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Reducing Seek Time of Tracking Actuator with Pulsed Excitation in Optical Disk

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Abstract

The latency time, which is the residual vibration of a fine actuator and track eccentricity, has been the aim for direct pull-in in optical disk system. Modified velocity profiles of the coarse actuator and control inputs of the fine actuator have been proposed for the minimum residual vibration.

Generally, there exists eccentricity due to mismatch of the disk center and the axis of a spindle motor. So, if a fine actuator is locked to the coarse actuator, another latency time must be need because of the track eccentricity.

The track eccentricity can be estimated as the rotation type of the spindle motor changes from CLV to CAV. In this paper, the fine actuator is excited with the same velocity of the track and the track pull-in is executed without any latency.

1 Introduction

A conventional optical disk system is shown in Fig. 1. When signals on a disk are read, the beam spot can follow the track by two dimensional fine actuator which consists of the fine tracking actuator and the fine focusing actuator. The pickup can move in a long distance by the coarse actuator. In other words, there are three actuators and these can be classified by their moving direction. One is the fine focusing actuator. The others are the fine tracking actuator and coarse actuator which are components of 2-stage tracking actuaor.

Tracks in compact disk(CD) have spiral form whose width is 0.5 μm and pitch is 1.6 μm. They also have eccentricity caused by distortion itself and center deviation when the disk is clamped to a spindle motor.

A matter of primary concern in the track seek is the minimization of seek time. And the residual vibration always makes the seek time delayed. For reducing the delay time, the residual vibration must be decreased and the final target is the locking of the fine actuator to the coarse actuator when the coarse actuator moves[1][2][3].

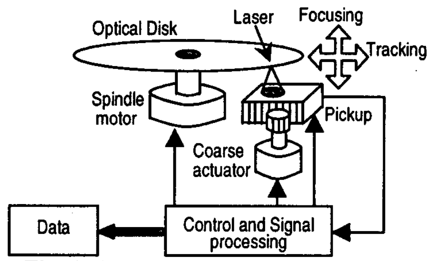


Fig. 1 Conventional optical disk system

But even if the residual vibration is absolutely removed, another time delay by the track eccentricity would remain. In this study, the time delay caused by the track eccentricity would be reduced or removed additionally. By excitation and velocity generation of the fine actuator, it has the same velocity as the track eccentricity. So the track pull-in would be executed without any delay.

2 Previous track seek servo

2.1 2-stage tracking actuator

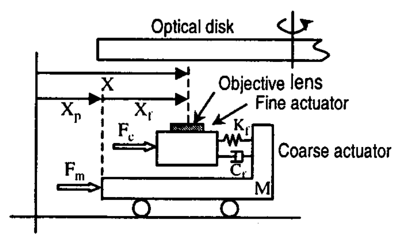


Fig.2 Schematic diagram of 2-stage tracking actuator

Schematic diagram of a 2-stage tracking actuator is shown in Fig. 2. The coarse actuator moves by the force of F_m which is generated from motor. The fine actuator is loaded on the coarse actuator. Fine actuator moves by the force F_c which is produced by the magnet and coil system. X_f and X_p are displacement of fine and coarse actuator respectively. So the position of beam spot, X is $(X_f + X_p)$.

And X_f and X_p can be represented as follows:

$$X_f(s) = \frac{K_c V_c(s) - M_f s^2 X_p(s)}{M_f s^2 + C_f s + K_f}, \quad X_p(s) = \frac{\gamma V_m(s)}{K_E s(1+\tau_M s)} \quad (1)$$

Where, V_c and V_m are voltage input of the fine and coarse actuator, respectively. M_f is the mass, C_f is the damping coefficient and K_f is the spring constant of the fine actuator. K_c is a constant which is determined by the coil and magnet of the fine actuator. K_E is back e.m.f. constant and τ_M is mechanical time constant of the coarse actuator. And γ is the ratio of pickup displacement to the rotation angle of the motor.

Because the mass of the fine actuator is negligible, the inertia force of the fine actuator do not affect to the coarse actuator. The acceleration of coarse actuator affects to the fine actuator. Especially, because of the acceleration or deceleration, fine actuator can be oscillated even if there is no voltage input of fine actuator. In another words, the vibration of fine actuator can be reduced by the feedforward. This is the feedforward compensator of the tracking controller.

2.2 Fundamental sequence of the track seek

The fundamental track seek sequence is shown in Fig.3.

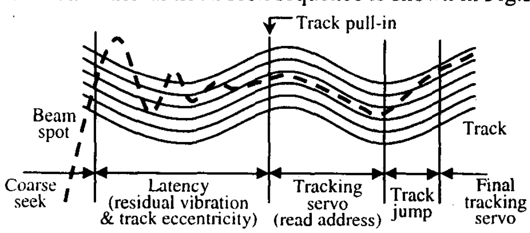


Fig.3 Sequence of the track seek

Coarse seek. Pickup actuator moves roughly to near the target track. Generally, the fine actuator is vibrated by the inertia force of the coarse actuator acceleration.

Latency. Actuators do not be controlled and wait until the velocity difference between the fine actuator and the track is smaller than the allowable error.

Track pull-in. If the velocity condition is sufficient, a track following servo operates. After the track pull-in, data on the current track come to be read.

Read address and Track jump. Generally the current track which is tried to pull-in of the fine actuator is not the target but the near one. So, after reading the address of the current track, the fine actuator jumps to the final target track.

Many optimized seek trajectories and control logic for the fast coarse movement were introduced[4][5]. And, these were also applied to hard disk drive(HDD)[6][7]. The fundamental and simple trajectory of the coarse actuator has a trapezoidal velocity profile with bang-bang control, first of all, because the coarse actuator is in need of moving fast. But the inertia force which affects the fine actuator becomes larger as the coarse actuator moves fast. So, if the coarse actuator has a larger acceleration and decceleration, the moving time would be shorten but the latency time would be longer.

2.3 Feedforward compensator of the fine actuator

The ultimate goal of the feedforward compensator is no vibration of the fine actuator to the coarse actuator, and the input of the fine actuator is generated by the inertia force due to the movement of the coarse actuator. There is no change of the coarse actuator input and no additional increase of coarse moving time. But if the coarse actuator model is not exact, there would be an unexpected vibration of the fine actuator. Fig.4 shows the block diagram of the feedforward compensator.

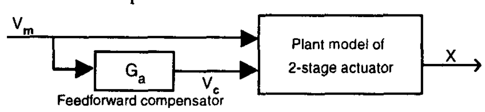


Fig.4 Feedforward compensator of the fine actuator

From Fig.4 and Eq.(1), the transfer function of the feedforward compensator can be derived as follows:

$$G_a(s) = \frac{\gamma M_f s}{K_c K_E (1+\tau_M s)} \quad (2)$$

2.4 Limit of the feedforward compensation

Table 1 shows the simulational result for the pull-in time, t_p which is the sum of coarse moving time, t_a and average latency time, t_{lat_avg}. When the feedforward compensator is used, pull-in time is reduced to about 50.9 ms. But the latency time of 7.6 ms due to the track eccentricity still remains. And, this is a fourth of the period of disk rotation, and also the limitation of the feedfowrard compensator.

Table 1. Pull-in time by the feedforward compensator

Feedforward Compensator	Coarse Moving Time t_a [ms]	Average Latency Time t_{lat_avg} [ms]	Pull-in Time t_p [ms]
OFF	124.3	58.5	182.8
ON	124.3	**7.6**	131.9

3 Reducing seek time by pulsed excitation

If the fine actuator has the same velocity as the track eccentricity, there would be no latency time for the track pull-in. To generate the derived velocity of the fine actuator, the pulse input is used before the coarse moving.

3.1 Velocity generation by pulsed excitation

After unit input voltage is applied to the fine actuator during t_p, its displacement and velocity becomes as Eq.(3).

$$
\begin{aligned}
x_{fp} &= \frac{K_c}{K_f}\left\{1-e^{-\sigma t_p}\left(\cos(\omega_d t_p)+\frac{\sigma}{\omega_d}\sin(\omega_d t_p)\right)\right\} \\
v_{fp} &= \frac{K_c}{K_f}e^{-\sigma t_p}\left(\frac{\sigma^2}{\omega_d}+\omega_d\right)\sin(\omega_d t_p) \qquad (3) \\
&\text{where, } \sigma=\xi\omega_n,\ \omega_d=\omega_n\sqrt{1-\xi^2}
\end{aligned}
$$

ω_n is undamped natural frequency and ξ is damping ratio of the fine actuator. Then, if the input is removed, the velocity and the acceleration after time of t_r becomes as follows.

$$
\begin{aligned}
v_{fr} &= e^{-\sigma t_r}\left\{v_{fp}\cos(\omega_d t_r)-\frac{(\sigma^2+\omega_d^2)x_{fp}+\sigma v_{fp}}{\omega_d}\sin(\omega_d t_r)\right\} \\
a_{fr} &= e^{-\sigma t_r}\Big[-\left\{(\sigma^2+\omega_d^2)x_{fp}+2\sigma v_{fp}\right\}\cos(\omega_d t_r) \qquad (4) \\
&\quad +\frac{1}{\omega_d}\left\{\sigma(\sigma^2+\omega_d^2)x_{fp}+(\sigma^2-\omega_d^2)v_{fp}\right\}\sin(\omega_d t_r)\Big]
\end{aligned}
$$

We can find the minimum positive t_r that makes the acceleration of the fine actuator to zero. Veloicty change would not occur for a while at this time. And the generated velocity is proportion to the input voltage level.

3.2 Apply the pulsed excitation to the track seek

Let ω be the rotational frequency of disk and R_0 be the maximum amplitude of eccentricity. Then, the track eccentricity could be defined as $R(t)=R_0\sin(\omega t+\phi_0)$.

When the coarse actuator stops, the velocity of the track eccentricity becomes as follows;

$$\dot{R}(t)=R_0\omega\cos(\omega T_c+\phi_0) \qquad (5)$$

where, T_c is moving time of the coarse actuator. Before the track seek is executed, R_0 and ϕ_0 can be measured and estimated by the tracking error signal which is proportion to the track eccentricity. The block diagram of the excitation input is shown in Fig.5.

From 3.1, pulse input $V_E(t)$ is derived as Eq.(6).

$$
V_E(t)=\begin{cases}
0 & : 0<t<T_c-(t_p+t_r) \\
-\dfrac{R_0\omega\cos(\omega T_c+\phi_0)}{v_{fr}} & : T_c-(t_p+t_r)<t<T_c-t_r \\
0 & : T_c-t_r<t<T_c
\end{cases} \qquad (6)
$$

Each voltage input profiles of the coarse and the fine actuator are shown in Fig.6 for 10 mm movement.

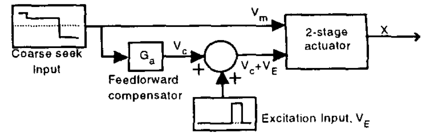


Fig. 5 Excitation input of the fine actuator

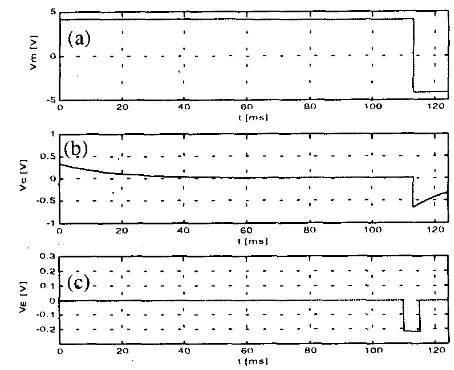


Fig.6 Input profiles of 2-stage tracking actuator
(a) Input profile of a coarse actuator
(b) Feedforward input profile of a fine actuator
(c) Excitation input profile of a fine actuator

3.3 Simulation

Displacements of the fine actuator are shown in Fig. 7, when the input profiles of Fig.6(a),(b) or Fig.6(a),(b),(c) are used.

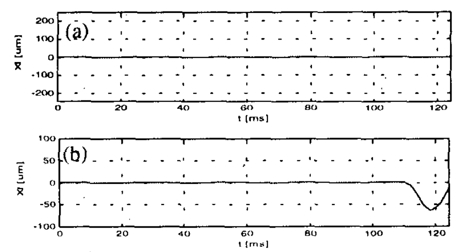


Fig.7 Displacement of the fine actuator
(a) Only feedforward input of the fine actuator
(b) Feedforward and excitation input of the fine actuator

Simulation results about the track pull-in and track following are shown in Fig.8. Fig.8(b) shows the track pull-in without any latency. There is no latency caused by the track eccentricity when it uses the pulsed excitation. And when the coarse actuator stops, the excited input voltage of the fine actuator is zero. This means that the excitation input does not affect the track pull-in.

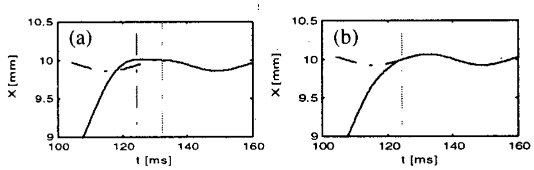


Fig.8 Comparison of the track pull-in according to the excitation method (a) Feedforward compensator, (b) Feedforward compensator and pulsed excitaton

4 Experiment

4.1 Experimental methods

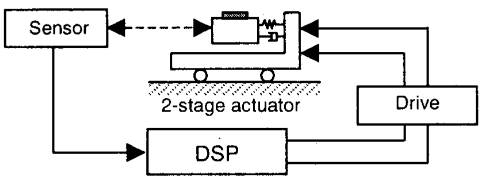
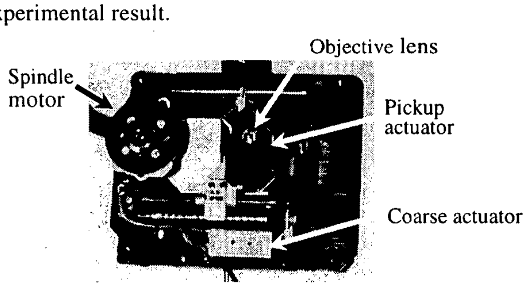
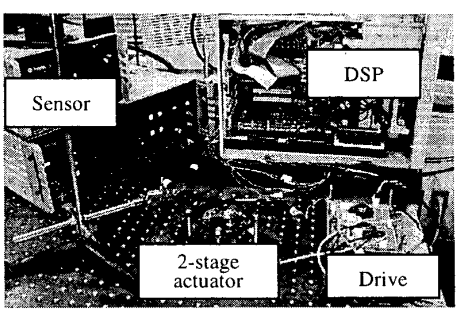


Fig.9 Schematic diagram of the experimental setup

The schematic diagram of the experimental setup is shown in Fig.9. CD-ROM which is composed a lead screw type coarse actuator and a 4-wire type fine actuator is used for the experiment. Actuators are controlled by digital signal processor. And, if the velocity error is larger than an allowable error, the input profiles would be modified by the experimental result.



(a) 2-stage tracking actuator



(b) Experimental setup

Fig. 10 2-stage tracking actuator and experimental setup

CD-ROM actuators including 2-stage actuator, focusing actuator and spindle motor are shown in Fig.10(a). Fig.10(b) shows the experimental setup. Sampling frequency of the DSP is 32 kHz and velocity profiles are measured by Polytec OFV502 Fiber Interferometer and OFV3000 Controller.

Experiments are divided into two sections. One is the experiment for feedfoward compensator, and the other is the experiment for the pulsed excitation with the feedforward compensator. The angular velocity of the spindle motor is set to be 1800 rpm and the distance for track seek is 10 mm (1/3 full stroke).

4.2 Experiments for the feedforward compensator

In this section, the feedfoward compensator is used for reducing seek time. It is shown experimentally that the dynamic model of the coarse actuator is not exactly same as the real one.

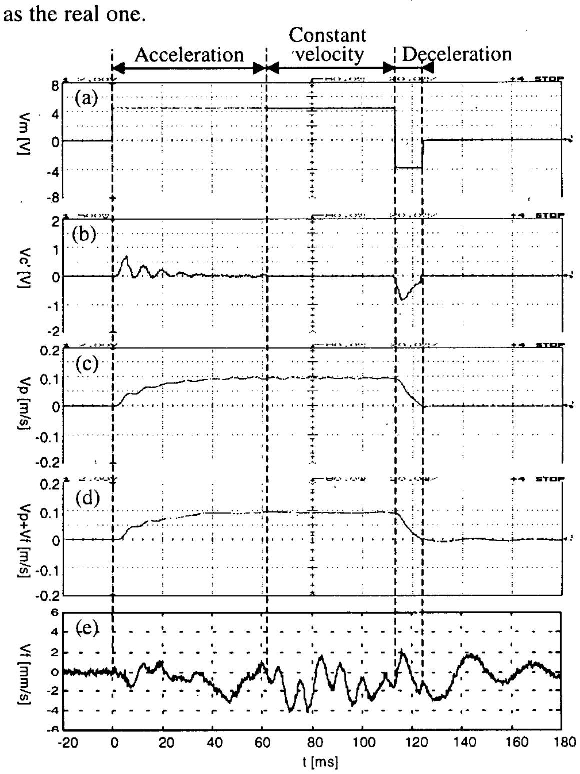


Fig.11 Experimental result of the track seek servo using time minimized velocity profile of the coarse actuator and feedforward compensator of the fine actuator
(a) Coarse actuator input
(b) Modified feedforward fine actuator input
(c) Velocity of the coarse actuator
(d) Absolute velocity of the fine actuator
(e) Relative velocity of the fine actuator

Track pull-in time is measured by 188.4 ms in case that there is no input of the fine actuator during the activation of the coarse actuator. But it becomes 131.9 ms when the feedforward compensator is used.

Velocity error of the fine actuator is greater than the allowable velocity error even though the feedforward compensator is used. The reason is due to the nonlinearty of the fine actuator. As shown in Fig.11(c), the velocity profile of the coarse actuator has some fluctuation, whose frequency is about 120 Hz but damping ratio varies 3 or 4 times. Therefore input profile of the fine actuator for the feedforward compensator is modified from Fig.6(b) to Fig.11(b) experimentally.

Table 2. Compare of velocity, displacement of the fine actuator and average latency time by using the feedforward compensator of fine actuator

	Simulation	Experiment
Displacement [μm]	0	10
Velocity [mm/s]	0	-1.22
Average latency time [ms]	7.6	7.6

Absolute and relative velocity of the fine actuator are shown in Fig.11(d) and Fig.11(e). Velocity error of the fine actuator is smaller than 4 mm/s during the coarse movement. When the coarse actuator decelerates, maxium velocity error of the fine actuator is about 2 mm/s. When the coarse actuator stops, displacement and velocity of the fine actuator are shown in Table 2.

Most of all average latency time by the experiment is equal to the result of simulation. Because the allowable velocity error is 3 mm/s, the average latency time for the every track eccentricity is not changed although displacement and velocity of the fine actuator have some errors. But if the velocity profiles of the coarse actuator is changed because of some reasons, the velocity error of the fine actuator would be lager than the allowable error. This is the limitation of the feedforward compensator.

4.3 Experiments for pulsed excitation

By adding the pulsed excitation to the fine actuator during coarse movement, the fine actuator would have a specific velocity which is equal to the track velocity.

The results are shown in Fig.12. Input profile for the maximum velocity and velocity profiles of the fine actuator are shown in Fig.12(a) and Fig.12(b),(c). Fig.12(d) and Table 3 shows the fine actuator velocities for each track conditions. Allowable velocity error of the fine actuator which obtained by simulation is 3 mm/s. As shown in Table 3, maximum velocity error is 1.2 mm/s. This is a tolerable range.

Table 3. Velocity of the fine actuator according to the velocity condition of the track by using the pulsed excitation

Phase of track eccentricity [deg]		0.00	41.4	60.0	75.5	90.0
Track velocity [mm/s]		13.2	9.9	6.6	3.3	0.0
Simulation	Displacement [μm]	-11.9	-8.9	-5.9	-3.0	0.0
	Velocity [mm/s]	13.2	9.9	6.6	3.3	0.0
	Velocity error [mm/s]	0.0	0.0	0.0	0.0	0.0
Experiment	Displacement [μm]	26	35	31	26	10
	Velocity [mm/s]	12.7	9.7	6.6	2.4	-1.2
	Velocity error [mm/s]	-0.4	-0.2	0.0	-0.9	-1.2

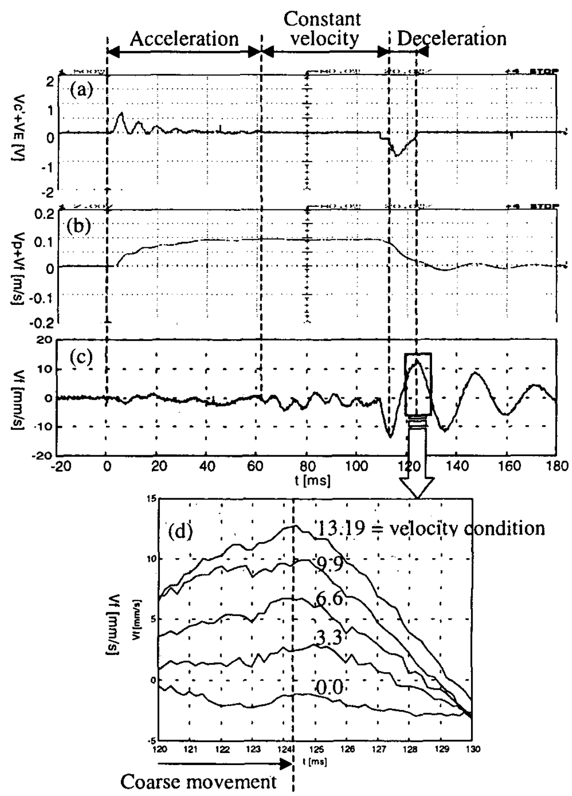


Fig.12 Experimental result of the track seek servo using modified feedforward compensator and pulsed excitation of the fine actuator
(a) Fine actuator input
(b) Absolute velocity of the fine actuator
(c) Relative velocity of the fine actuator
(d) Relative velocity of the fine actuator according to the velocity condition

5 Error Analysis

When the fine actuator is excited by the pulse input of Eq.(6), the sources of velocity error are alnalyzed. Generally, there are three reasons for the velocity error.

Error caused by the voltage input. Feedforward input and excitation input are generated by DSP controller. The range of voltage output is ± 10 V and they are divided into 16-bit digital data form. So the minimum interval of voltage output is 0.31 mV. And it makes about 0.04 mm/s of velocity error. But it may not be a dominant error source, because it is only 3 % of the maximum velocity error which is obtained from the experiment.

Measuring error. Velocity sensor in this experiment uses laser interferometer. And noise level to the zero velocity is about 50 mV. Being considered the sensitivity of 25 mm/s/V, this makes about 1.2 mm/s of velocity error. But the results are obtained from 5 times or more average. This also may not be a dominant error source.

Modeling error of actuators. Dynamic transfer function of the fine actuator is shown in Eq.(1), and it can be represented as follows.

$$\frac{X_f}{V_c} = \frac{K_0}{s^2 + 2\xi\omega_n s + \omega_n^2} \quad (7)$$

Where, K_0 is defined as K_c/M_f. By measuring the characteristics using the dynamic analyzer, it can be obtained as ξ =0.1131, ω_n=251.2 rad/s. And the allowable modeling error is shown in Table 4.

Table 4. Allowable modeling error of a fine actuator

Parameter		Allowable modeling error
Resonance frequency	$\frac{\omega_n}{2\pi}$	< ± 2 Hz
Q factor	$\frac{1}{2\xi}$	< ± 3 dB

Table 5 shows the maximum velocity error due to the modeling error. Modeling error of –3 dB in the Q-factor causes the maximum velocity error. But, this is not over the limitation of allowable velocity error for the track pull-in.

Table 5. Velocity error due to the modeling error

Modeling error		Max. velocity error [mm/s]
Resonance frequency	+ 2 Hz	- 0.23
	- 2 Hz	- 0.06
Q factor	+ 3 dB	+ 1.26
	- 3 dB	- 1.58

6 Conclusions

The feedforward compensator is used to reduce seek time in optical disk system. For the given system, it is shorten the seek time by 28 %. But the track pull-in could not be executed directly when the coarse actuator stops, because the track oscillate periodically which can be estimated because the spindle motor rotates with CAV mode. However, this is the limitation of the feedforward compensator.

For direct track pull-in with no latency, the fine actuator is excited by pulsed input and has a specific velocity which is equal to the velocity of the track eccentricity.

By simulation and experiment, additional time reducement by pulsed excitation of the fine actuator is calculated and measured by 6 %.

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