AN OBSERVER FOR RUNOUT OBSERVATION DURING TRACK SEEKING FOR THE TWO-ACTUATOR OPTICAL DISK DRIVE

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Abstract: Runout observation in optical disk drive is a common research interest, but very few researches were able to address the runout problem during the track seeking process. This study investigated the possibility of using an on-line observer to estimate the disk runout during track accessing. A model based feedback algorithm for the track-accessing servo is used as the base for the design. The observer in the controller not only helps to provide the necessary feedback information during accessing, but also made it possible to measure the disk runout in the removable media. The experimental results showed that proper tuning of the controller clearly provide the track wobbling information that will make possible further investigation on how to eliminate the runout effect in the accessing process.

Keywords: Observer, Optical Data Storage, Disk Oscillation, Disturbance Signals, Optimal Filtering.

1. INTRODUCTION

This paper studies the effect of disk runout on the optical disk drive track accessing. An on-line observer is designed that is able to perform on-line disk runout observation during track accessing. This observer will enable the controller to take into consideration the runout effect during accessing.

Track accessing is an important process in the disk drive operation. Most random access disk drives spent almost half of its operation time moving the data head across different tracks. The disk runout effect in a Winchester type hard disk drive is not obvious because the servo-write process will usually counter the runout action and creates concentric data tracks on the disks. The optical disk drive, on the other hand, has removable media, and the amount of runout is subject to each time the disk is inserted into the cartridge. The runout in these systems can thus be very severe. In addition, the data head in the optical drive contains the necessary optics (Imaino and Bhushan, 1991, Hitani and Tsunoda, 1984). It is heavier than the head in the other types of storage devices; the access time is also longer and is one of the major obstacles in its progress. Shortening the time can thus results in significant improvement in the drive performance.

The optical disk drive uses two-actuator solution: a fine actuator for the high resolution and a sled actuator to cover the large seek distance. For economic reason, the sled actuator is usually made of very crude plastic gearing driven by low cost DC motors, and the fine actuator is usually made of voice coil and leaf spring suspensions. This configuration allows for very fine track resolution, but it also introduces all kinds of undesirable nonlinear factors into its mathematical model (Kaneko, 1987). There are many results in the literature on the track-following control algorithms (Yen, et. Al., 1990, Soner, 1986a, Soner, 1986b, McCormick and Horowitz, 1991, Yang and Pei, 1996), but because of the double actuator nature of the optical head, very few has addressed the track accessing problem. McCormick and Horowitz (1991) adopted a
simplified model with two independent double integer plants to obtain an approximated analytical solution. Yang and Pei (1996) further discussed the detailed behaviour of the fine actuator for long track jump. Their main claim is that the control effort in the zero input periods should actually be a linear proportional effort. Basically, there is no result available on dealing with the track runout.

In this paper, the authors studied the effect of the disk runout. The result shows that a properly designed filter for the dual actuator system is able to distinguish between the fine actuator vibration and the disk runout. Thus, the filter is able to provide the runout information during the accessing process. It is than necessary to modify the track-accessing strategy. Experimental results show that if the velocity of the target track can be predicted, it is possible to modify the track accessing strategy to improve the settling characteristics.

The rest of this paper is divided as followings: The next section constructs the plant mathematical model that will be used throughout the paper. The model includes the coupling force between the sled and the fine actuator. Section 3 describes the track accessing servo and some of the problems encountered. Section 4 proposes an online observer for the disk runout during track accessing. Section 5 presents the experimental results and some discussions. Finally, section 6 presents the conclusions.

2. SYSTEM MODELING

Two stage actuators are adopted by almost all the commercial optical disk drives like CD players and DVD players to accomplish both high precision track following and long track seeking requirement.

Figure 1 shows the experimental TAODD actuator assembly. The actuator consists of a sled made of ball screw and DC motor with long stroke capability and a fine actuator with precise motion capability. Such dual actuator structure in the CD-ROM drive can accomplish as many as 45,000 tracks jumping and as precise as 0.16 mm positioning.

Figure 2 depicts the simplified mathematical model. The system shows a coupling effect from the acceleration of sled to fine actuator input. Generally the mass, \( M_s \), of the sled is larger than that of the fine actuator. It should be noted that the equilibrium point for the fine actuator is defined at the central point of its travel. \( M_s \) in figure 1 is the mass of the sled, and \( x_s \), the position of the sled, is measured absolutely to the global coordinate system and \( x_f \) the position of the fine actuator, is measured relatively with respect to the equilibrium point.

Several assumptions have been made before the derivation of this model: (1) The sled consists of a dc motor in nature and is assumed to have a second order dynamic relation between the input voltage to output velocity, (2) The reaction force from sled to fine actuator is considered while the reaction force from fine actuator to sled is ignored since sled has larger mass than fine actuator.

3. THE TRACK ACCESSING SERVO
The optical disk drive servo system takes charge of several necessary functions to enable data accessing from the optical disk. First of all, a focusing servo focuses the laser beam on the disk surface to bounce off the correct optical signal back to the light processing circuit. Secondly, a track-following servo will read the servo-tracking signal to keep the data head on track. Thirdly, the spindle motor will keep the disk spinning at designated rate to allow correct interpretation of the read back data. Finally, the track-accessing servo kicks in when there is need to access a different track.

The track-accessing strategy is usually based on the classical time-optimal control strategy. As mentioned before, the two-actuator MIMO time-optimal control solution is difficult to obtain. Therefore it is custom instead to use single actuator solution for the sled and try to lock the fine actuator in a neutral position to accommodate for the target track movement. That is to use a maximum acceleration profile for the acceleration phase until the velocity reaches the velocity limit, and then to curse at constant velocity before one can actually do anything with it. In the next section, we will propose an on-line observer that is aimed at observing the disk wobble as a way to achieve this goal.

Assuming that the noises are zero mean and uncorrelated, and assume the initial conditions:

\[
P_0 = P_{\hat{x}_0} \cdot \hat{x}_0 = \bar{x}_0.\]

It is possible to calculate the Kalman filter gains through a coupled procedures [1]:

**Sequence update:**

The error covariance:

\[
P_{k+1} = \Phi_k P_k \Phi_k^T + G_k Q_k G_k^T.
\]

State estimation:

\[
\hat{x}_{k+1} = \Phi_k \hat{x}_k + \Gamma_k u_k.
\]

**Measurement update:**

Error covariance:

\[
P_{k+1} = \left( P_{k+1} \right)^{-1} + H_k \Gamma_k R_k H_k^T.
\]

State estimation:

\[
\hat{x}_{k+1} = \hat{x}_{k+1} + P_{k+1} H_k \left( y_{k+1} - H_k \hat{x}_{k+1} \right).
\]

Compare with the Kalman filter, the filter gain is defined by

\[
L_k = P_k H_k R_k^{-1}.
\]

The disturbance of the system mainly arises from the track runout, which is typically 87 tracks from the optical head datasheet. Thus the value of \( R \) is set to \( 87^2 = 7569 \). The value of the matrix \( Q \) determines the observer bandwidth. A very small \( Q \) results in small observer bandwidth and should better reflect the true system behaviour; however, the low bandwidth loop usually results in sloppy performance and can lead to difficulties in track locking. A large \( Q \) may lead to inaccurate state estimation, but it may also provide better noise suppression. The experiment finally reached the following values of \( Q = \begin{bmatrix} 7 \times 10^6 & 0 \\ 0 & 7 \times 10^7 \end{bmatrix} \) to be a good choice. Figure 5 is a frequency of the resulted close-loop frequency response for the fine actuator. Figure 6 is the close-loop frequency response for the sled. One easily sees that the fine actuator can track error up to very high frequency. On the other hand, the sled control loop only has very low bandwidth capability.

\[
\begin{align*}
\dot{x}_2 &= \frac{k_2 s}{M_f s^2 + (B_f + k_2) s + K_f} \notag \\
\dot{x}_4 &= \frac{k_4 s}{M_s s^2 + (B_s + k_4) s + K_s} \notag
\end{align*}
\]

The state space representation of the discrete system then can be expressed as:

\[
\begin{align*}
x_{k+1} &= F_k x_k + G_k u_k + w_k \\
y_k &= H_k x_k + v_k
\end{align*}
\]

The observer is defined as

\[
\dot{\hat{x}}_{k+1} = F_k \hat{x}_k + G_k \hat{u}_k + L_k (y_k - \hat{y}_k)
\]
5. EXPERIMENTAL RESULTS AND DISCUSSIONS

5.1 Parameter Settings

The experimental settings are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum speed $v_{\text{max}}$</td>
<td>200,000 tracks/s</td>
</tr>
<tr>
<td>Maximum acceleration $a_{\text{max}}$</td>
<td>$1.115398 \times 10^7$ tracks/s²</td>
</tr>
<tr>
<td>Fine gain $K_2$</td>
<td></td>
</tr>
<tr>
<td>Constant velocity region</td>
<td>0.000005</td>
</tr>
<tr>
<td>Deceleration region</td>
<td>0.000035</td>
</tr>
<tr>
<td>Sled gain $K_4$</td>
<td>0.0003</td>
</tr>
<tr>
<td>Spindle speed</td>
<td>18X</td>
</tr>
<tr>
<td>Fine saturation voltage</td>
<td>1.8V</td>
</tr>
<tr>
<td>Sled saturation voltage</td>
<td>1.8V</td>
</tr>
</tbody>
</table>

Table 1 Parameter Setting

The numbers are experimentally determined for suitable performance.

5.2 Runout Observation

The following experiments use the observer designed in the last session to study the runout on the optical. First the system is tested for 18 times drive speed. The signals in figures 7-1 and 7-2 are:

- Channel 4: TE (the tracking error signal),
- Channel 3: Seek interval,
- Channel B: Track settling process (Track-following starts when the signal turns low. Locking completes when the signal turns back high again.)
- Channel D: Closer look at the TE signal.

Figures 7-3 shows the velocity portrait of the sled and fine actuators. Comparing figures 7-2 and 7-3, the observed find runout velocity is a little bit higher than the actual measured value, while the sled obviously does not follow the runout motion. The result matches the original design goal to using the fine actuator for the runout and leave the sled unaffected. Figure 7-4 shows the estimated and actual optical head position. It shows not only a periodical runout signal as expected, it is also an indication that the observer is capable of reflecting the needed runout signal.

Figures 8-1, 8-2, 9-1, 9-2, 10-1 and 10-2 shows the runout observation of disk drive running at 4, 8 and 24 times drive speed. Some of the observations are made:

1. First of all, runout can be characterized as a periodic oscillation whose frequency is proportional to the spindle speed but whose amplitude remains relatively unchanged.
2. The fine actuator literal velocity is around $\pm 2 \times 10^4$ (tracks/sec) at 4 times drive speed, while the sled moves at $\pm 2000$ (tracks/sec). When the drive reaches 24 times drive speed, the fine can get $\pm 7 \times 10^4$ (tracks/s), and the sled becomes $\pm 5000$ (tracks/s). That is the wobble velocity of the actuators also increases with increasing spindle speed.
3. The estimated speed is a little bit larger than the actual speed. This can be fixed by lowering the Kalman filter gain; however, this can also cause the position estimation to increase.
4. The position estimation seems to drift with time. This can arise from a bias voltage that has to be applied to the fine actuator.

6. CONCLUSIONS

This paper designed an on-line observer to estimate the disk runout during track accessing. The observer is base on the Kalman filtering technology and is basically easily implemented. Experimental results show that the observer is able to identify the track runout from the random tracking error signal and provide the servo system with an access to the track runout for future runout suppression controller design.

7. ACKNOWLEDGEMENTS

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8. REFERENCES


Figure 7-1. Track accessing signals under 18 times speed
Figure 7-2. Amplified signals to observe the runout signal under 18 times speed
Figure 7-3 Runout velocity estimation for disk drive under 18 times speed
Figure 7-4. The actual and estimated head position under 4 times speed
Figure 8-1 Runout velocity estimation for disk drive under 4 times speed
Figure 8-2. The actual and estimated head position under 4 times speed

Figure 9-1. Runout velocity estimation for disk drive under 8 times speed

Figure 10-1. Runout velocity estimation for disk drive under 24 times speed

Figure 9-2. The actual and estimated head position under 8 times speed

Figure 10-2. The actual and estimated head position under 24 times speed