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Internal model control for reduction of bias and harmonic currents in hybrid magnetic bearing

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ABSTRACT

Bias and harmonic currents, which are caused by rotor gravity, mass imbalance and sensor runout, are the dominant disturbances of the hybrid magnetic bearing (HMB) systems. To reject these disturbances and realize the low power control, a novel internal model control method based on positive current feedback and repetitive control is proposed. The positive current feedback can tune the levitation position of the rotor adaptively so that the rotor gravity can be supported precisely by the force resulting from the permanent magnet in the HMB. To suppress the harmonic currents caused by the mass imbalance and sensor runout, a novel plug-in repetitive controller is proposed. Compared to the conventional repetitive controller, the low-pass filter is removed from the internal time lag loop outside so as to improve the system stability and reduce the elimination error of the high-order current harmonics. The absolute stability of the whole closed-loop system is analyzed by using the Nyquist criterion to the time-delay system with the help of the regeneration spectrum method. Upon the phase-frequency characteristic, phase compensators in low, middle, and high frequencies are designed, respectively. Both simulations and experiments are carried out to demonstrate the validity of the proposed control method.

1. Introduction

In recent years, flywheel energy storage equipment, which is effective in power smoothing, restoring and leveling [1,2], has been studied and used in many fields, such as uninterrupted power supply, wind generation system, and spacecraft energy storage [3,4]. The flywheel energy storage equipment is a device which stores the kinetic energy in a rotating rotor system [5]. The amount of the stored energy depends on the inertia and the speed of the rotor. To achieve a high energy storage density without changing the inertia of the rotor, a high rotational speed is required. Compared to the conventional mechanical bearings, magnetic bearings (MBs) provide several significant advantages, such as absence of lubricants, contactless operating condition, high rotational speed, and active control ability [6]. Therefore, the MBs have been widely used in the flywheels [7,8].

Bias and harmonic currents are caused by the rotor gravity, mass imbalance and sensor runout. The bias and harmonic currents are the main disturbances that can induce considerable power loss and housing vibration [9–11]. Active MB (AMB), which has a high stiffness [12], however, suffers from high power consumption. This is because additional coil current is essential to produce the bias flux, because elimination of the bias flux will lead to a nonlinear region [13]. To reduce the power consumption, the coil current should be attenuated [14]. However, a certain amount of coil current is inevitable

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due to steady load, such as the rotor gravity. A position-flux zero-bias control is proposed to reduce the power loss [15], but a flux sensor is usually needed for the feedback control. Recently, more attention is being paid to a type of permanent-magnet-bias hybrid MB (HMB). It uses the permanent magnet instead of coil current in the AMB to produce the biased flux. HMB is proved to save the power loss [16]. To reduce the bias current caused by the rotor gravity, the rotor displacement should be well controlled so that the force generated by only the permanent magnet of the HMB can support the rotor gravity precisely. No force is generated by the electromagnet, and the coil current is cleaned. Ren proposed a dynamic feedforward control strategy, which tunes the rotor displacement according to the force/displacement relationship and the disturbance (gyro effect) characteristic [17]. However, the control precision depends on the accuracy of the system model. Mizuno proposed a transfer function approach to regulate the rotor displacement [18]. It can be proved that the zero-power control can be realized with a feedback of the integral of the current. Compared to the feedforward control strategy, the feedback method is of structural stability.

Mass imbalance, which occurs if the rotor's geometry center of is not coincident with its mass center, is regarded as the primary source of the synchronous current [19]. Sensor runout is essentially the displacement sensor noise caused by the nonuniform properties around the sensing surface of the rotor. Besides synchronous current, sensor runout can generate higher multiple harmonic currents [11]. The suppression methods of the harmonic disturbances can be divided into two categories. The former one is separated reduction method of each frequency signal. It is similar to the single disturbance reduction method, which extends the single frequency method to multiple frequency disturbances. For example, compact wavelets [20], adaptive notch filter with frequency estimator [21], response matching with FIR filter [22], phase-shift notch filter [23] and resonant controller [24] are designed for eliminate single-frequency sinusoidal signal. To identify or to suppress multi-frequency harmonic currents, multiple controllers can be constructed in series or parallel connection. Apparently, the computation load will sharply increase in direct proportion to the number of the harmonics considered. Moreover, discrepancies occur in the convergence characteristics of the different frequency components. The latter category, such as the repetitive controller, can attenuate periodic harmonic disturbances simultaneously [25]. It is noted the magnetically suspended rotor system is open-loop unstable [26]. Therefore, a low-pass filter is usually designed to improve the system stability [27]. The conventional repetitive controller with a low-pass filter in the internal loop is used to suppress the harmonic currents [28]. However, the low-pass filter will induce phase lag and amplitude attenuation in the high-frequency region. Therefore, the reduction precision decreases gradually from the first harmonic to the higher harmonics.

To reduce the bias current due to the rotor gravity, a positive current feedback method is designed. It can tune the levitation position of the rotor so that the force generated by the permanent magnet of the HMB can support the rotor gravity precisely. Therefore, the bias current is well reduced. To improve the suppression accuracy of the high-order harmonic currents, a novel plug-in repetitive controller is proposed. The low-pass filter is removed from the internal loop outside so as to reduce the phase lag and amplitude attenuation in the high-frequency region. The parameter determination and the closed-loop stability analysis are performed with the regeneration spectrum method. Upon the phase-frequency characteristic, phase compensators in low, middle, and high frequencies are designed, respectively. Simulation and experiment results are given to verify the superiority of the proposed repetitive controller.

The paper is organized as follows. Section 2 presents the model of the HMB-supported flywheel system. Section 3 introduces the bias current elimination with a positive current feedback control scheme. In section 4, we describe the harmonic current suppression system with the repetitive control. Section 5 presents the phase compensator design of the repetitive controller. Section 6 provides simulations and experiments which prove the proposed control method. Finally, Section 7 closes this paper with some concluding remarks.

2. Modeling of the HMB-supported flywheel

The HMB-supported flywheel system, whose diagram is shown in Fig. 1, is composed of two pairs of stators, two pair of displacement sensors, an imbalanced rotor, controller and power amplifier. Either pair of displacement sensors or MB stators is composed of two devices fixed in differential form so that the common noise can be well reduced. O is the origin of the coordinate XY and also the center of the stators. O_G and O_M are the geometric center and the mass center of the rotor, respectively. Ω is the rotational speed. F_g is the rotor gravity. The angle between F_g and the X, Y directions are both 135°, because the MB stators in the X and Y directions can support the rotor gravity evenly.

The displacements of O_G and O_M are defined as $r_G = (x_G, y_G)$ and $r_M = (x_M, y_M)$, respectively. Then the mass imbalance Δr can be expressed as [23]:

$$\Delta r = (\Delta x, \Delta y) = r_M - r_G = (\varepsilon\cos(\Omega t + \chi), \varepsilon\sin(\Omega t + \chi)) \tag{1}$$

where ε is the distance between O_G and O_M, χ is the initial phase.

The rotor has two degrees of freedom along the X and Y axes, respectively. The dynamics of the rotor along the two axes are uncoupled and similar except for a steady phase shift of 90°. Therefore, only the motion in the X axis is considered. The dynamics along the X axis can be written as [24,29]

$$m\ddot{x}_M = f_x + \mathrm{F\_g}\cos(135^\circ) \tag{2}$$