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Speed tracking control for the gimbal system with harmonic drive

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ABSTRACT

This paper presents a composite controller based on a disturbance observer for the gimbal system of double-gimbal magnetically suspended control moment gyro (DGMSCMG) with harmonic drives. The controller removes the influence by coupling moments and nonlinear transmission torques. The disturbances are estimated by the designed disturbance observer. By introducing a state feedback controller, the disturbances can be eliminated from the output channel of the system. The gain selection principle of the disturbance observer is also analyzed. Both the simulation and experimental results indicate that the proposed control method can reject mismatched disturbances and improve system performance.

1. Introduction

Control moment gyros (CMGs) are the key actuators used for attitude control of large spacecrafts (Bhat & Tiwari, 2009; Lappas, Steyn, & Underwood, 2002). Depending on the degree of freedom of the gimbal system, CMG can be classified into single-gimbal CMG and double-gimbal CMG (Ahmed, 2002). Depending on the supporting manner of high-speed rotor, it can be categorized into mechanical bearings CMG and magnetically suspended CMG (Fang, Ren, & Fan, 2014). DGMSCMG possesses advantages in large torque amplification, high precision and the ability to output torque with two degrees of freedom, making it very attractive for the attitude control system of space stations and satellites (Fang, Zheng, & Han, 2013; Su & Xu, 2013).

DGMSCMG consists of a magnetically suspended high-speed rotor system and the inner and outer gimbal systems. With a specific rotation of inner and outer gimbals, the vector direction of the rotor's angular momentum is changed to produce the desired gyro torques. Thus the precision in angular speed of the gimbal system directly affects the output torque accuracy of CMG (Fang, Li, & Han, 2012; Wu & Zhang, 2007). Achieving high-precision angular rate tracking control of gimbal system is of vital importance to output torque accuracy.

Due to the strong gyroscopic effect, notable coupling torque is generated between the inner and outer gimbals (Wilson, 1975). The coupling torque is nonlinear and is related to the angular position and speed of the inner and outer gimbals (Wei & Fang, 2010), and it is one of the main factors which influence the angular speed of gimbal system. Thus, the gimbal system of DGMSCMG is a two-input–two-output, multivariable, strongly coupled system. To solve the afore-mentioned problems, a composite control compensation method has been proposed in Wei and Fang (2010). While the effect of coupling torque and moving gimbal is attenuated to some degree, the complete elimination of coupling torque was not achieved. In order to obtain the precision control of DGMSCMG, differential geometry method was adopted to achieve the exact linearization and decoupling among the rotation motions and the gimbal system (Chen & Ren, 2014). A combined internal modal controller with a dynamic compensator is introduced to guarantee the system robustness and eliminate the influence of the unmodeled dynamics (Chen & Chen, 2013). However, the influence of the harmonic drive was not considered in Chen and Ren (2014) and Chen and Chen (2013), and the disturbances are matched.

The weight and size of CMG are subjected to strict requirements for applications in space (Fang, Zheng et al., 2013). Transmission mechanisms are frequently used in the inner and outer gimbals to reduce the weight and volume of torque motors (Han, Chen, Li, & Yang, 2013; Zheng, Han, & Guo, 2014). Compared to other reducers, harmonic drive has several advantages such as compact design, low weight, high gear reduction with near zero backlash, high torque-to-weight ratio, high efficiency transmission under vacuum condition, etc. (Tuttle & Seering, 1996). Therefore, it is currently the best choice for the DGCMGs gimbal system (Fang, Chen, & Li, 2014). It is well known that harmonic drives have some nonlinear characteristics such as nonlinear torsional stiffness and friction (Curt, Thomas, & Deming, 2012; Zhang, Ahmad, & Liu, 2015a, 2015b), which seriously influence the angular speed precision of gimbal system due to the structure characteristics and assembly error.

Based on the above analysis, the coupling moment and the nonlinear characteristics of harmonic drive are the main factors which influence the stability and precision of the gimbal system in DGMSCMG, which is a two-input–two-output, multivariable, strongly

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coupled speed servo system. Though the unbalanced vibration of the magnetically suspended rotor is another influence factor, we neglect it because the base frequency of the high speed rotor is very high. Each gimbal, the inner or the outer gimbal, can be regarded as a two-mass system with a flexible joint and nonlinear load (Han et al., 2013), and the joint flexibility could result in poor dynamic performance.

In order to achieve superior tracking performance, a number of feedforward techniques have been used. Among these is the zero-phase error tracking (ZPET) method proposed by Tomizuka (1987), which is based on partial plant inversion. However, it is not easy to achieve a relatively accurate plant model (Lu & Lin, 2007). Numerous methods based on modern robust control theory have been proposed to improve the control precision in the servo system with nonlinear transmission and load. A linear H_∞ controller is designed to deal with disturbance rejection in a two-mass system (Peter, Scholing, & Orlik, 2003). To restrain the torsional vibration and design a position controller, a robust control method based on immersion and invariance is proposed (Khan & Dhaouadi, 2015). In Orlowska-Kowalska and Szabat (2008), an adaptive sliding neuro-fuzzy speed controller is presented, and the torsional vibrations are successfully damped in the control structure with only one feedback from the motor speed. According to the problem that the flexible modes affect the performances of the drive, a fuzzy Luenberger observer is designed (Szabat, Tran-Van, & Kamiski, 2015), and the dynamic states are recognized. Kaminski and Orlowska-Kowalska (2015) analyzed and compared four types of neural-adaptive controllers and apply the methods for a drive system with an elastic mechanical coupling. However, all the control approaches are focused primarily on the stability of the nonlinear systems with disturbances. The robustness and the disturbance rejection performance are generally achieved at the cost of sacrificing their nominal control performance (Li, Sun, Yang, & Yu, 2015).

As a practical and feasible approach, disturbance-observer-based control (DOBC) has proven to be an effective method to reject the external disturbance and improve the robustness of the system without sacrificing its nominal control performance. With the development of the DOBC theory, both the matched disturbances and the mismatched disturbances can be attenuated by DOBC. The so-called matching condition is defined as the disturbances and the control input enters the system via the same channel. Under the conditions of matched disturbance, the DOBC has been successfully applied in various engineering system, such as robotic system (Nozaki, Mizoguchi, & Ohnishi, 2014), hard disk drive system (Chen & Tomizuka, 2012; Ishikawa & Tomizuka, 1998), and motor servo system (Li, Zhou, & Yu, 2013; Zhang, Sun, Zhao, & Sun, 2013).

In practice, the inner and outer gimbal systems of DGMSCMG suffer from two main disturbances, the coupling moment caused by the gyro effect and the nonlinear transmission torque of the harmonic drive. The disturbances can be regarded as mismatched disturbances because they enter the gimbal system via different channels from the control input. To deal with the mismatched disturbances, some researchers propose using the DOBC combined with some traditional robust control methods. DOBC is only used to reject the matched disturbances, while the mismatched disturbances are attenuated via robust feedback control methods, such as H_∞ control and sliding-mode control. In Yang, Li, and Yu (2013), DOBC combined with sliding-mode control method is used for the mismatched disturbances in a MAGLEV suspension system. Peng, Fang, and Xu (2015) developed a composite controller using DOBC with H_∞ control method and improves the suspension precision of AMB system. An adaptive disturbance observer approach is used to reject the current disturbances and improves the torque output precision (Mohamed, 2007). It is also reported that the mismatched disturbances therein are constrained to be H_2 norm bounded (Li, Sun et al., 2015). Yang, Chen, and Li (2011), Yang,Zolotas,and Chen (2011), and Yang, Li, and Chen (2012) proposed a new way to deal with the mismatched disturbances using only the DOBC by designing a novel disturbance compensation gain, which has been verified by simulation results and a PMSM speed regulating system application. However, how to select the parameters of the controller and disturbance observer have not been given clearly.

In this study, the mismatched disturbances rejection control problem in the gimbal servo control system with harmonic drive of DGMSCMG is studied. Targeted at the problems caused by coupling moment and nonlinear transmission torque of harmonic drive, this paper improves the gimbal angular speed precision of the DGMSCMG by developing a novel composite controller based on disturbance observer. The idea of the proposed controller is to reconstruct the original system to an equivalent controllability canonical form by introducing a novel transformation matrix and the pole assignment method is used to design the control law. In combination with a generalized disturbance observer, the mismatched disturbances can be attenuated from the output channels. There are mainly two advantages of the proposed control method. Firstly, the DOBC scheme is successfully used in the decoupling control of the double gimbal system. Secondly, the gain selection principle is given clearly, and strong anti-interference ability and high precision of angular speed can be acquired with this principle.

This paper is arranged as follows. In Section 2, the model of double gimbal servo system with harmonic drive is established and analyzed. Section 3 presents the design method and the stability analysis of the composite controller. Section 4 introduces the simulation and experimental results to validate the control method. Some important conclusions are summarized in Section 5.

2. Modeling of the gimbal system with harmonic drive

From the design diagram shown in Fig. 1, a DGMSCMG consists of inner and outer gimbal servo systems and a high-speed AMB-rotor system, the stator components of outer gimbal are fixed on the base.

2.1. Modeling and analyzing of the coupling moment of gimbal system

The structure and coordinates of DGMSCMG are defined in Fig. 2.,where O is the geometry center of the stator, θ_g and θ_j are the rotational angles of the inner and outer gimbal servo systems, Ω is the rotor speed, α and β are the rotational angles of the rotor about X and Y axes. The model of the inner and outer gimbal systems can be expressed as follows (Chen & Ren, 2014):

$$\begin{cases} P_{gx} = (J_{gx} + J_{rr})\ddot{\theta}_g + (J_{gy} - J_{gz})\dot{\theta}_j^{\,2}\sin\theta_g\cos\theta_g + H_{rz}\dot{\theta}_j\cos\theta_g + T_{fx} \\ P_{jy} = (J_{jy} + J_{gy}\cos^2\theta_g + J_{gz}\sin^2\theta_g + J_{rr}\cos^2\theta_g)\ddot{\theta}_j - H_{rz}\dot{\theta}_g\cos\theta_g \\ \qquad - (J_{rr} + 2J_{gy-2J_{gz}})\dot{\theta}_g\dot{\theta}_j\sin\theta_g\cos\theta_g + T_{fy} \end{cases} \tag{1}$$

where H_{rz} is the angular momentum of the high speed rotor, J_{gx}, J_{gy} and J_{gz} are defined as the rotational inertial along the coordinates of

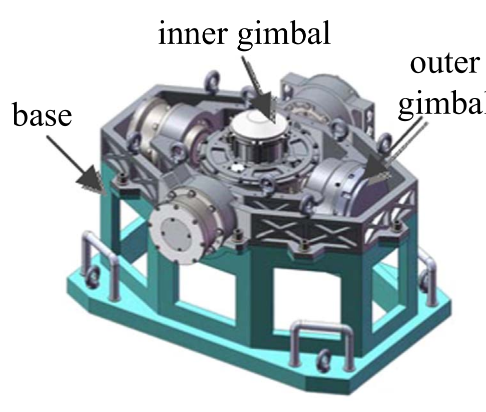

Fig. 1. Diagram of DGMSCMG.