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Integral sliding mode control with a disturbance observer for next-generation servo track writing

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ABSTRACT

In this paper, we propose a new control scheme that provides position and velocity profile tracking control for next-generation servo track writing (STW). Whereas conventional servo track writers require controllers that perform fast positioning control with fast track seeking and regulation, spiral servo track writers require accurate position and velocity profile tracking control to achieve high quality servo patterns on the media disk. Because STW timing eventually renders geometrically accurate servo patterns, both position and velocity error signals should be regulated within small bounds in a constant velocity region. Regulation via an integral sliding mode controller (SMC) is known to provide good tracking performance; however, use of a high switching gain is inappropriate for an actuator with resonance modes. In this paper, we therefore apply integral sliding mode control with a disturbance observer to STW. The relationship between eigenvalues and control gains is mathematically analyzed to improve dynamic tracking response. To verify the utility of the proposed position and velocity profile tracking control, we perform a comparative study between the proposed and conventional control methods and experimentally validate the performance of the proposed method.

1. Introduction

Servo track writing (STW) is becoming an important process in the drive industry [1,2]. STW is the most time-consuming process in disk drive manufacturing. Most conventional technologies require unacceptably long STW time and have become obsolete. New STW technologies, such as spiral writing, have been introduced to provide fast (semi-self) STW. Those new STW technologies require new control methods that are very different from those in conventional STW control. Whereas conventional servo track writers require controllers that perform a fast positioning control with fast track seeking and regulation, some new servo track writers require accurate position and velocity profile tracking control to provide high-quality servo patterns on the media disk. With these new technologies, STW timing eventually produces geometrically accurate servo patterns. Unlike conventional hard disk drives (HDDs) where point-to-point seeking performance is critical, STW using spiral servo patterning requires a different type of settling performance [2,3]. For advanced STW using spiral servo patterning, a fast settling time to a constant-velocity is an important specification to increase disk drive productivity. In a constant-velocity region, both the position error signal (PES) and the velocity error signal (VES) should be well-controlled within small bounds such that they are well controlled, even before the head reaches the constant-velocity region.

In the disk drive industry, comprehensive compensation schemes for structure resonances and unknown disturbances can now guarantee the seeking and settling performance [4–13]. A previous study performed a survey of control issues in HDDs [4]. A disturbance observer using the fractional order method in the frequency domain has been successfully applied to vibration suppression [5–7]. A loop-shaping methodology for robust control design and multi-rate resonance filtering beyond the Nyquist frequency has been proposed to suppress structured and unstructured uncertainties [8,9]. A feedback control scheme to adaptively enhance the servo performance at multiple unknown frequencies has been proposed in [10]. In addition, sliding mode control (SMC) has been successfully applied to the disk drive industry by introducing a discontinuous switching action [11–13]. SMC is an effective way to improve the settling performance within an invariant manifold using a linear combination of integrated PES, PES and VES, and it achieves robust performance against disturbances. However, because the discontinuous switching action performed to cancel the disturbances can excite the structure resonances, the control

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systems can become unstable in high disturbance cases. To remedy that problem, a notch filter can be used with SMC unless it severely distorts the control signal. However, the chattering problem remains an important issue for the discontinuous switching action because the notch filter reduces the phase margin of the system and distorts the control signal. To solve those problems, an integral SMC (I-SMC) was introduced to force the states to achieve an integral sliding surface, and drives the states to the desired equilibrium point in the presence of disturbance [14]. However, no study has reported a method to avoid overshoot and oscillation in the PES and VES with I-SMC. To enhance the transient response, sliding-mode disturbance observers (SDOBs) have been developed [15–19]. An SDOB yields a nonzero steady-state error against time-varying disturbances in the form of a parabolic function or sinusoidal signals. However, an STW controller must guarantee uniform PES and VES performances without steady-state errors in the presence of disturbance.

In this paper, we propose a new control scheme: position and velocity profile-tracking control for next-generation STW. The proposed control scheme is implemented using the I-SMC with disturbance observer (DOB) to estimate disturbance. Regulation via I-SMC is used for the proposed control scheme [20]. Because the chattering phenomenon due to the discontinuous switching action to cancel model uncertainty is inevitable, we use an add-on type DOB to estimate the disturbance caused by the model uncertainties including bias force by the flex cable, and viscous damping [22,23]. As reported in [22], the DOB with PID control improves the transient performance. Therefore, we applied the DOB to I-SMC to get improved the transient response. In the general SMC law, it is important that closed-loop eigenvalues be optimally designed to reach the sliding manifold in a finite-time without oscillation. To regulate both PES and VES, we proposed a controller design method to construct the eigenspace of the sliding manifold and select control gains using an eigenspace analysis. Therefore, in the design guideline of SMC, we chose the SMC gains through the eigenspace analysis, as in [24]. We performed a comparative study between the proposed method and the conventional control method using a PID controller in the feedback loop and the feedforward control. The results show that the proposed control scheme reduces the settling time to the constant-velocity region and further improves regulation of PES and VES in the constant velocity region. In addition, we observed less oscillation in the control input during the acceleration and deceleration periods compared to that in the conventional method. Therefore, the resonance modes of the actuator are less excited with the proposed method than with the conventional method. We thus experimentally validated the performance of the proposed method via comparisons with the conventional method. The experimental set-up was composed of a voice-coil motor (VCM) type rotary positioner used for STW, a sinusoidal optical encoder, a trans-conductance servo amplifier, and a digital signal processing board for motion control.

This paper is organized into five sections. Section 2 describes the STW modeling and provides the problem statement for the compensator design. In Section 3, we explain the I-SMC design with the add-on type DOB. Section 4 presents the experimental implementation and its results. Conclusions follow in Section 5.

2. Modeling and problem description

2.1. Modeling

In this section, we present the dynamic model of an actuator used for spiral STW, as depicted in Fig. 1. In the STW process, a VCM type rotary positioner is used with a push-pin to move the HDD actuator on which a head-stack assembly is mounted. A sinusoidal optical encoder is mounted inside the positioner. The controlled variables are the position and velocity of the head. A trans-conductance power amplifier drives the rotary actuator of the positioner. It is common in the HDD industry for the driving current u and the head position y to be considered the actuator input and output, respectively. In that case, a simple nominal dynamic model of a VCM actuator can be represented as a second-order rigid body in state-space as follows [1–3]:

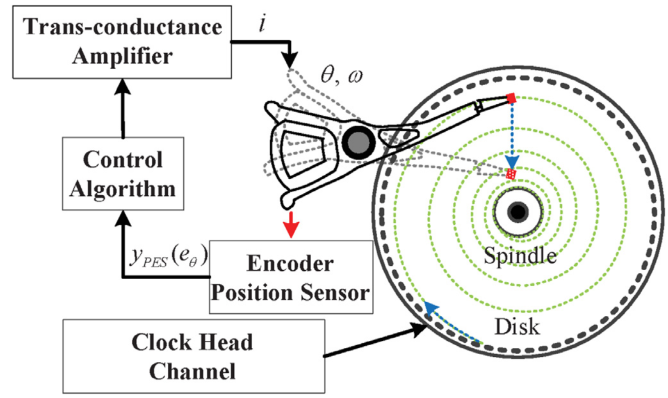

Fig. 1. Illustration of spiral servo track writing.

$$\begin{bmatrix}\dot{\theta}\\ \dot{\omega}\end{bmatrix} = \underbrace{\begin{bmatrix}0 & 1\\ 0 & 0\end{bmatrix}}_{A}\begin{bmatrix}\theta\\ \omega\end{bmatrix} + \underbrace{\begin{bmatrix}0\\ \frac{K_aK_t}{J_m}\end{bmatrix}}_{B}u$$

$$y = \underbrace{\begin{bmatrix}1 & 0\end{bmatrix}}_{C}\begin{bmatrix}\theta\\ \omega\end{bmatrix} \quad (1)$$

where θ and ω are the position and velocity of the actuator, respectively. K_a is the gain including a servo amplifier gain, the arm length of the head, and the interpolator gain of the sinusoidal encoder and A/D and D/A converters. K_t and J_m are the torque constant and the moment of inertia of the actuator mass, respectively. If $U(s)$ and $Y(s)$ are the Laplace transforms of $u(t)$ and $y(t)$, respectively, then the transfer function of the simple nominal dynamic model, $P_{no}(s)$ from the actuator input, $U(s)$ to the actuator output, $Y(s)$ is represented by

$$P_{no}(s) =: \frac{Y(s)}{U(s)} = C(sI - A)^{-1}B = \frac{K_aK_t}{J_m s^2}. \quad (2)$$

Then a model with resonance modes can be represented by

$$P(s) = P_{no}(s) + P_r(s)$$

and

$$P_r(s) = \frac{K_aK_t}{J_m}\sum_{i=1}^{N}\frac{\alpha_i}{s^2 + 2\zeta_i\omega_i s + \omega_i^2}$$

where α_i, ζ_i, ω_i are parameters of resonance models. Numerical value of each parameter is listed in Table 1. And N is the number of resonance modes considered for modeling.

The conventional control design approach uses the frequency response of the actuator as illustrated in Fig. 2. The experimental model represents the experimentally measured frequency response using a dynamic signal analyzer program. The simulation model is a curve fitting model obtained by using a system identification toolbox in MATLAB/Simulink with $N = 11$. The nominal model is the response for the second-order rigid-body model (2). To suppress the resonance modes at high frequency in the track-following mode of HDDs, it is common to use gain stabilization with notch filters or phase stabilization [3,25]. In the seeking mode, various approaches have been proposed, such as finite state control and