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REPEATABLE RUNOUT FOLLOWING IN BIT PATTERNED MEDIA RECORDING

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ABSTRACT

An adaptive feedforward controller design for tracking repeatable runout (RRO) in bit patterned media recording (BMPR) is proposed for single stage hard disk drives (HDD). The technique is based on modified filtered-x least mean squares (MFX-LMS) algorithm with deterministic periodic input, and a novel variable step size that boosts both the convergence rate and the steady state error. Comprehensive simulations and comparisons are provided to show the effectiveness of the proposed method.

1 INTRODUCTION

In conventional HDDs that have continuous media, data is written on concentric circular tracks, while in bit patterned media (BPM), data should be written on tracks with predetermined shapes, which are created by lithography on the disk. As shown in Fig. 1 the trajectories that are required to be followed by the servo system in BPR are servo tracks, which are characterized by the servo sectors written on the disk. Deviation of a servo track from an ideal circular shape is called RRO. Therefore, the servo controller in BPR has to follow the RRO which is unknown in the time of design, and as a result the servo control methodologies used for conventional drives [1, 2] cannot be applied to BPMR directly.

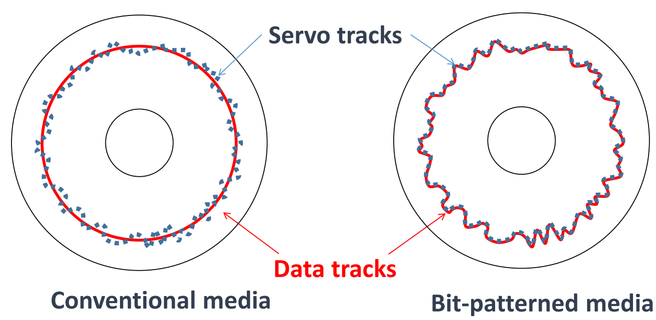

FIGURE 1: Servo Track (dotted blue) and data track (solid red) in conventional and bit-patterned media

BPMR has some specific challenges in terms of servo control design which are briefly listed here.

1. RRO profile is unknown.
2. RRO frequency spectrum can spread beyond the bandwidth of the servo system; therefore, it will be amplified by the feedback controller.
3. RRO spectrum contains many harmonics of the spindle frequency (e.g. ~ 200 harmonics) that should be attenuated,

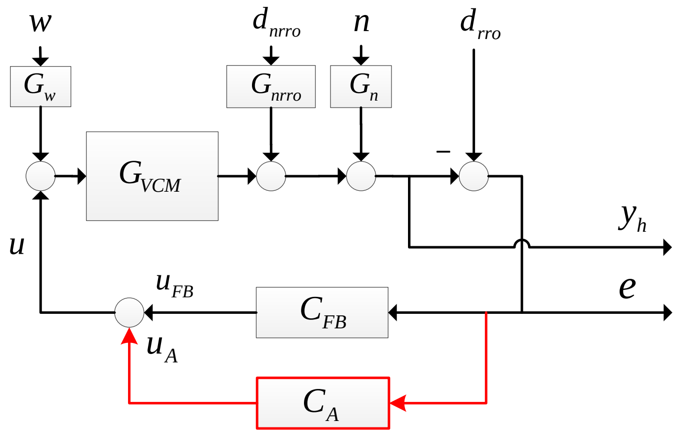

FIGURE 2: Control architecture.

and this raises computational load in the controller.

4. RRO profile is changing from track to track (i.e. it is varying on radial direction).

Section 2 presents our control algorithm and section 3 shows the results of numerical simulations in MATLAB.

2 Control Design

The architecture that is considered for the servo control system is shown in Fig. 2. Here, G_{VCM} is the voice coil motor (VCM) model, and C_{FB} is the built in track following controller of the servo system. This controller is designed to attenuate the non-repeatable runout (NRRO) that is injected through G_{nrro}, measurement noise (injected through G_n) ,and windage (injected through G_w). The adaptive controller, C_A, is added in a *"Plug-in"* fashion to attenuate the repeatable runout, denoted as d_{rro}. We aim to design C_A, such that the error signal e is minimized in terms of H_2 norm.

2.1 Control Algorithm

The control algorithm is presented in table 1. Here, $u_{A,k}$ and e_k denote the adaptive feedforward control actuation and the position error signal (PES) at time step k respectively. The initial time is $k=1$ and if there is no prior knowledge about the variables, they are initiated from zero. R denotes the nominal transfer function from adaptive control injection point to the PES, modeled as an infinite impulse response (IIR) filter, and $R[x]$ denotes the output of R when the input is sequence x. We assume that the RRO spectrum only contains components at the fundamental (spindle) frequency and its harmonics. In other words, the disturbance d_{rro} is a linear combination of lagged sinusoids running at the multiples of spindle frequency. Hence, the reference signal (i.e. ϕ_k) in the adaptation algorithm is

$$\phi_k^T := [\alpha_1 sin(\omega_1 k), \cdots, \alpha_n sin(\omega_n k), \alpha_1 cos(\omega_1 k), \cdots, \alpha_n cos(\omega_n k)]$$

where ω_i's denote the spindle harmonics that should be followed in frequency domain. In order to increase the convergence rate of high-frequency harmonics, we scale the sinusoids by α_i's, which are proportional to the inverse of VCM gain at the associated ω_i's.

1. Apply the feedforward control, $u_{A,k}$, to VCM.
2. Subtract $\tilde{e}_k$ from PES to determine the auxiliary error $\bar{e}_k$
$$\bar{e}_k = e_k - \tilde{e}_k$$
3. Use the algorithm in Table 2 to calculate the step size, μ_k
4. Update the parameters
$$\hat{\theta}_{k+1} = \hat{\theta}_k + \mu_k R[\phi_k]\,\bar{e}_k$$
5. Calculate the feedforward control for the next step
$$u_{A,k+1} = \phi_{K+1}^T \hat{\theta}_{k+1}$$
6. Calculate and update $\tilde{e}_{k+1}$
$$\tilde{e}_{k+1} = R\left[u_{A,k+1}\right] - \left(R\left[\phi_{k+1}\right]\right)^T \hat{\theta}_{k+1}$$

TABLE 1: Adaptive control algorithm

2.2 Adaptation Step Size

In this subsection, we propose a new adaptive step size for the parameters update equation. Since the system is contaminated with noises, the real parameters cannot be calculated perfectly, and the estimated parameters are always fluctuating around the real values. The variation of estimated parameters produces *excess error* that can be very large compared to the output (PES). Our key idea is that as the estimated parameters get closer to the real ones, the step size becomes smaller and the parameters will be frozen in time when a certain desired performance (in terms of 3σ-value of PES) is attained. This removes the excess error from the output and results in smaller steady state errors. It is also required that the step size becomes positive (i.e. adaptation starts again) whenever the error becomes large (e.g. the head seeks to another track with a different RRO). These characteristics can be formalized by various possible equations. We propose the method given in Table 2 for such a step size, since this formulation satisfies all the aforementioned conditions and it is very easy to compute.

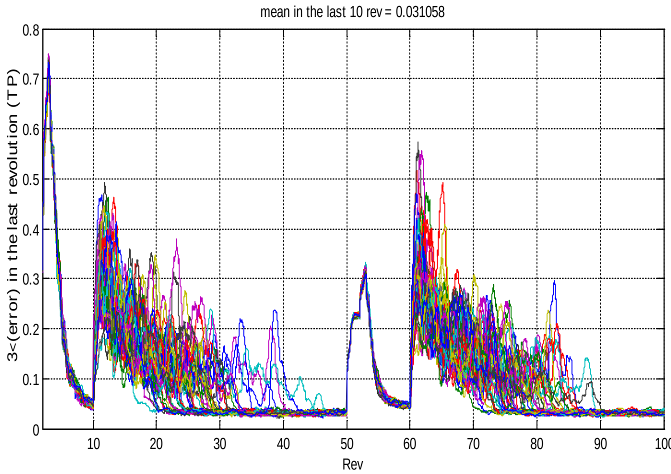

FIGURE 3: 3σ of the disk on different track for the plant with 10 % uncertainty.

$$
\begin{array}{l}
1.\ V_k^h = V_{k-1}^h + \frac{1}{h}\bar{e}_k^2 - \frac{1}{h}\bar{e}_{k-h+1}^2 \\
2.\ \bar{\mu}_k = \rho(V_k^h - V^d) \\
3.\ \mu_k = \begin{cases} min(\bar{\mu}_k, \mu_{max}) & \text{if} \bar{\mu}_k \geq 0 \\ 0 & \text{if} \bar{\mu}_k \leq 0 \end{cases}
\end{array}
$$

TABLE 2: Parameter update algorithm and step size adaptation

In Table 2, ρ is a scalar gain, V^d is the desired PES variance, and V_k^h is an approximated variance of auxiliary error. μ_{max} denotes the maximum step size to guarantee the convergence of the second moment of error, and it should be less than $1/\left(3tr\left(R[\phi_k]R[\phi_k]^T\right)\right)$ for all values of k.

3 Simulation Results

The simulations are based on the data collected from a 2.5-inch drive provided by HGST, a Western Digital company. In this simulation, G_w , G_n, and G_{nrro} are modeled based on the power spectral density of real PES. G_{VCM} and C_{FB} are modeled based on the frequency responses provided by our industry partners.

5% uncertainty is added to the nominal values of VCM resonance frequencies to create 50 uncertain plant dynamics. Performance of the proposed method is tested on each individual plant model and the results are presented here. Performance of the system is quantified in terms of 3σ value of PES. In this particular simulation we aim to learn and follow almost all the multiples of fundamental frequency up to the Nyquist frequency(the first 190 harmonics out of 200). Fig. 3 shows approximated 3σ value of PES calculated by averaging on root mean square (RMS) of PES in one revolution, and Fig. 4 shows the Fourier transformation of

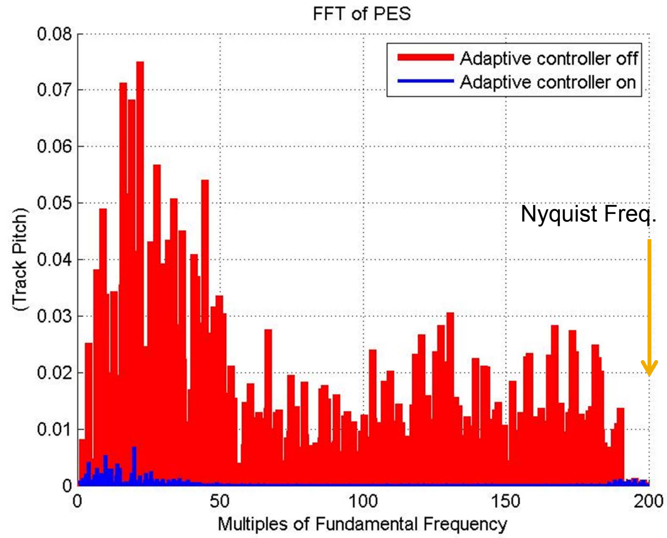

FIGURE 4: 3σ of the disk on different track for the plant with 10 % uncertainty.

the steady state PES. Different colors on the figure correspond to the performance of different uncertain plant models simulated for 100 revolutions of the disk. In the first 50 revolutions the head is moving on MD and so the controller is trying to follow RRO on MD. As can be seen from the figure, all the plants has reached steady state performance by 50 revolutions. RRO profile is changed to OD RRO after revolution 50. In both cases in order to decrease the transient error, the adaptation for harmonics $1-80$ starts first and for harmonics $81-190$ starts after 10 revolutions. The 3σ value of error is approximately 3% of track pitch in all cases (both tracks and all of the plants). This result is impressive if we compare it to the baseline (perfect RRO following) which is 2.8% of track pitch.

Acknowledgment

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