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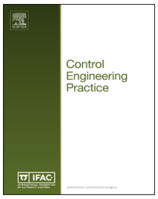

Sensor runout compensation in active magnetic bearings via an integral adaptive observer

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ABSTRACT

Sensor runout is one of the main sources of harmonic disturbances in active magnetic bearing systems. This type of the disturbance not only causes harmonic vibrations in the system but also changes the steady-state position of the axis of rotation from the geometric center of the AMB. In this paper, an integral adaptive observer is proposed to identify the dc and harmonic content of the sensor runout and to estimate the states of the system at the same time. The Lyapunov method is used to prove asymptotic stability of the proposed observer. Unlike the proportional observer which amplifies the measurement error, the sensor runout can be completely compensated when the states of the integral adaptive observer are used for feedback stabilization. It is shown that the proposed technique can also attenuate rotor displacements, when both sensor runout and mass unbalance disturbances are applied to the system. Simulation results have been presented for both cases to demonstrate the performance of the integral adaptive observer. Experimental results are also obtained by an AMB test rig, which confirm the effectiveness of the proposed method.

1. Introduction

Active magnetic bearing (AMB) is a special kind of bearing which uses electromagnetic forces to levitate the rotor in rotating machinery. Exclusive features of this type of bearing such as lack of physical contact, no need for lubrication and withstanding harsh temperature conditions have made AMBs appropriate for use in applications such as high speed turbo machinery (Schweitzer & Maslen, 2009). Moreover, harmonic disturbance rejection and active vibration control of flexible rotors (Okada, Shimizu, & Ueno, 2001) are the major advantages of AMBs which are absent in other types of bearings.

In common AMBs, eddy current proximity sensors are used to measure position of the rotor for closed-loop stabilization. The electromagnetic coil of these sensors is excited by a high frequency alternating current which induces eddy currents in the conductive target. Eccentricity of the rotor surface or inhomogeneity in its material (Atashkhooei, Urresty, Royo, Riba, & Romeral, 2014) causes harmonic disturbances in output signal of the sensor which is called sensor runout. Sensor runout was first addressed by Sacks, Bodson, and Messner (1995) in disk data storage systems and is one of the main sources of periodic disturbances in AMB systems (Setiawan, Mukherjee, & Maslen, 2001). This type of disturbance contains harmonics with synchronous rotational frequency of the rotor and its integer multiples. When this noisy output signal is fed into the controller, a periodic control input is generated which induces harmonic current and displacements in the system and changes the steady-state position of the axis of rotation from the geometric center of the AMB. Therefore, it can be concluded that sensor runout could also cause misalignment which itself is another important source of harmonic disturbances in rotating machinery.

Regardless of the sensor runout, mass unbalance is the major source of harmonic disturbances in AMB systems. Mass unbalance is generated when the principal axis of inertia and the geometric axis of the rotor are not coincident, which causes harmonic disturbances with synchronous rotational frequency of the rotor (Betschon & Knospe, 2001). It is difficult to identify or compensate the disturbance, when both mass unbalance and sensor runout are applied to the system. There are some methods to eliminate the source of these disturbances, such as balancing or fine surface finishing of the rotor. But these procedures cannot perfectly remove the disturbance. In this regard, some approaches have been proposed to precisely control the position of the rotor by identifying the disturbance. However, most researches conducted in this area have been focused on unbalance disturbance and there are few investigations which cover both unbalance and sensor runout.

Generally, one of the most attractive features of AMBs is their

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ability to actively control the harmonic vibrations caused by unbalance. However, AMBs may bring additional harmonic disturbances to the system themselves. This happens when the runout disturbance deteriorates the measured signal. The runout generates currents at synchronous and multiple frequencies of the rotational speed even in high speed machines. Harmonic currents produce noise and reaction forces in foundation and power loss in coils, which are not desirable, especially in high frequencies. Recent studies performed by researchers show that when an adaptive algorithm is specifically designed to compensate only the unbalance, it can be inefficient in the presence of both unbalance and runout (Fang, Xu, & Xie, 2015). Therefore, it is necessary to compensate both unbalance and runout in high precision AMB systems.

Kim and Lee (1997) used the influence coefficient method to estimate and reject the sensor runout. In this method, the system transfer function and runout coefficients are estimated by several trial measurements under a given operating condition of the AMB system. Kanemitsu, Kijimoto, Matsuda, and Park (2000) utilized the least-square estimation technique to identify the disturbances due to sensor runout and mass unbalance. To attenuate the harmonic disturbances by AMB, the approach of most researchers is to estimate the disturbance by an identification method and compensate it in a feedforward scheme (Bi, Wu, Jiang, & Liu, 2005; Shi, Zmood, & Qin, 2004). However, reduction in stability and performance of the closed-loop system is a known problem in adaptive feedforward methods. To overcome this deficiency, Na and Park (1997) suggested an adaptive feedforward algorithm for rejection of periodic disturbances which does not alter characteristics of the original closed-loop system. Setiawan et al. (2001, 2002) also proposed the adaptive bias excitation method to compensate the unbalance and runout, simultaneously. They used the Lyapunov theorem to prove the stability and robustness of their method. Recently, Xu, Fang, Liu, and Zhang (2015) utilized a simple dead time compensator to suppress the unbalance and runout in the AMB system.

The problem of sensor fault identification has always been a concern of researchers in the field of fault-tolerant control systems (Kiltz, Mboup, & Rudolph, 2012; Rahme & Meskin, 2015; Xie & Alleyne, 2014). In the present study, the problem of sensor runout rejection by an integral adaptive observer has been investigated. An integral observer is an extended version of the well known Luenberger observer that has been specifically used to estimate the measurement output disturbance, as well as states of the system (Busawon & Kabore, 2001; Gao & Ho, 2004; Khedher, Benothman, Maquin, & Benrejeb, 2009; Koenig & Mammar, 2002; Saif, 1993; Zhang, Li, & Schmidt, 2013). Since the amplification of the measurement noise is unavoidable in high-gain proportional observers (Suzuki, Ito, & Kobayashi, 2008; Xiong & Saif, 2003), there is need to have a state estimator which is robust against output disturbances. In this regard, integral observers are successfully applied to identify constant (Saif, 1993) and slowly time-varying (Gao & Ho, 2004; Khedher et al., 2009) sensor faults and to guarantee the robustness against the measurement noise (Busawon & Kabore, 2001). However, there is no observer with the capability of harmonic sensor fault identification in previous studies.

This paper will give an account of a new integral adaptive observer which can be used to identify and compensate the periodic disturbances due to sensor runout in AMB systems. Stability of the proposed observer is proved via the Lyapunov theorem. It is shown that the estimation error will be bounded even if the unbalance disturbance is also applied to the system. The proposed method is implemented on a three-pole AMB test rig. Simulation and experimental results indicate that contrary to the proportional observer which amplifies the runout, the integral adaptive observer can effectively attenuate the periodic disturbances due to both runout and unbalance.

2. System description and model dynamics

2.1. Active magnetic bearing

Since the performance of the presented technique for sensor runout rejection is validated by a three-pole AMB test rig, first a brief formulation of the three-pole AMB dynamics is given. It is noteworthy that this method is applicable in conventional eight-pole AMBs as well. As depicted in Fig. 1, a three-pole AMB with minimum number of power amplifiers is considered in this study (Chen & Hsu, 2002). This configuration consists of three poles, which are located circumferentially at 120° to each other. The current through the upper coils is the same, while a different current passes through the lower coil.

It is assumed that the effects of eddy current losses, magnetic reluctance of the iron core and flux leakage are negligible. Hence, they are not included in the dynamics of the model. The magnetic force of each pole is proportional to the square of the magnetic flux in the gap between the pole face and the rotor. Therefore, the resultant applied force to the rotor in the x- and y-directions can be obtained as follows (Darbandi, Behzad, Salarieh, & Mehdigholi, 2014):

$$\begin{aligned} f_x &= \frac{\sqrt{3}}{4\mu_0 A}\left(\varphi_3^2 - \varphi_2^2\right) \\ f_y &= \frac{1}{4\mu_0 A}\left(\varphi_3^2 + \varphi_2^2 - 2\varphi_1^2\right) \end{aligned} \tag{1}$$

where φ_j is the magnetic flux of pole j, A is the pole face area, and $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H\,m^{-1}}$ is the permeability of free space. The major weakness of the three-pole AMB is the magnetic flux coupling between the poles, which results in highly nonlinear electromagnetic forces in the x- and y-directions. To eliminate this problem, a bias is added only to the upper coils and the variables $\bar{i}_1$ and $\bar{i}_2$ are introduced as

$$i_1 = \bar{i}_1, \quad i_2 = i_b + \bar{i}_2 \tag{2}$$

where i_b is the bias current. Expanding (1) by Taylor series expansion, one can obtain the nearly linear and decoupled forces as (Darbandi et al., 2014)

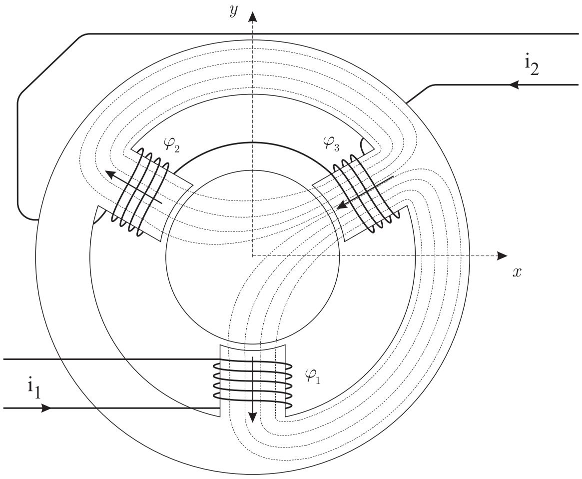

Fig. 1. The three-pole AMB.