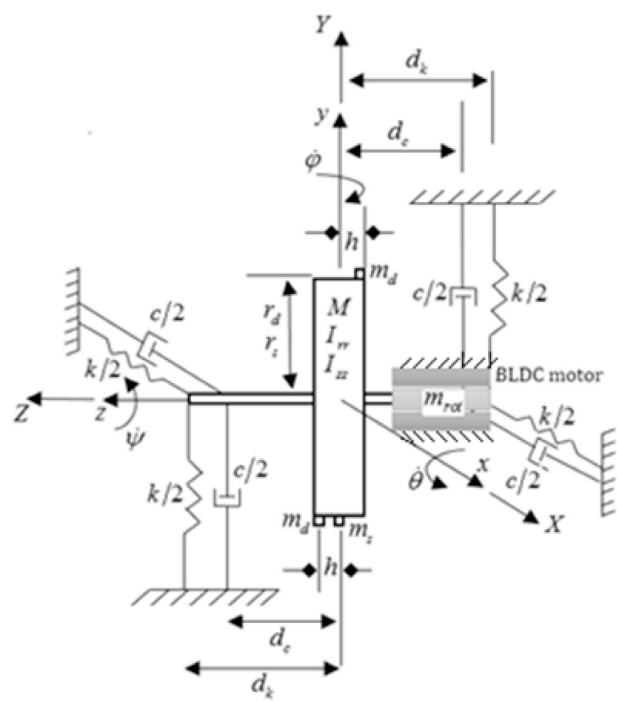

Fig. 2. Reaction wheel model.

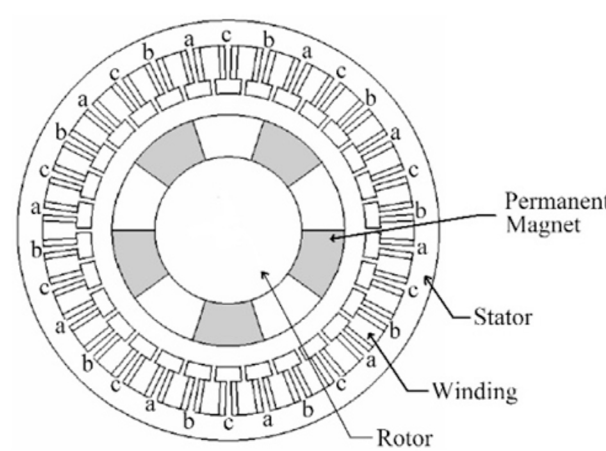

Fig. 3. Fundamental 3 phases BLDC motor mechanical structure.