Direct Seek Control for Swing-arm Type Dual Stage Actuators in Blu-Ray Disc Drive Systems

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Abstract: This paper presents a direct seek control algorithm for swing-arm type dual stage servo system that consists of a coarse actuator and a fine actuator. The proposed scheme is to design a control system that attenuates the effect of dynamic coupling between the two actuators so that the seek operation can be performed in a single-shot with stability.

In an optical drive system with dual stage servo mechanism, the effect of dynamic coupling between the two actuators needs to be handled during the coarse seek operation due to its inherent structure. In an extreme case, the two actuators can collide each other, which leads to critical degradation of the seek performance. To handle this problem, our proposed control scheme is to generate the drive signals such that the two actuators behave as if they are a single fixed body. To this end, a feedforward controller and two feedback controllers are designed that enable the current drive system perform wide range of track seek. Simulation results are provided to show the validity and feasibility of our proposed algorithm.

Key Words: Direct seek control, Disc Drive, Swing-arm type dual stage actuators

I. INTRODUCTION

As an application of optical storage technology based on blue-violet laser (Blu-ray), a miniature portable optical drive is being under development. The goal of this small form factor (SFF) drive would be for facilitating 4GB of storage capacity on a coin-sized optical disc. Due to the dimensional constraint, miniaturization of the optical head and actuator is essential. In addition, for large capacity of data storage, the track density of the Blu-ray disc is very high. High bandwidth servos are necessary for track following with such a narrow track pitch.

With the conventional rotary-to-linear translation mechanism using a stepping motor or a DC motor for sledding motion, it is hard to meet our structural design spec of 5mm height drive. A swing-arm type actuator system consisting of a coarse actuator and a fine actuator has its merit in that it makes an optical drive with ultra compact size realizable while achieving high servo bandwidth which is required for high positioning accuracy.

In optical disc drive systems, direct seek control that involves moving the beam spot to the target track with a short access time is the key issue in terms of servo control design. In particular, for a miniature mobile Blu-ray system featured by its ultra compact size and large capacity (or equivalently high track density) the role of servo system becomes more significant.

Swing-arm type dual stage actuators have been studied by many researchers ([1], [2], [3], [4], [7]), however, most of them are concerned with hard disc drive systems. This paper presents a control system design for direct seek operation of an optical disc drive employing dual stage servo mechanism.

II. PROBLEM STATEMENT

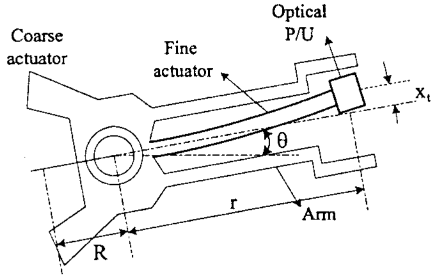

Fig. 1. A Simplified Structure of Swing-arm type Actuators

Figure 1 shows a schematic structure of swing-arm type actuators. The fine actuator is used for fast and fine but range-limited motion and the coarse actuator, usually a voice coil motor, is used for wide range of track jump and seek operation. As can be seen from the figure, since the two actuators are connected, the motion of the two actuators are dynamically coupled. In rotary-to-linear type drive systems, the effect of dynamic coupling between the fine actuator and the stepping motor is negligible because the rotational axis of the stepping motor is stiff enough. The dynamic interference of the dual stage servo system can be a critical problem during coarse seek or track jump operation while searching for the target track. This is the major problem that needs to be considered in designing a control algorithm for a swing-arm type servo system.

Optical disc drive systems are subject to disturbances such as disc eccentricity, actuator vibration, disc surface vibration, and objective lens shift etc. Due to these disturbances, an accurate velocity control is required for direct seek control rather than a position control.

Direct seek operation can be divided into two types; a fine seek operation and a coarse seek operation depending on the number of tracks to be crossed. Usually, for less than 500 tracks, the fine actuator actively drives the objective lens for searching for the target track. Meanwhile, for more than 500 tracks, the coarse actuator actively performs the direct seek operation.

The mathematical model for the swing-arm type actuators can be represented as follows.

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \tag{1}$$

where $x = [x_t \quad \dot{x}_t \quad \theta \quad \dot{\theta}]^T$, $u = [u_f \quad u_c]^T$,

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ \frac{-K_f}{m_f} - \frac{r^2 \cdot K_f}{J_c} & \frac{-C_f}{m_f} - \frac{r^2 \cdot C_f}{J_c} & \frac{r \cdot K_c}{J_c} & \frac{r \cdot C_c}{J_c} \\ 0 & 0 & 0 & 1 \\ \frac{r \cdot K_f}{J_c} & \frac{r \cdot C_f}{J_c} & -\frac{K_c}{J_c} & -\frac{C_c}{J_c} \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & 0 \\ \frac{\phi_f}{m_f \cdot R_f} & -\frac{\phi_c \cdot R \cdot r}{R_c \cdot J_c} \\ 0 & 0 \\ 0 & \frac{\phi_c \cdot R}{R_c \cdot J_c} \end{bmatrix}, \quad C = [1 \quad 0 \quad r \quad 0].$$

Note that x_t is the relative displacement of the fine actuator with respect to the center axis of the coarse actuator and $x_t = 0$ means that the dual stage actuators are moving like a single body without independent motion.

TABLE I

PARAMETER VALUES OF THE ACUATOR MODEL

Parameters	Values	Parameters	Values
$m_f\ (g)$	0.25	$J_c\ (Kg \cdot m^2)$	$0.7e-7$
$k_f\ (N/m)$	98.7	$k_c\ (Nm)$	$1.73e-3$
$c_f\ (Kg/sec)$	0.0497	$c_c\ (Nmsec)$	$2.2e-6$
$\phi_f\ (N/A)$	0.02	$\phi_c\ (Nm/A)$	$1.33e-3$
$R_f\ (\Omega)$	3	$R_c\ (\Omega)$	12
$r\ (mm)$	19.7	$R\ (mm)$	5.9

III. PROPOSED DIRECT SEEK CONTROL ALGORITHM

Our proposed coarse seek control scheme is shown in Figure 2. In general, the direct seek operation is performed by letting the laser beam spot follow or track the pre-defined velocity profile, v_r. $G_{cv}(s)$ and $G_{fv}(s)$ are the transfer functions from the input signals, u_c and u_f to the output signals, v_c and v_f, respectively. These two transfer functions represent their velocity models and can be easily derived from the state space equation (1).

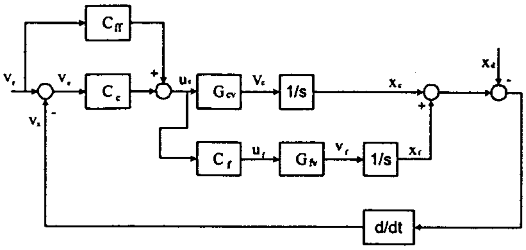

Fig. 2. A Block Diagram of The Proposed Direct Seek Control Scheme

When coarse seek command is given for wide range of track seek, the swing-arm (the coarse actuator in our case) starts to rotate along the θ axis by the drive signal (u_c) generated by a feedback controller $C_c(s)$, and a feedforward controller $C_{ff}(s)$.

If the swing-arm abruptly starts rotational motion, the fine actuator moves in the opposite direction with the optical head due to the inertia force. This reaction deteriorates the performance of the seek operation and can possibly leads to collision of the swing-arm and the fine actuator. In our seek control scheme, the controller for the fine actuator $C_f(s)$ will be designed such that the two actuators move in the same direction with $x_t = 0$ as if they are a single body. This control strategy attenuates the effect of dynamic interference caused by the independent motion of the two actuators. Now let us describe design procedure for the three controllers shown in Figure 2. The relative velocity of the objective lens with respect to the rotating disc can be written as

$$v_x = v_c + v_f - \dot{x}_d, \tag{2}$$

where v_c and v_f denote the velocity of the coarse and the fine actuator, respectively and x_d is the disturbance. The velocity error, $v_e = v_r - v_x$, can be obtained as follows.

$$v_e = \frac{1 - G_{cv}C_{ff} - G_{fv}C_fC_{ff}}{1+L} \cdot v_r + \frac{1}{1+L} \cdot v_d, \tag{3}$$

where $L = G_{cv}C_c + G_{fv}C_fC_c$. Equation (3) provides a clue how to design the controller to make the velocity error, v_e, as small as possible. One can see that this can be achieved if the following conditions are satisfied,

$$C_{ff} = \frac{1}{G_{cv} + G_{fv}C_f} \tag{4}$$

and

$$\|L(j\omega)\| \gg 1, \quad for\ \omega \geq \omega_d \tag{5}$$

where ω_d is the frequency of the disturbances that affect our drive system. If these two conditions hold, $v_e \approx 0$.

First, we consider the feedforward controller, C_{ff}. Since G_{cv} and G_{fv} are velocity models, once C_f is determined,

C_{ff} can be easily obtained. Note that when the denominator of equation (4) is strictly proper, an extra fast pole(or poles) which is beyond the servo bandwidth needs to be added to C_{ff}.

Secondly, let us describe how to determine the controller for the fine actuator, C_f. As can be seen from Figure 2, the total displacement of the optical head can be written as

$$x_T = x_c + x_f, \tag{6}$$

where x_c and x_f denote each moving displacement resulted from the drive signals u_c and u_f, respectively. Also, from Figure 1, x_T alternatively can be expressed as

$$x_T = x_\theta + x_t, \tag{7}$$

where $x_\theta = r \cdot \theta$, and we assume that θ is small angular displacement. Note that from equations (6) and (7), $x_f \neq x_t$. Referring to the Figure 1 and 2, one can obtain the following equation.

$$\begin{bmatrix} x_\theta \\ x_t \end{bmatrix} = \begin{pmatrix} T_{\theta c} & T_{\theta f} \\ T_{tc} & T_{tf} \end{pmatrix} \begin{bmatrix} u_c \\ u_f \end{bmatrix} \tag{8}$$

where T_{ij}'s ($i = \theta, t$ and $j = c, f$) are the transfer functions that represent the input-output relation for the two input signals and the corresponding output signals.

Now we consider direct seek operation again. As mentioned earlier, our control strategy is to suppress independent motion of the objective lens with respect to the swinging arm during coarse seek operation. To this end, we see that the following condition should hold.

$$x_t = 0 = T_{tc}u_c + T_{tf}u_f. \tag{9}$$

Substituting $C_f u_c$ for u_f in the above equation, we obtain

$$C_f = -\frac{T_{tc}}{T_{tf}}. \tag{10}$$

This is the design constraint on C_f for realizing our control strategy.

Finally, we present how to design the feedback controller for the coarse actuator, $C_c(s)$. Note that our design approach for C_c is based on the shaping of the open-loop transfer function, $L(S)$ provided in equation (3). Since C_{ff} was designed such that the first term of the right hand side of the equation (3) be cancelled out, we consider only the second term as follows.

$$v_e = \frac{v_d}{1 + L(s)}. \tag{11}$$

Taking the absolute values on both sides, we get

$$\frac{|v_e|}{|v_d|} \leq |\frac{1}{1 + L(s)}| = |S(s)|, \tag{12}$$

where $S(s)$ is the *sensitivity function*. It is well-known that a disturbance attenuation performance specification (nominal performance) can be written as [5]

$$\bar{\sigma}(S(j\omega)) \leq |W_s^{-1}(j\omega)|, \tag{13}$$

where W_s is the weight which is to bound on S and $\bar{\sigma}(M)$ denotes the maximum singular value of M. Allowing W_s to depend on frequency ω enables us to specify a different attenuation factor for each frequency. From equations (12) and (13) with the fact that $L = G_{cv}C_c + G_{fv}C_fC_c$, one obtains

$$|G_{cv}(j\omega)C_c(j\omega) + G_{fv}(j\omega)C_f(j\omega)C_c(j\omega)| > |W_s(j\omega)| \tag{14}$$

for all ω. This is the design condition for $C_c(s)$.

In other words, if we design $C_c(s)$ that meets the requirement provided in inequality condition (14), the proposed velocity control scheme enables our drive system perform the direct seek operation despite the shaking disturbance. One thing to be noted though is that in determining the weight function W_s, the disturbance characteristics which is dependent on frequency and the stable pull-in condition [6] of the objective lens at the end of track jump must be carefully reflected.

IV. DESIGN RESULT

As a result, three controllers are designed as follows.

$$C_{ff}(s) = \frac{243.8(s + 31.43)}{s + 38956} \tag{15}$$

$$C_f(s) = \frac{1.17s}{s + 31.43} \tag{16}$$

$$C_c(s) = \frac{136(s + 125.7)(s + 2073)}{(s + 207.3)(s + 1068)} \tag{17}$$

The resulting loop transfer function, $L(s)$, is graphically represented in Figure 3 in terms of frequency response.

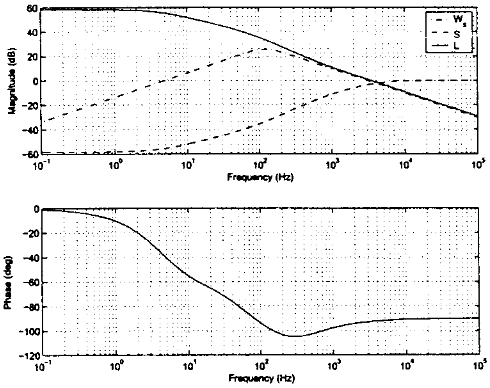

Fig. 3. Bode Plots of $L(s)$ (solid), $S(s)$ (dashed), and $W_s(s)$ (dash-dot)

We assumed that the current optical drive is subject to disc eccentricity of 30 μm. Also we assumed that for stable track pull-in at the end of seek operation, the speed of the objective lens should be restricted less than or equal to 1.2×10^{-3} m/sec. The weight function, W_s, was derived based on these two assumptions.

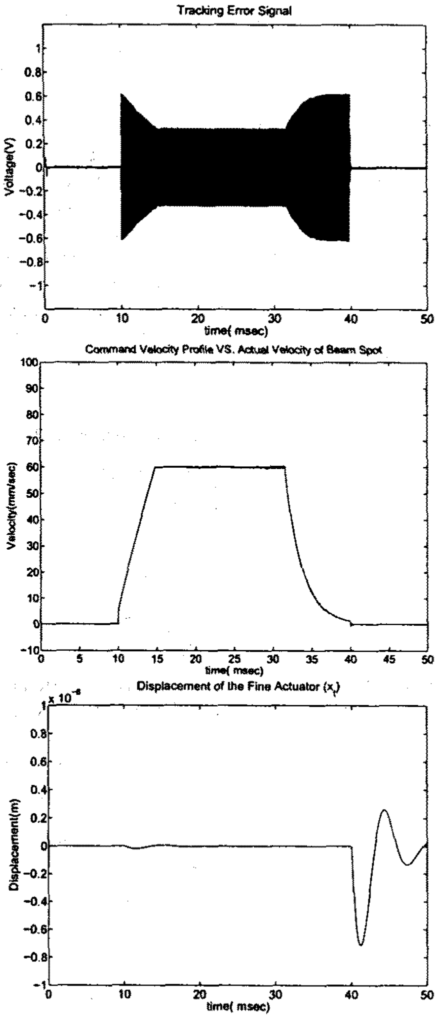

Fig. 4. Simulation Result of 4050 Track Seek using the Propose Control Algorithm

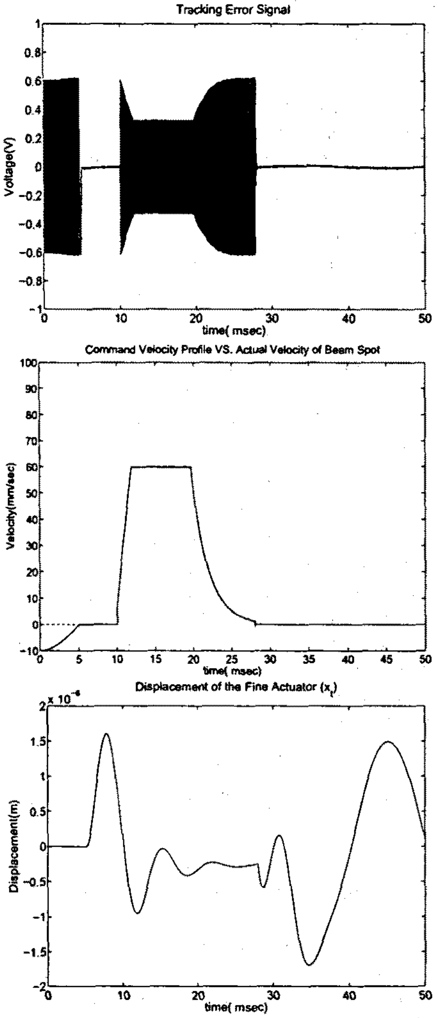

Fig. 5. Simulation Result of 2050 Track Seek using the Propose Control Algorithm

Time-domain simulation is conducted using the three controllers. Figure 4 shows the simulation results of 4050 track-seek operation. As can be seen from the figure, track jump for the target track followed by track following is performed successfully. From the second plot of Figure 4, note that one can hardly distinguish the actual velocity of the laser beam spot from the pre-defined command velocity profile, which means that the beam spot follows the the command velocity perfectly. In particular, the time response for x_t demonstrates that there is no individual motion of the fine actuator during the seek test as was intended by our control scheme.

Another simulation is conducted to see what happens when the initial value of $x_t \neq 0$ at the moment when the objective lens starts to jump for track seek. In the previous simulation, $x_t = 0$ which is actually a rare case. The scenario of the second simulation is that track pull-in is attempted at 0.005 seconds and track following continues until 0.01 seconds when seek operation starts. After crossing 2050 tracks, the lens arrives at the desired track and tries pull-in. The simulation result is shown in Figure 5. Looking at the third plot of Figure 5, although $x_t \neq 0$ during the track seek because of its non-zero initial condition, we see that it still remains within the region of $1\mu m$. We can say the relative motion of the fine actuator is negligible and our control scheme is still valid and applicable irrespective of the initial condition of x_t, that is, initial value of x_t when the seek command starts to be executed.

V. CONCLUSION

We presented a new direct seek control algorithm for an optical drive system employing a swing-arm type dual stage servo mechanism. The motivation of adopting this type of mechanism is due to its configurational size constraint and high servo bandwidth requirement in Blu-ray optical storage system. Our proposed control scheme is to provide the dual stage servo system with good performance of track seek while minimizing the vibration that results from the dynamic coupling of the two, coarse and fine actuator. Three controllers, a feedforward controller (C_{ff}) and two feedback controllers (C_f and C_c), are designed based on this scheme. Each controller has its own duty. The duty of the feedforward controller is for command velocity following, the function of the feedback controller for the fine actuator (C_f) is to suppress the individual motion of the fine actuator during the seek test, and the feedback controller for the coarse actuator (C_c) is designed such that the drive system can attain the nominal performance property considering the open loop transfer characteristics.

Simulation results are quite encouraging and shows that the proposed control algorithm can be applied to a small form factor optical drive system.

VI. REFERENCES

[1] S. L. Schroeck and W. C. Messner, "On Controller Design For Linear Time-Invariant Dual-Input Single-Output System," *Proceedings of the American Control Conference*, San Diego, CA, June 1999, pp. 4122–4126

[2] J. Ding, M. Tomizuka, and H. Numasato, "Design and Robustness Analysis of Dual Stage Servo System," *Proceedings of the American Control Conference*, Chicago, IL, June 2000, pp. 2605–2609

[3] M. Kobayashi, T. Yamaguchi, and R. Horowitz, "Track-Seeking Controller Design for Dual-Stage Actuator in Magnetic Disc Drives," *Proceedings of the American Control Conference*, Chicago, IL, June 2000, pp. 2610–2614

[4] D. Hernandez, S. Park, R. Horowitz, and A. K. Packard, "Dual-stage Track-Following Servo Design for Hard Disc Drives," *Proceedings of the American Control Conference*, San Diego, CA, June 1999, pp. 4116–4120

[5] J. C. Doyle, B. A. Francis, and A. R. Tannenbaum, *Feedback Control Theory*, New York: Macmillan, 1992

[6] M. Suzuki, H. Tanaka, and Y. Miura, "Pull-in Condition and Method of Tracking Servo in Optical Disc Drive," *Jpn. J. Television*, vil. 44, no. 10, pp. 1391–1397

[7] J. R. Ryoo, K. B. Jin, T. Doh, and M. J. Chung, "New Fine Seek Control for Optical Disc Drives," *Proceedings of the American Control Conference*, San Diego, CA, June 2000, pp. 3635–3639