# Runout Compensation in Active Magnetic Bearings with Iterative Learning Control Scheme

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***Abstract*--Active magnetic bearing is a promising candidate for next generation spindle motors of hard disk drives. In this paper, an Iterative Learning Control scheme is proposed to suppress the rotor poison runout induced by the unbalanced forces in AMB. The ILC controller can produce the synchronous compensation force by iteratively "learning" rotor runout information. This compensation force makes the rotor rotate about its geometric axis.**

***Index terms*—active magnetic bearings, spindle motors.**

## I. Introduction

MANY potential bearing solutions are considered to replace ball bearing and fluid dynamic bearing to reduce vibrations and non-repeatable runout (NRRO) of spindle motors, which limit data recording density of hard disk drives (HDD). The contact-free suspension by active magnetic bearing (AMB) is one of them [1]. Fig. 1 shows an AMB spindle motor prototype. Unbalance effect, resulting from the misalignment of rotor's geometric axis, inertial axis, and axis of electromagnetic (EM) field, brings difficulties to read/write process and vibrations in HDD. The unbalance problem in the AMB could be solved by control scheme. The paper proposes a new control method based on time-domain iterative learning control (ILC). The ILC controller generates synchronous compensation current to suppress unbalance effect in AMB. Experimental results show the significant improvement in rotor position control with the proposed ILC scheme.

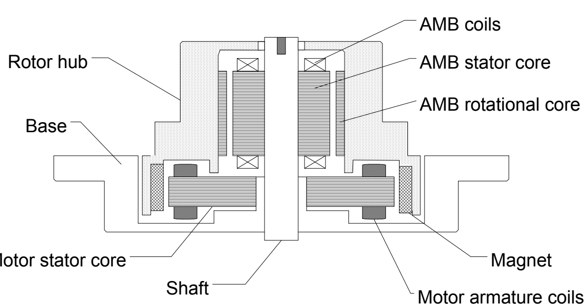


Fig.1. A prototype of AMB spindle motor for HDD.

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## II. AMB System

The principle of position control in AMB can be explained with Fig. 2, where every two opposite electromagnets control the rotor positioning in one Degree-of-Freedom (DOF). Currents in these two opposite electromagnet coils are respectively $i_1 = i_0 + i_c$, $i_2 = i_0 - i_c$, where $i_0$ is bias current and $i_c$ is position control current. The linearized EM force in this DOF is

$$f_m = K_i \cdot i_c + K_s \cdot s \tag{1}$$

where $K_i$ is force-current factor, $K_s$ is force-displacement factor, and $s$ is rotor displacement in this DOF. Thus, rotor position can be controlled through control current $i_c$, which is generated by the controller.

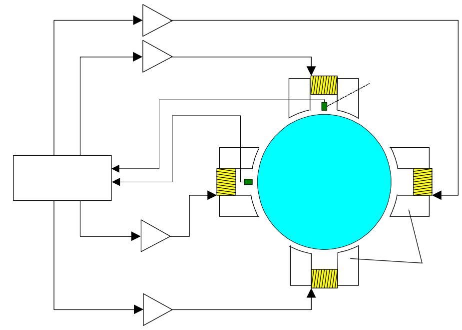

Fig.2. The structure of a 2-DOF radial magnetic bearing system.

## III. Iterative Learning Control Scheme

The basic idea of ILC is to improve the control performance of the present cycle by incorporating past control information in instant control input [3]. A time-domain iterative learning law can be described by

$$u_{j+1}(t) = u_j(t) + \Phi \cdot e_j(t+1), \quad t \in 0,1,2,...,t_f - 1 \tag{2}$$

where $u(t)$ is the system input, $j$ is iteration number, $u_{j+1}(t)$ is the new input for the next cycle, $t_f$ is the number of time steps in one cycle, the scalar $\Phi$ is learning gain, position error signal $e_j(t) = -y_i(t+1)$, $y_j(t)$ is the rotor position signal.

Suppose a discrete closed-loop AMB system looks like

$$\begin{aligned} \mathbf{x}(k+1) &= \mathbf{A}\mathbf{x}(k) + \mathbf{B}u(k) \\ y(k) &= \mathbf{C}\mathbf{x}(k) \end{aligned}, \tag{3}$$

then according to the convergence criterion [3], if the learning gain in (2) satisfies $|1-\mathbf{C}\cdot\mathbf{B}\Phi|<1$, for all $t \in [0, t_f - 1]$,

$$\lim_{j\to\infty} e_j(t) = 0 . \tag{4}$$

Actually, a suitable value of the learning gain can be easily obtained by on-line tuning besides the system model method.

A forgetting factor $\alpha$ is applied to the learning process to increase ILC controller robustness against noises and other

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perturbations. A negative effect of forgetting factor is that it will weaken control convergence, making final error not converge to zero [4]. Therefore, $\alpha$ should be kept small provided that controller robustness is adequate. The learning law becomes

$$u_{j+1}(t) = (1 - \alpha)u_j(t) + \Phi \cdot e_j(t+1) \quad (5)$$

The ILC controller provides only compensation current for rotor balancing. A PID feedback controller, which has been designed for optimum transient response, is responsible for stabilizing the AMB system. The whole control scheme is shown in Fig. 3.

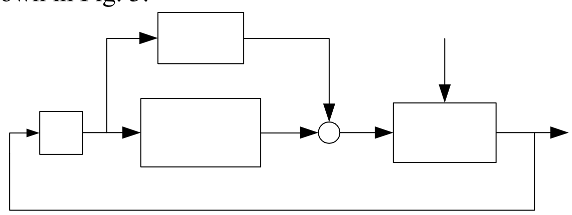

Fig.3. Time-domain ILC scheme for AMB unbalance compensation.

## IV. Experimental Results

An AMB prototype system is used to test the effectiveness of time-domain ILC scheme. A dSPACE DS1103 controller board is used to perform real-time digital control. The rotation speed is 3000rpm. A low-pass filter is used to attenuate noises in position signals. The two parameters of time-domain ILC controller are $\Phi = 6\times10^{-4}$A/μm and $\alpha$=0.005.

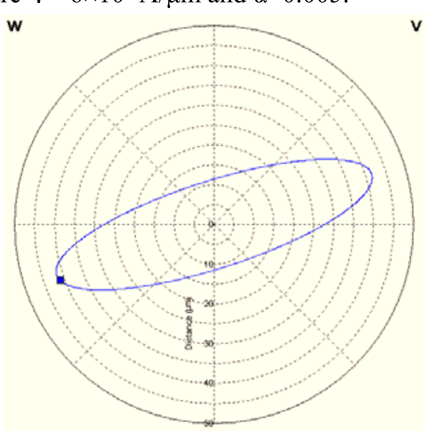


Fig.4. Rotor position obit without ILC.

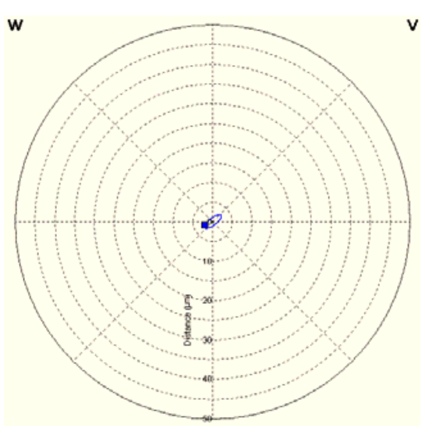


Fig. 5. Rotor position obit with ILC.

Fig. 4 and 5 show the position orbits of one radial plane without and with proposed ILC scheme respectively. In Fig. 4, the maximum runout is 42μm. With the effective control of ILC scheme, maximum runout is reduced to 2.5μm, as shown in Fig. 5. Fig. 6 shows the rotor position waveforms in one DOF. In comparison with the position waveform without compensation, the position waveform is almost flat with the proposed time-domain ILC scheme. The synchronous component, which is caused by synchronous unbalance force, contributes to most portions in the position runout. With the ILC scheme, the synchronous component, the one at 50Hz, is reduced to a very small value. Thus, the overall runout value decreases substantially. The unbalance force is compensated and the precise positioning in AMB system is realized.

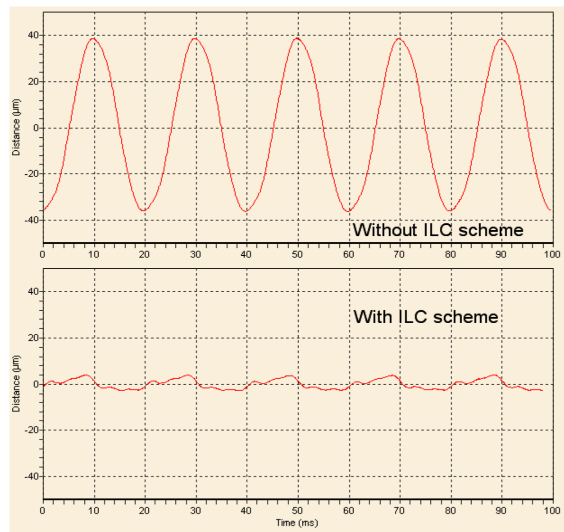


Fig.6. Rotor position runouts without and with ILC scheme.

## V. Conclusions

In this paper, a time-domain iterative learning control scheme is proposed to accomplish the unbalance force compensation in AMB systems. Rotor position waveforms and obits of the AMB are presented in this paper to show the effectiveness of the ILC method. Experimental results prove that, the proposed ILC scheme is effective in reducing the rotor position runout of the AMB system. All these show that the role of AMB is not neglectable in the HDD spindle motors in future.

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