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Disturbance-observer based control for magnetically suspended wheel with synchronous noise[☆]

Yuanjin Yu[a], Zhaohua Yang[b,*], Chao Han[c], Hu Liu[b]

[a] School of Mechanical Engineering, University of Science and Technology Beijing, Beijing, 100083, China
[b] School of Instrumentation Science and Opto-electronics Engineering, Beihang University, Beijing, 100191, China
[c] School of Astronautics, Beihang University, Beijing, 100191, China

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ABSTRACT

A disturbance-observer based method is proposed to attenuate the synchronous vibration of a magnetically suspended wheel (MSW). When the rotary speed is nonzero, the synchronous vibration exists. To analyze this vibration, a precise dynamic of the MSW is researched and the synchronous vibrations model is established. A novel vibration attenuation method is proposed by combining a disturbance observer and a state-feedback method. Using Lyapunov's stability theorem, parameters of the controller are determined. Finally, results of numerical simulations and experiments indicate that the proposed method dramatically reduces the synchronous jitter and thus significantly improves precision of the deflection angle.

1. Introduction

A wheel is a common instrument that is widely used in industry and aerospace. For a spacecraft, the wheel is an efficient attitude actuator on the basis of momentum exchange. The actuator is called flywheel that includes reaction wheel and momentum wheel. A magnetically suspended wheel (MSW) is a flywheel suspended by magnetic bearings (MBs). There exist many advantages such as non-friction, slight vibration, and high precision. MSWs can meet the requirements of longevity, high precision, and high stability in spacecraft application (Tang & Chen, 2009; Tsiotras, Shen, & Hall, 2001).

A MSW is a complex hybrid system of rotor and MBs. By changing the angle momentum of MSW, the control torque for attitude control of spacecraft can be generated. Generally, MSW generates the torque in one degree of freedom (DOF) by changing the amplitude of angle momentum, called rotary torque. Because the rotor shaft can be actively deflected by MBs, MSW can generate the gyroscopic torques in two DOFs by changing the direction of angle momentum, called deflection torques (Hideyuki, Tatsuaki, & Keiken, 2000; Seddon & Pechev, 2009; Yu, Fang, Xiang, & Wang, 2014). Thus, one MSW has the capability of attitude control in three axes. Because the gap between the rotor and MBs is very small, precise position of the rotor is required to avoid contact between the rotor and MBs. Further more, MSWs require higher position precision to generate high precision deflection torques.

A MB control system is a complex system with nonlinearity and unmodeled dynamic. For a MB control system, cross feedback control is widely used since it not only can effectively solve the problem of instability caused by the gyroscopic effect but also is easy to implement with simple structure (Ahrens & Kucera, 1995; Liu, Fang, & Liu, 2010; Zhao, Zhang, Zhu, & Zhao, 2002). The fuzzy observer based method (Li, Gao, Shi, & Lam, 2015; Li, Wu, Yin, & Lam, 2015) and dynamic output-feedback method (Li, Wang, & Shi, 2015) are efficient for the nonlinear plant without precise model. The robust method (Balini, Scherer, & Witte, 2011; Sun, Zhao, & Gao, 2013) and sliding-mode method (Li, Wang, Lam, Zhou, & Du, 2016) are suited to deal with uncertainties and unmodeled disturbances. There are many disturbance sources such as the linearization error of the nonlinear magnetic force, the coupled magnetic force and the rotor imbalance. The disturbance caused by the rotor imbalance is a type of synchronous vibration whose frequency is equal to the rotary frequency. Limited to the manufacturing precision, rotor imbalance is always existed for the rotary machine. The reason causing dynamic imbalance can be considered to be the non-coincidence between the inertial axis and the geometric axis of rotor. Theoretically, no synchronous vibration exists if the coincidence between the inertial

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* Corresponding author.
E-mail address: yangzh@buaa.edu.cn (Z. Yang).

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axis and the geometric axis is guaranteed. However, because the rotary axis does not exactly coincide with the geometric axis of the rotor for the MSW, an additional synchronous vibration exists. Researchers have demonstrated that such synchronous vibration could be greatly alleviated by the magnetic bearing through active control (Knospe, Hope, Fedigan, & Williams, 1995). Knospe et al. tested the performances of three open loop control algorithms experimentally (Knospe et al., 1995). Ideally, the disturbance can be efficiently attenuated by the open loop controller with pre-scheduled bearing force. If the scheduled forces are accurate, nearly perfect alleviation can be realized. However, open loop methods rely on the accuracy of the pre-computed schedule, which imposes severe limitations on their application to rotor vibration. Closed loop methods are more feasible for most systems. The feed-forward control is a common method to alleviate the disturbance. Shi et al. designed a feed-forward method that injected a synchronous signal at the summing junction of the magnetic bearing feedback control loop and adjusted its amplitude and phase to minimize the vibration (Shi, Zmood, & Qin, 2004). Zheng et al designed a parallel-mode notch filter to achieve greater notch depth and faster convergence, while the phase-shift notch filter was used to maintain stability in a wide range of speeds (Zheng, Chen, & Ren, 2016). A multiple resonant controller is applied in a magnetic bearing system to suppress the current harmonic induced by mass imbalance and sensor runout disturbance (Peng, Sun, Song, & Fang, 2017). Jiang et al realized imbalance compensation according to the position of the rotor's imbalance mass, thereby avoiding recalculation with variation of the rotor speed (Jiang, Zhu, & Chen, 2015). Liu et al designed a sliding-mode observer based adaptive compensation method to improve the autobalance performance when considering the parameter perturbation of the magnetic bearing (Liu & Liu, 2016). The disturbance observer method is another widely used method to alleviate the disturbance. Chen et al. used a force observer to estimate the disturbance forces and combined it with a self-tuning fuzzy proportion-integration–differentiation control to deal with imbalanced vibration (Chen, Tung, Tsai, & Fan, 2009). Schuhmann et al. applied an extended Kalman filter and an optimal state feedback regulator to improve position accuracy, where the extended Kalman filter is used to estimate the unbalance-caused disturbance (Schuhmann, Hofmann, & Werner, 2012).

For the MSW with synchronous vibration, this paper proposes a disturbance observer based method for improving the accuracy of the deflection angle. The precise dynamic model of the deflection control system is established and the model of the synchronous vibration is obtained. Based on the model of the system and the disturbance, a composite disturbance observer based control (DOBC) method for the synchronous vibration is designed. Many numerical simulations and experiments are constructed to validate the effectiveness of this method. The results indicate that this method can realize higher tracking precision than the conventional cross feedback method. The paper is organized as follows. In Section 2, the main frames of the MSW used to describe the dynamic of the free rotor are introduced, and then the dynamic models of the MB control system and the synchronous vibration are analyzed and modeled. In Section 3, the disturbance observer and the state feedback control method are designed. And the stability of the observer and the closed-loop system are proofed by the Lyapunov stability theory. In Section 4, many simulations and discussions are performed to validate the effectiveness of the proposed method. In Section 5, the proposed method is applied to an engineering production of the MSW. Finally, the conclusions are drawn in Section 6.

2. System modeling

A MSW is an instrument with rotary rotor suspended by MB. The MB system of a MSW is shown in Fig. 1. This system is expected to suspend the rotor stably within narrow magnetic gap.

In the MB system of Fig. 1, translations and deflection angles are controlled variables. MBs are the actuators for rotor suspension.

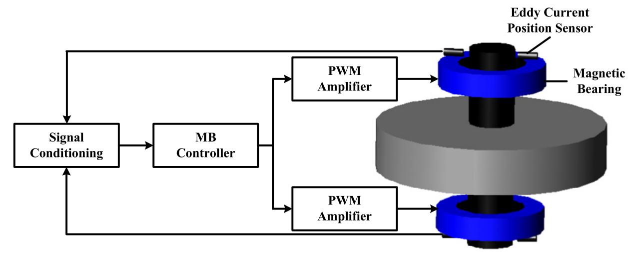

Fig. 1. MB system of a MSW.

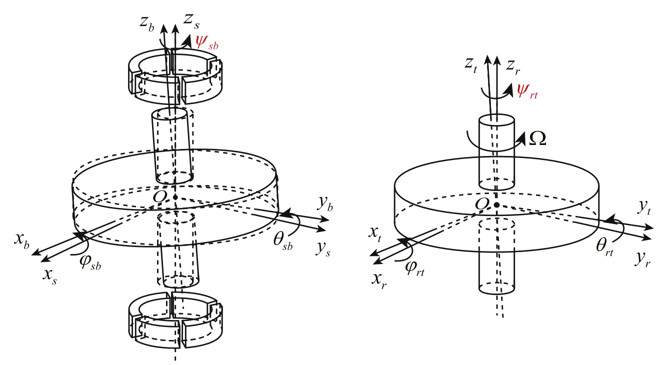

Fig. 2. Frames of MB system.

The eddy current position sensors measures the translations of the rotor shaft, and the measured signals are output to the MB controller after signal conditioning. The MB controller regulates rotor positions according to MBs driving by pulse-width modulation (PWM) amplifiers. The controlled plant model mainly includes dynamics of the free rotor and MB actuator. To model this system, five frames are defined initially.

2.1. Frame definition

The frames of the MB and rotor are shown in Fig. 2.

(1) Geometric coordinate of the MB is defined as $ox_sy_sz_s$(s for short). The origin is the midpoint of the line joining the center of the lower bearing and that of the upper one. The z_s-axis coincides with the center line of the stators of the two bearings, and both the x_s-axis and the y_s-axis are perpendicular to the z_s-axis.

(2) Body coordinate of the rotor is defined as $ox_by_bz_b$(b for short). The origin is the geometric center of the rotor. The z_b-axis lies along the symmetrical axis of the rotor shaft. The x_b-axis and the y_b-axis are perpendicular to the z_b-axis and located at the plane that parallels to the disk plane of the rotor. Coordinate b is fixed on the stator and does not rotate with the rotor. The three Euler angles between frame r and frame b are defined as φ_{sb}, θ_{sb} and ψ_{sb}, where φ_{sb} and θ_{sb} denotes the deflection angles about x_s-axis and y_s-axis respectively, ψ_{sb} equals to zero.

(3) Geometric coordinate of the rotor is defined as $ox_ry_rz_r$ (r for short). The origin is the geometric center of the rotor. The z_r-axis is coincident with z_b-axis. The x_r-axis and the y_r-axis are perpendicular to the z_r axis and located at the plane that parallel to the disk plane of the rotor. Coordinate r is fixed on the rotor and rotates with rotary speed Ω.

(4) inertial coordinate of the rotor is defined as $ox_ty_tz_t$ (t for short). The origin is the mass center of the rotor. The x_t, y_t and z_t axes are the three perpendicular principal axes of the rotor. The three Euler angles t and r are defined as φ_{rt}, θ_{rt} and ψ_{rt}, where ψ_{rt} equals to zero, φ_{rt} and θ_{rt} can be set as constants.

(5) inertial coordinate of the equator is defined as $ox_iy_iz_i$ (i for short). The origin coincides with the center of the earth, and the x_i-axis is