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Unbalance vibration suppression for AMBs system using adaptive notch filter

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ABSTRACT

The unbalance of rotor levitated by active magnetic bearings (AMBs) will cause synchronous vibration which greatly degrade the performance at high speeds in the rotating machinery. To suppress the unbalance vibration without angular velocity information, a novel modified adaptive notch filter (ANF) with phase shift in the AMBs system is presented in this study. Firstly, a 4-degree-of-freedom (DOF) radial unbalanced AMB rotor system is described and analyzed, and the solution of rotor vibration displacement is compared with the experimental data to verify the preciseness of the dynamic model. Then the principle and structure of the proposed notch filter used for the frequency estimation and online identification of synchronous component are presented. As well, the convergence property of the algorithm is investigated. In addition, the stability analysis of the closed-loop AMB system with the proposed ANF is conducted. Simulation and experiments on an AMB driveline system demonstrate the effectiveness and the adaptive characteristics of the proposed ANF on the elimination of synchronous controlled current in a widely operating speed range.

1. Introduction

In recent years, active magnetic bearings (AMBs) are being applied widely in the rotating machinery owing to several significant advantages, such as no lubricant, no friction losses, the ability of long-term operation at high speeds, and the possibility to adjust bearing stiffness and damping characteristics [1]. In particular the contactless makes them receive considerable attention for high-speed rotating machinery [2–4].

Despite the advantages, vibrations caused by the unbalance which occurs if the geometric axis of the rotor is not coincident with its inertial axis are a primary common problem in active magnetic bearing applications at high speeds. The vibration force is in proportion to the square of the rotor speed which may lead to the magnetic actuator saturation at high speeds even if the unbalance is relatively small. Although the unbalance of rotor can be reduced by off-line balancing, a certain amount of unbalance still exist due to the working conditions changed and the limited correction accuracy [5]. When the rotor is spinning rapidly, the unbalance vibration forces will transfer to the chassis and produce unwanted vibration. Therefore the synchronous vibration force suppression should be achieved by control method.

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It is possible to provide an unbalance compensation control to minimize the rotor orbit or minimize the vibration force with the controllability of magnetic bearing [6]. In the former strategy which aims at keeping the rotor rotating around its geometric axis would generate a force transmitted to the chassis and also easily lead to a saturation of amplifier circuit [7]. Obviously, this strategy is not suitable for the operation at high speeds. The latter one, which keeps the rotor rotating around the inertial axis, could significantly reduce the unbalance force, and would avoid a saturation of amplifier circuit [8]. Many researchers have paid much attention to this approach.

Matsumura et al. used a state-space approach to reject the disturbances and keep the rotor rotating around its axis of inertia [9]. As mentioned in [10], a typical current nulling technique plus a proportional feedback from displacement to current was given to achieve complete removal of unbalance vibration. However, the effect would decrease at high speeds because of the low-pass characteristic of amplifier. To compensate the power amplifiers, Zheng used a feedforward controller based on the inverse model of first-order power amplifier in place of the proportional coefficient to solve the problem of high-speed rotor unbalance [11]. A gain phase modifier (GPM) to achieve suppression of the unbalance force and torque was proposed in [12]. The GPM can adaptively tune the gain and phase of the closed-loop system to compensate the low-pass characteristic of amplifier. Recently, an adaptive compensation method that can form two closed-loop systems to tune the synchronous amplitude of the feedforward controller and the phase of the plural notch filter was proposed to fulfill the automatic balancing of the AMB system [13].

In many practical application of the AMB system, the unbalance vibration suppression strategies have been reported to only reduce the synchronous current. It is because the control methods are much simpler, and the fluctuating force related to the displacement negative stiffness can be ignored, especially at high rotating speeds. The insertion of a generalized narrow-band notch filter into the control loop without destabilizing the system stability depending on the T matrix to eliminate the undesirable synchronous current was proposed by Herzog [14]. The Fourier coefficients of rotor unbalance disturbance was implemented real-time identification by injecting a control signal into the system [15]. Least mean square (LMS) adaptive filter algorithm and adaptive variable step-size least mean square algorithm are used to achieve current nulling in active magnetic bearing control systems [16,17]. Zheng proposed a novel notch filter using coordinate transformation based on the unique characteristics of two radial synchronous displacement signals in the x-axis and y-axis to eliminate the synchronous controlled current [18].

However, the above-stated methods require the unbalance frequency of spinning rotor by angular velocity sensor. There are several constraints to the angular velocity sensor in many applications including installation difficulty of mechanics, low reliability, and limited size of the machine. Therefore, it is desirable to estimate the unknown angular velocity information of unbalance vibration signals. An angular position differentiation method to achieve unbalance compensation on AMB system without a rotational sensor was proposed in [19]. It is an open-loop algorithm and susceptible to noise pollution. An adaptive frequency tracking method by difference equation has been proposed to achieve unbalance vibration suppression on the magnetic bearing system [20]. However, the effect of the recursive control method is closely related to the initial value of the algorithm. Due to the displacement signal measured by the eddy current sensors in each channel is a sinusoidal signal. Estimating frequency of a sinusoid is of great interest in the field of signal processing. The methods including adaptive observer structures [21], frequency-locked loop [22], marginal-median discrete Fourier transform [23], and neural network theory [24], have been applied. The adaptive notch filter (ANF) in Eq. (1) has become a common technique to extract sinusoids from a measurable signal [25]. Several modified ANFs that directly extract a single unknown sinusoidal signal have been devised to offer a high degree of insensitivity to power system disturbances in [26,27].

$$\begin{cases} \ddot{x} + 2\zeta\theta\dot{x} + \theta^2 x = 2\zeta\theta^2 y(t) \\ \dot{\theta} = -\gamma x(\theta^2 y(t) - \theta\dot{x}) \end{cases} \tag{1}$$

In this paper, the unbalanced AMB rotor model is described at first. Then the principle and structure of the proposed ANF used for the frequency estimation and online identification of synchronous component are presented. As well, the convergence property of the algorithm is investigated. In addition, the stability analysis of the closed-loop AMB system with the proposed ANF is conducted. Elimination of synchronous controlled current can be achieved in a widely operating speed range.

2. Dynamics model of the unbalanced AMB rotor

A description of the rotor system suspended by AMB with unbalance is shown in Fig. 1. The maximum rotating speed is less than 0.7 times of the first order bending mode frequency, so the paper considers only the rigid modes of the shaft. The AMB-rotor system is composed of AMB stators, displacement sensors, stabilizing controller, power amplifier and an imbalanced rotor.

Equations of motion are given as follows [28]: