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Multi-rate Observer Based Sliding Mode Control with Frequency Shaping for Vibration Suppression Beyond Nyquist Frequency ⋆

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Abstract: Nyquist frequency limits the frequency range of the continuous-time signals that can be reconstructed through the sampled discrete-time signals. In hard disk drives (HDDs), there exist resonance modes near and beyond the Nyquist frequency in the voice coil motor (VCM). Such resonance modes, if excited, may generate vibration beyond the Nyquist frequency which would seriously degrade the servo performance. To capture such vibration, a multi-rate extended observer is designed based on the nominal dynamic model of the excitation process. This observer estimates both the states and the vibration at a fast rate based on the sampled position error signal (PES) at a slow rate. The estimated states are utilized to design a sliding mode control algorithm at the fast rate with frequency shaping to suppress vibration beyond the Nyquist frequency. Meanwhile, the estimated vibration are incorporated in the control signal to further compensate the actual vibration. Simulation results demonstrate the benefits of the proposed algorithm: large off-track behaviors of the VCM are mostly detected and the vibration beyond the Nyquist frequency are suppressed.

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Keywords: Multi-rate estimation, Kalman filter, Frequency shaping, Nyquist frequency, Sliding mode control

1. INTRODUCTION

In hard disk drives (HDDs), the sampling frequency of the position error signal (PES) is strictly limited by the number of the servo sectors which cannot be increased arbitrarily. Meanwhile, one or more resonances beyond the Nyquist frequency exist in the voice coil motors (VCM) of HDDs and may generate the vibration which cannot be directly captured by the sampled position error signal (PES). Such 'unobservable' vibration may seriously degrade the servo performance, and even wipe data and damage the disks. Therefore, it is of fundamental importance to quickly reconstruct and suppress such high-frequency head motions.

Multi-rate control is a promising technique to estimate high-frequency behaviors of PES, enable fast updating of the control signal and reduce possible vibration excitations (Tomizuka, 2004). Many multi-rate control algorithms have been proposed and developed for HDDs in the past decades. For example, Hara and Tomizuka (1998) modified the traditional zero-order-hold estimator and estimated the inter-sample PES based on the open-loop plant model. The inter-sample PES estimation was further improved by a stochastic optimal estimator (Hara and Tomizuka, 1999) and an optimal $H\infty$ estimator based on the sample-data system theory (Hirata et al., 2003). Ohno and Horowitz (2003, 2005) proposed new multi-rate nonlinear state estimators for the track-seeking control in HDDs. Most of these research focuses on smoothening the control signal and improving the servo performance below the Nyquist frequency.

As mentioned, vibration beyond the Nyquist frequency may exist and cause off-track behaviors which cannot be fully detected by sampled PES. Therefore, it is important and challenging to enhance the servo performance of HDDs beyond the Nyquist frequency. Weaver and Ehrlich (1995) applied multi-rate notch filters to reduce the gain of the system beyond the Nyquist frequency for the stability purpose. Atsumi et al. (Atsumi et al., 2006, 2008; Atsumi, 2010) derived the sensitivity function in the sampled-data HDD control systems and designed stable resonant filters. These frequency domain algorithms were able to decrease the gain of the sensitivity function beyond the Nyquist frequency.

This paper proposes an alternative approach to enhance the servo performance beyond the Nyquist frequency. Considering that the vibration beyond the Nyquist frequency is usually generated through the excitation of the resonances in HDDs, it is reasonable to assume a known nominal dynamics of the vibration (Atsumi and Messner, 2012). Motived by extended state observer (Gao et al., 1995; Zheng et al., 2016) and Kalman filter (Simon, 2006), this paper proposes a multi-rate extended observer to estimate the inter-sample behaviors of PES and high-frequency vibration by incorporating the vibration dynamics. The estimated vibration is incorporated into the control signal to compensate the actual vibration; meanwhile, a frequency-shaped sliding mode control (FSSMC) algorithm is proposed to further suppress vibration beyond the Nyquist frequency.

The remainder of the paper is organized as follows. Section 2 describes the problem caused by the vibration beyond the Nyquist frequency. Section 3 proposes a multi-rate extended observer to estimate the inter-sample behaviors of both the

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PES and the vibration. Section 4 designs a sliding mode control algorithm with frequency shaping beyond the Nyquist frequency. Section 5 validates the effectiveness of the proposed algorithms by simulations. Section 6 concludes the paper.

2. PROBLEM DESCRIPTION

During the track-following process of HDDs, the read/write head is expected to stay on the reference track with small PES. This process is subjected to vibration both below and beyond the Nyquist frequency. Most of the external vibration is below the Nyquist frequency, and many feedforward and feedback algorithms are available for the vibration suppression. The vibration beyond the Nyquist frequency, however, is mainly caused by the excitation of resonances and difficult to suppress.

Figure 1 shows the frequency response of a practical HDD model (IEEJ, 2007) with one resonance beyond the Nyquist frequency. This resonance, if excited, would cause vibration beyond the Nyquist frequency. Such vibration, as illustrated by Figure 2, may cause large off-track behaviors of the heads which cannot be captured through the sampled PES. Therefore, in the presence of such vibration, a good estimate for the inter-sample behaviors of PES is fundamental to enable fast updating of the control signal and suppress the vibration beyond the Nyquist frequency.

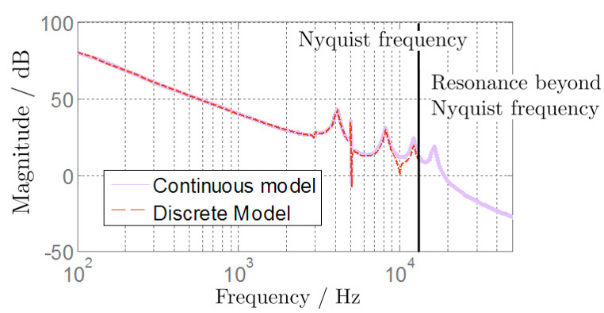

Fig. 1. Frequency Response of a HDD model (IEEJ, 2007)

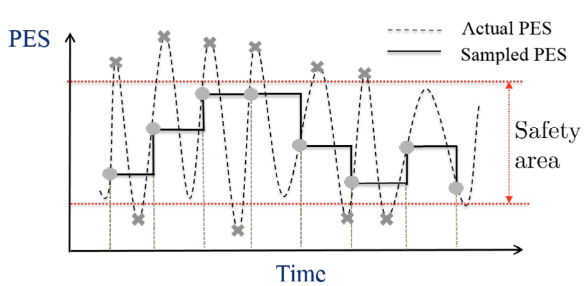

Fig. 2. PES with Components beyond Nyquist Frequency

With the vibration beyond the Nyquist frequency, the HDD control system becomes a multi-rate system with fast vibration injection and slow PES measurement:

$$x_p[(i+1)T_f] = A_p x_p[iT_f] + B_p(u[iT_f] + d[iT_f]) \quad (1a)$$
$$y[jT_s] = C_p x_p[jT_s] + v[jT_s] \quad (1b)$$

where x_p is the state variable; u is the control signal; y is the measured PES; d is the vibration; v is the measurement noise; T_f is the control signal updating rate and T_s is the PES sampling rate; $T_s = NT_f$ where $N \geq 2$ is an integer. A_p, B_p and C_p are the plant matrices with compatible dimensions. The Nyquist frequency is $1/(2T_s)$. To make the notations more clear, rewrite Equation (1) as

$$x_p(i+1) = A_p x_p(i) + B_p u(i) + B_p d(i) \qquad (i = 1,2,3,..) \quad (2a)$$
$$y(j) = C_p x_p(j) + v(j) \qquad (j = N, 2N...) \quad (2b)$$

The control goal is (1) to estimate x_p and d at the fast rate (T_f) based on the measured PES at the slow rate (T_s), and (2) to suppress d (which contains the components beyond the Nyquist frequency) through the control signal u which is updated at the fast rate (T_f).

3. MULTI-RATE EXTENDED OBSERVER

To estimate the inter-sample behaviors of PES and the vibration, this section proposes a multi-rate extended observer by incorporating the nominal dynamics of the vibration. This observer is designed based on the techniques of extended state observer (ESO) and Kalman filter. ESO allows estimation for both the states and the disturbances by treating the disturbances as state variables (Han, 2009; Zheng et al., 2016). Rewrite the system dynamics of Equation (2) as follows:

$$\begin{bmatrix} x_p(i+1) \\ d(i+1) \end{bmatrix} = \begin{bmatrix} A_p & B_p \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x_p(i) \\ d(i) \end{bmatrix} + \begin{bmatrix} B_p \\ 0 \end{bmatrix} u(i) + \begin{bmatrix} 0 \\ 1 \end{bmatrix} w(i)$$
$$y(j) = [C_p \;\; 0] \begin{bmatrix} x_p(j) \\ d(j) \end{bmatrix} + v(j) \quad (3)$$

where $w(i) = d(i+1) - d(i)$. ESO is essentially a state observer for the augmented system in Equation (3). If $w(i)$ is deterministic but unknown, a high-gain state observer can be designed. If $w(i)$ is process noise, Kalman filter can be designed. In both ways, ESO implies an assumption of the disturbance dynamics as follows

$$d(i+1) = d(i) + w(i) \quad (4)$$

That is, d is assumed to be a constant disturbance plus some uncertainties w. This explains why ESO works well for slowly time-varying / low-frequency disturbances.

Motivated by the assumption of Equation (4) made by the standard ESO theory, more complex vibration dynamics can be introduced for high-frequency (beyond the Nyquist frequency) vibration estimation. Such high frequency vibration dynamics includes resonances of HDD beyond the Nyquist frequency of the PES sampling. In HDDs, the nominal vibration dynamics is usually available and can be utilized to estimate the inter-sample behaviors of PES. Assume d is generated through certain dynamics which is driven by broadband noise w, i.e.,

$$x_d(i+1) = A_d x_d(i) + B_d w(i)$$
$$d(i) = C_d x_d(i) \quad (5)$$

Combining Equation (2) and Equation (5), the augmented system becomes

$$\begin{bmatrix} x_p(i+1) \\ x_d(i+1) \end{bmatrix} = \begin{bmatrix} A_p & B_p C_d \\ 0 & A_d \end{bmatrix} \begin{bmatrix} x_p(i) \\ x_d(i) \end{bmatrix} + \begin{bmatrix} B_p \\ 0 \end{bmatrix} u(i) + \begin{bmatrix} 0 \\ B_d \end{bmatrix} w(i)$$
$$y(j) = [C_p \;\; 0] \begin{bmatrix} x_p(j) \\ x_d(j) \end{bmatrix} + v(j)$$
$$d(i) = C_d x_d(i) \quad (6)$$

which is further written in a compact format

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