

A Precise Track-following Control using a Single-stage Tracking Mechanism for Magneto-optical Disk Drives

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1. Introduction

The authors have developed a low-cost, high-performance *magneto-optical disk drive* whose track-following control was achieved using a novel *single-stage tracking mechanism*. Conventionally, the track following has been performed using the *dual-stage tracking mechanism*, which consists of a coarse positioner driven by a voice coil motor (VCM) and a fine lens actuator loaded on the positioner. The positioner and the actuator are simultaneously driven in the radial direction of the disk while following the track. The lens actuator is driven also in the direction of the optical axis of the lens for focusing control. Such a two-dimensional lens actuator has a complicated mechanism and increases the number of mechanical parts as shown in Fig.1 (a).

In the newly developed *single-stage tracking mechanism* shown in Fig.1 (b), the track following is performed only by a VCM-driven positioner, and the lens actuator only performs the focusing control. And slide bearings are employed for positioner suspension replacing ball bearings. Thus, the mechanism is drastically simplified and the cost is reduced. Moreover a shorter seek time is achievable because the simplified positioner has a smaller mass.

However, the Coulomb friction caused by the slide bearings of the positioner is a critical problem for achieving precise track following. In this paper, we propose a novel track-following control system with a learning controller which suppresses the influence of Coulomb friction and achieves precise track following.

2. An ideal VCM current signal to compensate for Coulomb friction disturbance

Fig.2 shows the Coulomb friction characteristic. The disturbance caused by the Coulomb friction is difficult to compensate for, because the Coulomb friction force rapidly changes its direction when the direction of the

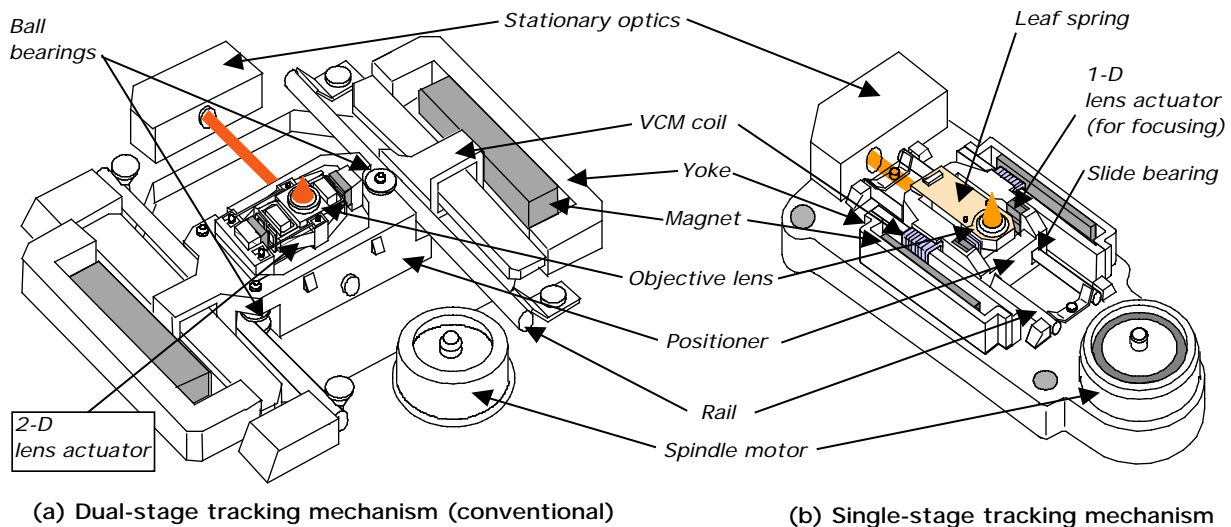


Fig.1 Dual- and single-stage tracking mechanisms

positioner motion changes. In the other words, the friction disturbance includes high frequency components.

Fig.3 shows the relation, during track following under the influence of Coulomb friction, among the waveforms of the (a) positioner's acceleration to follow a sinusoidal track runout, (b) change of the friction disturbance, and (c) required VCM drive current. Waveforms for three disk rotations are displayed. The VCM current shown in (c) includes not only a signal to generate the positioner's acceleration shown in (a), but also a

step signal to cancel the friction disturbance shown in (b). Therefore this VCM current can achieve precise track following by compensating for the friction disturbance perfectly, and we call it an *ideal VCM current* in this paper. For the conventional feedback controller, it is impossible to generate this kind of current waveform including such steep changes because of the limitation of the control bandwidth. Since it is hard to increase the bandwidth because of the limitation of the positioner's mechanical resonance, large and steep tracking errors occur.

In order to solve this problem, we developed a learning controller, which generates and feeds an approximated signal of the *ideal VCM current* forward for precise tracking. As in **Fig.3**, the *ideal VCM current* is a kind of repetitive signal that almost has a time-invariant signal pattern synchronized to the rotation of the disk, and therefore, the controller can *learn* this signal.

(In **Fig.3**; Disk rotational frequency: 75 Hz (i.e. rotational period: 13.33 ms), radial runout of the track: 80 $\mu\text{m-p}$, friction coefficient μ of slide bearing: 0.4 (for simplicity, the same coefficient is used for both static and kinetic friction), positioner's mass: 2.7 g, and positioner's acceleration coefficient: 99.5 $\text{m/s}^2/\text{A}$, are assumed.)

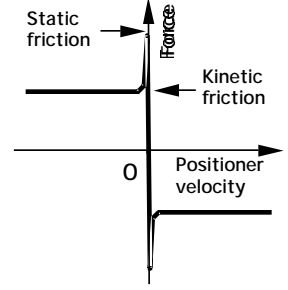


Fig.2 Coulomb friction

3. Track-following controller with *ideal VCM current learning*

3.1 Structure of the track-following controller

Fig.4 shows the structure of the proposed track-following controller. I is the VCM current to drive the positioner. X , X_{RO} , and e denote the positioner's position, the target track's runout, and the tracking error (TE) respectively. The learning controller takes the output signal of the feedback controller I_{FB} as its input, and generates an approximated function I_{FF} of the *ideal VCM current*. The I_{FF} is added to I_{FB} as a feed-forward compensation signal.

3.2 Feedback controller

The feedback controller is implemented with an ordinary PID-like controller that consists of a series connection of a PI regulator, a 2nd-order phase-lead compensator, and a notch filter $G_{notch}(s)$ to eliminate the influence of mechanical resonance of the positioner existing from around 15 to 25 kHz.

$$G_{FB}(s) = \frac{I_{FB}}{e} = K_p \left(1 + \frac{K_i}{s}\right) \frac{(1+T_{Z1}s)(1+T_{Z2}s)}{(1+T_{P1}s)(1+T_{P2}s)} G_{notch}(s) \quad (1)$$

Fig.5 shows the open loop frequency characteristics of the feedback control system. The actual controller was implemented on a fixed-point DSP. The sampling rate was 55 kHz. A control bandwidth of 2.1 kHz was achieved with a gain margin of 7 dB and a phase margin of 34 degrees.

3.3 Learning controller

Fig.6 shows the principle of the unknown function approximation. The bold solid line indicates an unknown *ideal VCM current* $I_{ideal}(t)$ to suppress the repetitive disturbance synchronized to the disk rotation. Time t in **Fig.6** and the following eqs. (2) to (4) is the time synchronized to the disk rotation, and is reset to zero at a

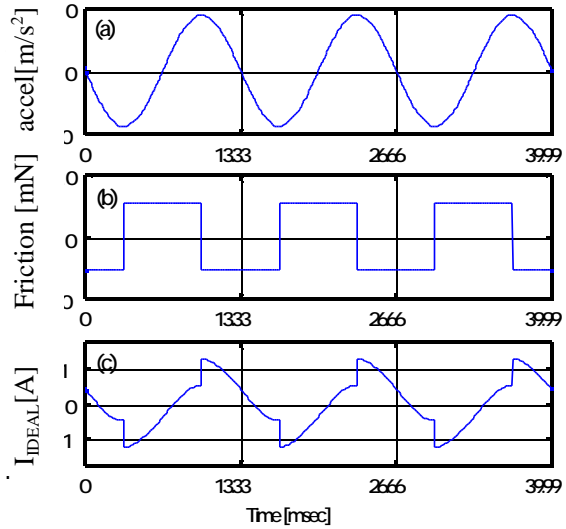


Fig.3 Ideal VCM current for precise tracking

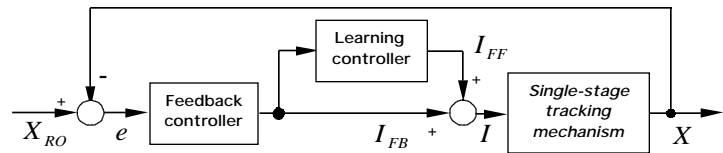


Fig.4 Track-following controller structure

certain time in every rotation period (i.e. $0 \leq t < T_L$, T_L : period of disk rotation).

Now we try to get an approximated function $\hat{I}_{ideal}(t)$ using a set of the heights of N rectangular functions, indexed from 0 to $N - 1$.

$$\hat{I}_{ideal}(t) = \hat{c}_i, \quad \text{--} \quad \text{--} \quad \text{--} \quad (2)$$

where $i = \text{floor}(t/T)$, and T is the time width of each rectangular function (i.e. $T = T_L / N$, and $0 \leq i < N - 1$). $\text{floor}(x)$ is a function that rounds x to the nearest integer less than or equal to x .

The height \hat{c}_i for each rectangular function is updated in real-time by a simple learning algorithm using the output of the feedback controller $I_{FB}(t)$ as the learning input.

$$\hat{c}_i = \begin{cases} k I_{FB}(t) & \text{if } iT \leq t < (i+1)T \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

Where, k is a constant learning gain. This learning algorithm changes the height of each rectangular function in the direction that $I_{FB}(t)$ approaches toward zero.

Finally the learning controller outputs the feed-forward signal $I_{FF}(t)$ as follows.

$$I_{FF}(t) = \begin{cases} \hat{I}_{ideal}(t + t_{lead}) & \text{if } 0 \leq t < (T_L - t_{lead}) \\ \hat{I}_{ideal}(t + t_{lead} - T_L) & \text{if } (T_L - t_{lead}) \leq t < T_L \end{cases} \quad (4)$$

Δt_{lead} is a constant time lead factor for stabilizing the learning convergence.

4. Learning simulation

Fig.7 followed by Fig.8 shows the simulation result. A sinusoidal runout of $80 \mu\text{m-p}$ at 75 Hz and a Coulomb friction of $\mu = 0.4$ were applied as disturbance. The characteristic of the feedback control system was set equivalent to that of Fig.5. For reference, the ideal VCM current, which was calculated using the applied disturbance in the simulation, is indicated with gray lines in these figures. The learning law eq.(3) was started at 0 ms, and the feed-forward output by eq.(4) was started at 13.33 ms. Therefore during the first disk rotation until 13.33 ms, the positioner was driven by the feedback current I_{FB} only, and large tracking error (TE) e peaks occurred, when the friction direction changed. The TE caused by the sinusoidal runout was also conspicuous. After the second rotation, the TE was gradually reduced toward zero, as the learning progressed through one disk rotation after another. As shown in Fig.8, the learning output I_{FF} was precisely converging to the ideal VCM current and the TE became almost zero within 174 ms from the start of learning.

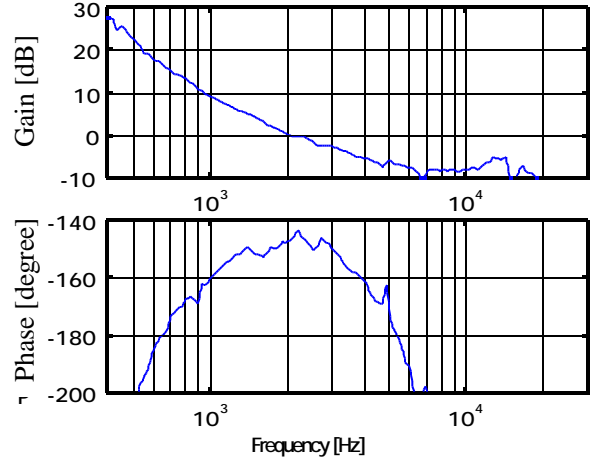


Fig.5 Open-loop characteristics of the system

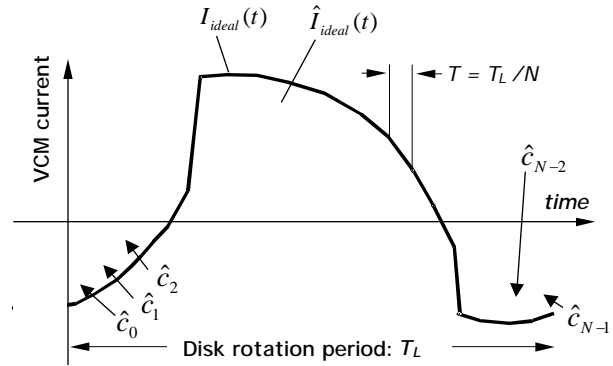


Fig.6 Reconstruction of unknown ideal VCM current

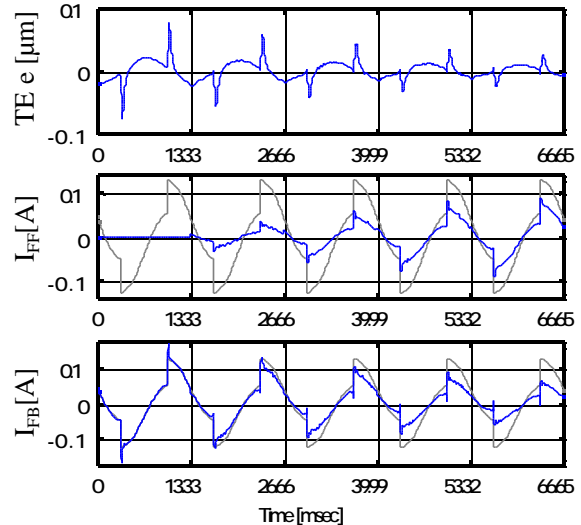


Fig.7 Learning simulation - at the beginning -

(Learning-related parameters in this simulation were set as follows; $N = 128$, $T_L = 13.33$ ms, $T = 104$ μ s, $\Delta t_{lead} = 109$ μ s, and $k = 1852$ /s.)

5. Experimental results

We also checked the efficiency of the proposed control system on a prototype drive using the *single-stage tracking mechanism* as shown in Fig.1 (b). A 640MB MO disk having a track pitch of 1.1 μ m and an actual radial track runout of 77 μ mp-p, and rotating at 75 Hz was used. Fig.9 shows the experimental results. The TE had large peaks before learning and was drastically reduced after learning. Since the learning gain was reduced because of a noise problem, time required for learning convergence was about 640 ms, longer than in the case of simulation. Fig.10 shows the learning result I_{FF} recorded simultaneously with the TE data in Fig.9 (b). It is obvious that the steep change caused by Coulomb friction is acquired by learning. We can estimate the friction coefficient μ at about 0.3 from this figure.

(Learning-related parameters in this experiment were set as follows; $N = 91$, $T_L = 13.33$ ms, $T = 146$ μ s, $\Delta t_{lead} = 109$ μ s, and $k = 336$ /s.)

6. Conclusion

We proposed a track-following controller with an *ideal VCM current learning controller* for achieving precise track following even under the Coulomb friction disturbance of the *single-stage tracking mechanism*.

The effect of the proposed controller was verified both by simulation and experiment.

The tracking error less than about 0.02 μ m was confirmed under the Coulomb friction disturbance of $\mu = 0.3$ using a MO disk rotating at 75 Hz with a radial track runout of 77 μ mp-p. Also, a fast learning convergence of less than 640 ms was obtained.

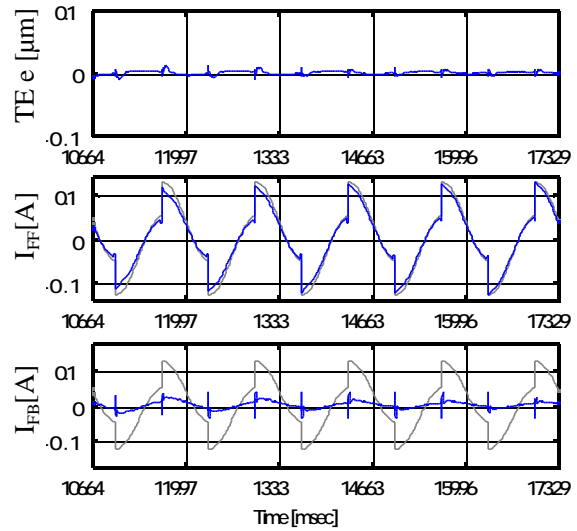


Fig.8 Learning simulation - almost converging -

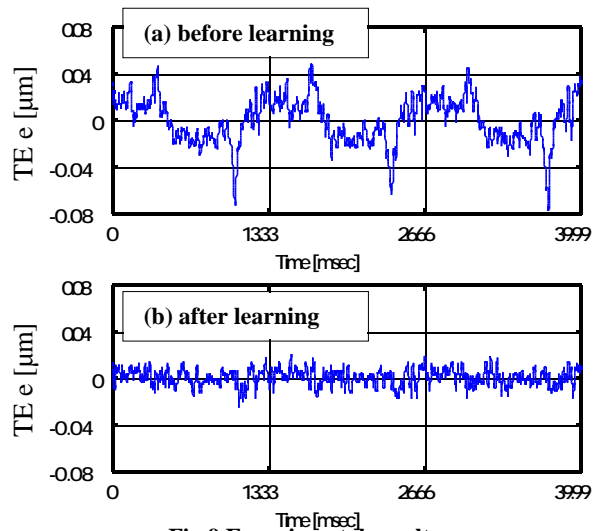


Fig.9 Experimental results

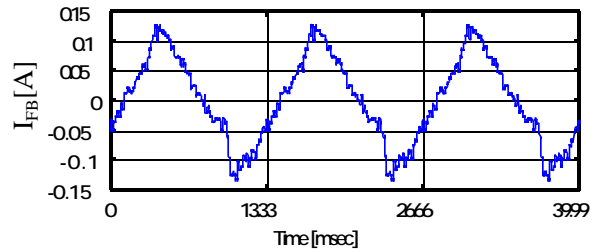


Fig.10 Learning result I_{FF} during Fig.9 (b)