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A non-saturated sliding-mode control of shaft deflection for magnetically suspended momentum wheel with coupled disturbance and saturated amplifier

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ABSTRACT

The magnetically suspended momentum wheel (MSMW) expands its fresh functions through deflecting the rotary shaft. An improved nonsingular terminal sliding-mode control (NTSMC) method is proposed to achieve high precision tracking of shaft deflection for the MSMW under coupled disturbance and saturated amplifier. A novel structure designed for this MSMW is introduced initially. Its magnetic torque model and coupled disturbance are analyzed, and a tracking error dynamic model is established. Then a NTSMC method is applied to shaft tracking control. As the saturation of amplifier influences tracking performances, an improved NTSMC is designed to deal with saturation problem. Finally, several simulations are performed to validate the effectiveness of the proposed method. The results indicate the proposed method improves the tracking precision and velocity compared with the conventional integral sliding-mode method, and solves the saturation problem compared with existing NTSMC method.

1. Introduction

Momentum wheel (MW) has played an important role in spacecraft attitude control. In the process of generating torque, MW changes rotary speed of the rotor to exchange the angular momentum with spacecraft. Magnetically suspended momentum wheel (MSMW), whose rotor is magnetically suspended, avoids mechanical contact between the rotor and the stator. The special structure characteristics bring considerable advantages such as low vibration, non-friction and high precision. In early researches, several conclusions have made that MSMW fairly meets the requirements of fast attitude maneuver, longevity [1,2].

Like traditional ball bearing suspended MW, MSMW could change the amplitude of momentum by changing rotary speed of rotor. Meanwhile the rotor shaft of special designed MSMW could be actively deflected, making it possible to generate gyroscopic torque in two degrees of freedom (DOFs) [3]. The attitude control capability involves three axes in active MSMW system. Sawada et al. described the specific composition of MSMW, and presented a control method to improve attitude stability. Fast attitude reorientation was obtained based on the shaft deflection [4]. A medium-frequency disturbance attenuation strategy is proposed based on the virtual-gimbal effect of the active MSMW, improving pointing stability for high resolution observation of the spacecraft [5]. Seddon et al. modeled the three axis attitude control actuation by active magnetic bearing (AMB), and designed a control loop to deflect the rotor [4]. Experiment results of high bandwidth and torque output of the wheels validated the advantages of MSMW on high attitude stability and fast attitude reorientation. The rapid deflection control with high precision in turn brings new challenges to the MSMW system.

The rotor of active MSMW is suspended and deflected by AMB, which means the AMB control method has a significant influence on the torque output of MSMW. Various types of controllers have been implemented on AMB systems and numerous studies in the AMB control system have been conducted. As classical control methods, the conventional PID and hybrid PID methods are widely applied in order to make AMBs reliably stabilized [6–8]. In Ref. [9], a strategy based on complex PID-controller design was presented, including optimization process with multiple objective genetic algorithms. The cross feedback controller was introduced in AMB control system for simple structure and strong algorithm portability, and it was utilized to correct MSMW stability and phase

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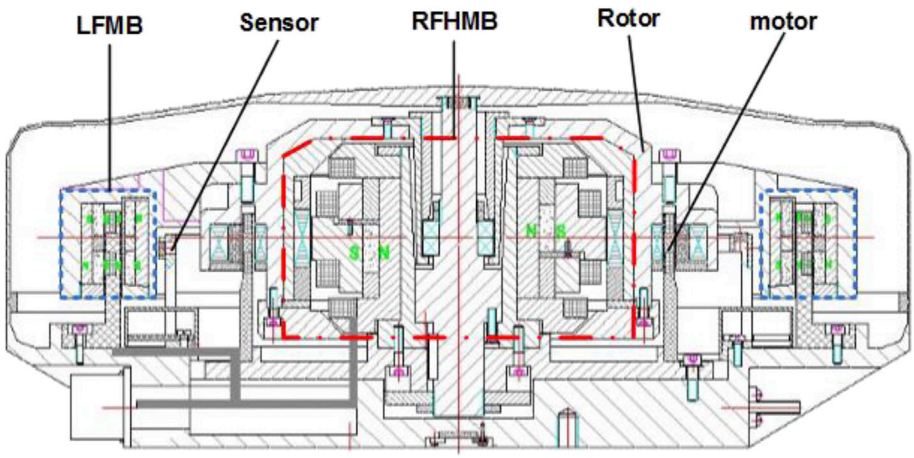

Fig. 1. The structure of the novel MSMW.

compensation [10]. To obtain more accurate control, Mushi et al. developed a μ-synthesis controller to validate rotor-AMB model and provided improved stability and performance over the PID law [11]. The inverse system method [12] and H_∞ control method [13] also have been utilized to design AMB controller.

Real control system of AMB is highly nonlinear, including electromagnetic torque, amplifier and sensor nonlinearity. Meanwhile, according to analysis of magnetic torques, the wide-range shaft deflection may lead to serious coupled disturbance. Chen et al. designed a nonlinear disturbance observer to estimate the disturbance including model uncertainties and the system nonlinearities [14]. Grochmal et al. proposed an observer to estimate the disturbance affecting precision tracking, and a fast convergence velocity observer was designed to reduce the order of disturbance observer, where static offset and synchronous vibration are considered [15]. Hong et al. established a Takagi-Sugeno-Kang fuzzy model to represent nonlinear magnetic bearing and applied a nonlinear fuzzy logic control method to deal with the harmonic disturbances and parameter uncertainties [16].

Considerable nonlinear control methods have been conducted without accurate model, because the accurate model of nonlinear magnetic torque is difficult to describe. Sliding-mode control (SMC) method is widely used in control and state observation of uncertain dynamic systems, mainly due to its robust characteristics with respect to parameter uncertainties and external disturbances [17–22]. Yeh et al. proposed a SMC method to robust against the nonlinear, uncertain dynamics of magnetic bearing systems, and it was validated in a single input and single output system [18]. Liu et al. treated the time-varying nonlinearity and unknown disturbances as lumped disturbance, and designed a nonlinear observer to estimate the disturbance combining with a sliding-mode fuzzy neural network method [19]. Kang et al. applied a SMC method to reduce disturbance responses subject to base motion, and the feasibility of the proposed technique was verified with experimental results [20]. Lin et al. adopted integral sliding-mode control (ISMC) method to fully active controlled magnetic bearing system [21]. Furthermore, Chen et al. presented a robust nonsingular terminal sliding-mode control (NTSMC) method to adjust the rotor position in finite time, and proposed a recurrent Hermite neural network to eliminate lumped uncertainty, while only axial direction was considered in this work [22].

Most researches on AMB control only focus on rotor stable suspension, while amplifier saturation is unconsidered. In the situation of rapid shaft deflection, saturation would significantly affect the performances and therefore the saturation problem should be solved. Mazenc et al. studied low-bias stabilization of AMBs subject to voltage saturation and constructed a stabilizing controller [23]. Du et al. presented a robust Takagi-Sugeno-model-based fuzzy-control strategy to stabilize the AMB with fast response speed subject to control saturation [24]. Gerami et al. designed a nonlinear modeling and control method for AMBs with material saturation, while the coupled disturbance was not considered [25].

The performance of existing methods could be degraded under the amplifier saturated condition because the shaft is required to deflect in a very wide range of velocity. Furthermore, the coupled disturbance induced by magnetic coupling is complex when shaft deflects in wide range. Motivated by the above-mentioned factors, this work focuses on high precision tracking control of shaft deflection while considering the coupled disturbance and saturated amplifier. A novel structure augmenting the maximal deflection angle is introduced. Then a tracking dynamic model is established through analyzing the magnetic torque model and coupled disturbance, and the saturation problem is described. The conventional ISMC and NTSMC methods are applied to this system for comparisons. An improved NTSMC method is designed to tackle with amplifier saturation on the basis of the NTSMC method. The output of the designed controller is saturated, thus the proposed method maintains the control performance under the saturated and unsaturated condition.

The remainder of this paper is organized as follows. Section 2 describes the novel structure augmenting the maximal deflection angle, and the amplifier saturation is presented. In section 3, a conventional ISMC method and a NTSMC method are designed initially. Then, considering the saturated amplifier, an improved NTSMC method is derived on the basis of NTSMC method. In Section 4, several numerical simulations and discussions are provided to validate the proposed method. Section 5 concludes the work.

2. Problem formulation

In terms of the gyroscopic force theory, the MSMW maximum of gyroscopic torque is dominated by the maximal tolerant deflection velocity, and the maximal tolerant deflection angle determines the ability of angular momentum variation. Therefore, the maximal tolerant deflection angle and velocity are supposed to be enlarged. However, the electromagnetic interval is quite limited for most AMB system. To deal with this problem, a novel structure of the MSMW is designed to expand the maximal deflection angle, which is shown in Fig. 1 [26].

A free rotor has six motion degrees of freedom (DOFs) including three translation DOFs and three rotary DOFs. As shown in Fig. 1, the three translation DOFs are controlled by a reluctance force-type hybrid magnetic bearing (RFHMB) located at the center. The rotary DOF around the axis of rotor shaft is controlled by the motor, while the other two rotary DOFs are determined by a Lorentz force-type magnetic bearing (LFMB)