Consideration on Feedforward Controller Design for Self Servo Track Writer

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Abstract— **In the production process of Hard Disk Drive (HDD), there is a process of writing servo signals on magnetic disks to move the head to target address. However, conventional servo track writer takes longer time to draw servo signals because of recent increase of the capacity of HDD. Therefore, they desire a low-cost method to draw servo signals. In order to resolve the problems, Self Servo Track Writing(SSTW) method which draws servo signals with its own head was already suggested. In SSTW method, there are problems to realize it. One is how to know where the absolute position of head is. The other is that written servo tracks diverge because gain of the feedback controller is higher than 0[dB] in high frequency domain.**

In our past work, new method for SSTW has already been suggested [1][2]. This method is essentially different from other methods, and performance is dramatically improved. However, servo tracks diverge gradually if we apply this method to real product. The purpose of this paper is to make it clear why servo tracks diverge gradually by using Hard Disk Benchmark Software, which is produced by IEEJ Specialized Committee on Servo Technology for Next Generation Mass-Storage System [3]. We concluded that the reason is in measurement noise. Furthermore, consideration for a new feedforward input is discribed.

I. Introduction

Recent years, Hard Disk Drive(HDD) becomes more important device for our society. HDD is now used in many ways. Depending on these huge demands, the capacity of HDD is increasing very rapidly [4].

In the production process of HDD, there is a process to write servo tracks using Servo Track Writer(STW). Servo tracks include a servo sync mark, a track address, and offset information. HDD servo controller uses them to move the actuator with magnetic heads to the target track position. Therefore, it is important to improve accuracy of servo patterns. At the same time, the efficiency of production cost and time for writing should be considered.

The conventional STW, the pushpin STW, has been used for servo track writing for many years. This apparatus writes servo tracks using the encorder which measures the head's absolute position on the disk from outside. However, there are some problems in this system.

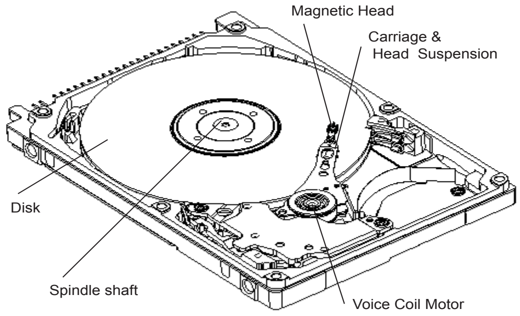

Fig. 1. Overview of hard disk drive

- Width of servo track is getting much narrower than before. Therefore, we should consider disturbances which were ignored in the past.
- It takes too much time to write servo tracks because of higher density of servo track. Therefore, we can't produce them in low cost.
- Servo track writing process should be done in clean room and its maintenance is very costly.

In order to solve these problems, new methods have already been suggested [5][6][7][8][9]. One of them, there is a Self Servo Track Writing method. SSTW writes servo tracks using its own write head and position control system which is installed on each HDD. However, until now, it has been difficult to realize this. In our past work, we applied our method to real product and improved the performance greatly, but servo tracks still diverge gradually. In this paper, we aim to reveal the reason why servo tracks diverge and discuss how to make a new feedforward input.

II. Problems of SSTW

A. Explanation of Servo Track

Track data of HDD consist of two kinds of data, namely servo data and user data. In the production process of HDD, servo data was written on blank disks. HDD needs these servo data to move its head to target address because its head can't know the absolute position by itself. The reason of using relative postion is that there are some disturbances in HDD. Therefore, if we want to control the head precisely, it is important to use relative coordinate.

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TABLE I
DEFINITION OF SYMBOLS

$y_{R,n+1}$	absolute position of the read head when head writes (n+1)th servo track
$y_{W,n+1}$	absolute position of the write head when head writes (n+1)th servo track
$y_{r,n}$	ideal (n)th servo track
$y_{r,n+1}$	ideal (n+1)th servo track
y_n $(=y_{W,n})$	written servo track in (n)th track
l	distance between tracks
N	the number of sectors in one track
Δy_n	the error between written (n)th servo track and ideal n(th) servo track
ξ_{n+1}	sensor noise of (n+1)th track
d_{n+1}	torque noise of (n+1)th track
SPM_{n+1}	RRO and flutter noise of (n+1)th track

In the next section, we will discuss the SSTW in detail.

B. Block Diagram and Conditions of SSTW

In the SSTW method, we use read and write head of HDD to write servo tracks. In order to simplify problems, we suppose that the distance between the read head and write head is equal to the width of track (Fig.2) and servo track which is located in the most inner circle has already written by some ways.

Here, we explain the procedure of servo track writing concretely in the SSTW method. First, when the read head follows first track, the write head writes next track. In next step, the write head writes third track when the read head follows the second track. By repeating these steps, we can write servo tracks one by one.

In this paper, used variables are defined as Table.I. By using these variables, eqs.(1) and (2) are obtained.

$$\begin{aligned} y_n[k] &= y_{r,n}[k] + \Delta y_n[k] && (1) \\ y_{n+1}[k] &= y_{r,n+1}[k] + \Delta y_{n+1}[k] && (2) \end{aligned}$$

In these equations, $\Delta y_n[k]$ means the error between written (n)th track and ideal (n)th track. Therefore, the block diagram of SSTW is shown in Fig.3. In this figure, C is the controller which is well tuned for following mode of HDD. In addition, d and SPM are distrubances. Sensor noise is expressed by ξ in equations.

The gain of feedback controller is higher than 0[dB] in higher frequency domain. Therefore, these disturbances make servo tracks divergent as servo track writing proceeds. The transfer function from the reference input to output is described as eq.(3).

$$\Delta y_{n+1}[k] = \frac{CP}{1+CP}\Delta y_n[k] + \frac{CP}{1+CP}\xi_{n+1} + \frac{P}{1+CP}d_{n+1}[k] + \frac{1}{1+CP}SPM_{n+1}[k] \quad (3)$$

This is the basic equation to express the system of SSTW.

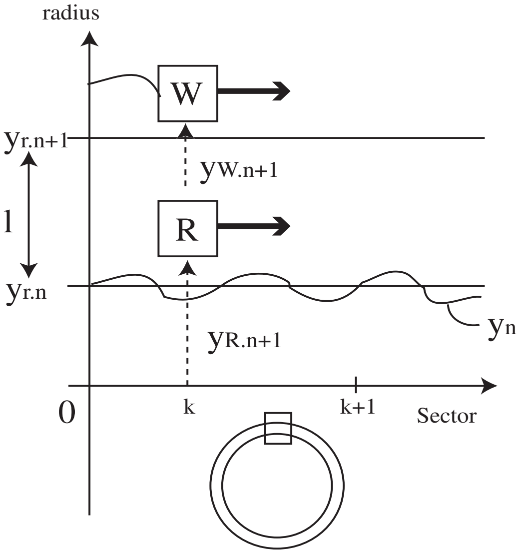

Fig. 2. Coordinates of servo track

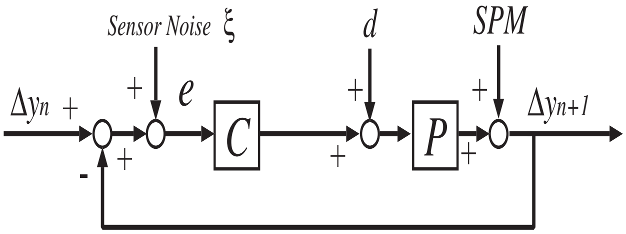

Fig. 3. Block diagram of SSTW with error coordinates

C. Problems of SSTW

It is difficult to realize SSTW because of three major problems as following.

- Gain of the complementary sensitivity function of the control system is higher than 0[dB] in high frequency domain. Hence, disturbances in these frequencies are easily amplified.
- There are some kinds of disturbance, such as wind disturbance caused by disk, sensor noise and repeatable runout (RRO).
- The number of observable signals is limited. In this system, only the position error signals (PES) expressed as symbol "e" is observable.

In the next section, we introduce our method proposed in the past to solve these problems and verify them using Hard Disk Benchmark Software.

III. ESTIMATION OF HEAD POSITION AND DESIGN OF FEEDFORWARD INPUT

A. Estimation of Head Position

One problem of SSTW is that we can't know the absolute position of head as it is pointed in section II. In this section, we introduce an idea to estimate it.

In this system, the observable signal is position error signal (e) described in section II. Position error signal of each track is expressed by eqs.(4)~(6).

$$e_{n+1}[k] = y_n[k] - y_{R,n+1}[k] + \xi_{n+1}[k] \quad (4)$$

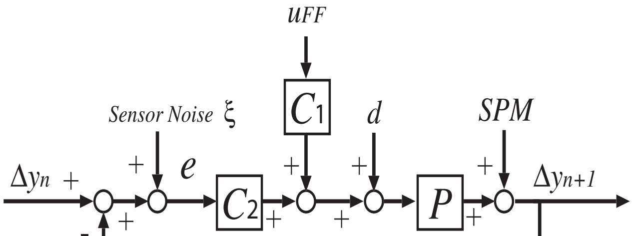

Fig. 4. Block diagram with feedforward input(1)

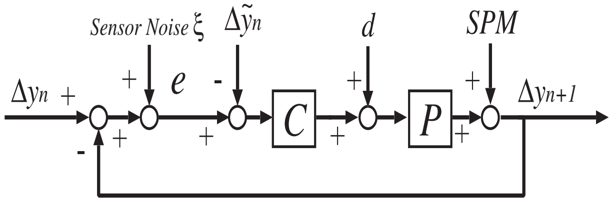

Fig. 5. Block diagram with feedforward input(2)

$$
\begin{aligned}
e_n[k] &= y_{n-1}[k] - y_{R,n}[k] + \xi_n[k] && (5)\\
&\vdots\\
e_2[k] &= y_1[k] - y_{R,2}[k] + \xi_2[k] && (6)
\end{aligned}
$$

By taking the summation in left and right terms respectively, eq.(10) is finally obtained.

$$
\begin{aligned}
e_{n+1}[k] \quad + \quad & e_n[k] + \cdots + e_2[k]\\
= \quad & y_1[k] + (n-1)l - y_{R,n+1}[k] + \sum_{m=2}^{n+1} \xi_m[k] && (7)\\
= \quad & y_1[k] + nl - y_{W,n+1}[k] && (8)\\
= \quad & y_1[k] - \Delta y_{n+1}[k] && (9)
\end{aligned}
$$

therefore

$$
\Delta y_{n+1} \quad = \quad -\sum_{m=2}^{n+1} e_m[k] \qquad (10)
$$

In eq.(7), ”ξ” is the white noise and it means that the sum of ”ξ” equals to be 0. Therefore, we ignore this parameter. In eq.(10), Δy_{n+1} means the error between written servo track and ideal servo track. Therefore, we add Δy_{n+1} to $y_{r,n+1}$, and then get the absolute position of head.

It enables us to solve the problems which have been difficult for previous researches. By using this estimated absolute position, we can design the feedforward input. In the next section, we introduce the actual design of feedforward input.

B. Design of Feedforward Input and Simulation Results

B.1 Design of Feedforward Input

Using the proposed method, we designed a feedforward controller. Fig.4 shows the block diagram, where the feedforward input is added to the configuration in Fig.3. Transfer function is expressed by eq.(11).

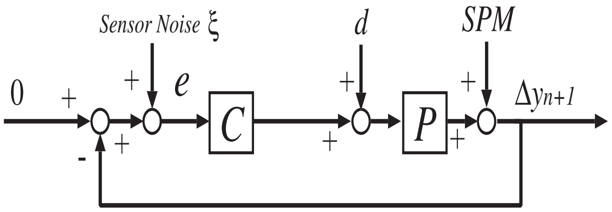

Fig. 6. Block diagram with reference 0

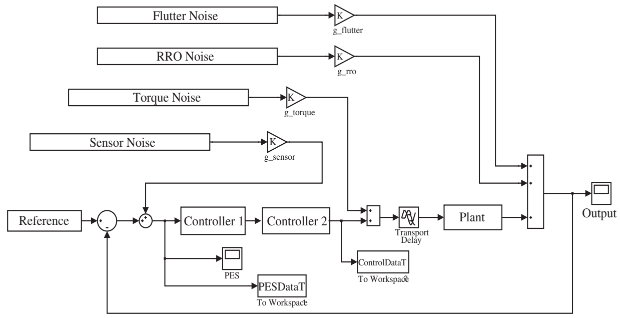

Fig. 7. Block diagram without FF input (Matlab simulink)

TABLE II
SIMULATION PARAMETER

Parameter	value
Disk size	3.5[inch]
Revolution of Disk	7200[rpm]
The number of sectors	220
Sampling Time	37.9[μs]
Track width	2.54×10^{-7}[m]

$$
\Delta y_{n+1}[k] = \frac{C_2 P}{1+C_2 P}\Delta y_n[k] + \frac{C_1 P}{1+C_2 P}u_{FF}[k] \qquad (11)
$$

In eq.(11), we design the feedforward input so that $\Delta y_{n+1}[k]$ becomes 0. In order to realize this, we define the controller and the feedforward input as $C_1 = C_2, u_{FF}[k] = -\Delta y_n[k]$. Then, eq.(12) is obtained.

$$
\begin{aligned}
\Delta y_{n+1}[k] &= \frac{C_2 P}{1+C_2 P}\Delta y_n[k] - \frac{C_2 P}{1+C_2 P}\Delta y_n[k]\\
&= 0 && (12)
\end{aligned}
$$

Therefore, using this feedforward input, we can suppress the error $\Delta y_{n+1}[k]$. Furthermore, block diagram (Fig.4) can be changed into Fig.5. Fig.5 equals to Fig.6. Fig.6 shows that this system follows reference=0, namely ideal servo track. This means that we can write an ideal servo track.

B.2 Simulation Setup

We used simulation software which was produced by IEEJ Specialized Technical Committee on Servo Technology for Next Generation Mass-Storage System[3]. The software was made carefully using MATLAB (Fig.7) so that

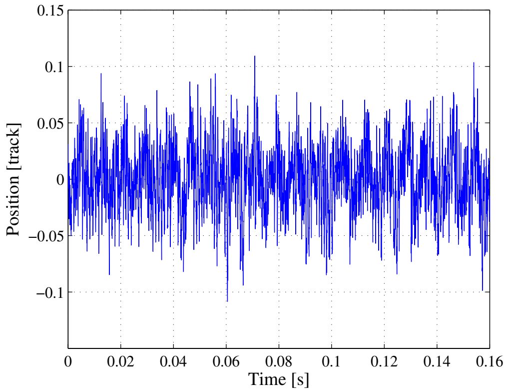

Fig. 8. Time series of output
Appearance of 1st servo track

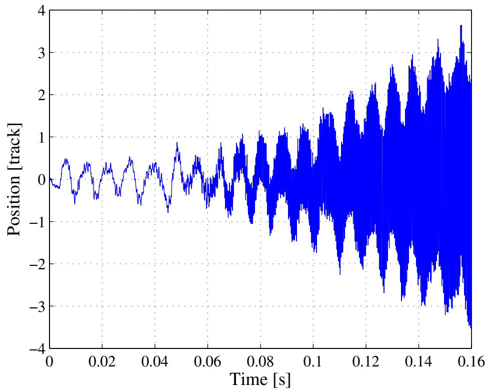

Fig. 9. Time series of output without FF input
Appearance of 20th servo track

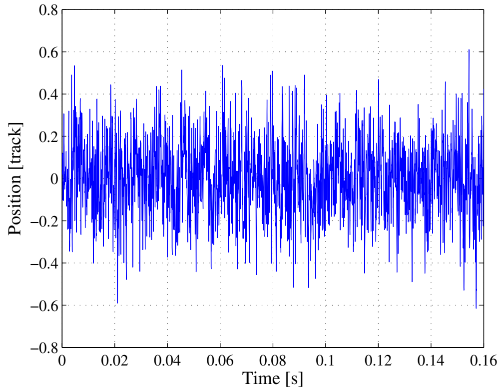

Fig. 10. Time series of output with FF input
Appearance of 20th servo track

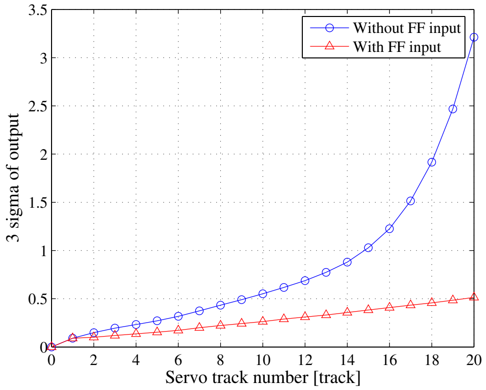

Fig. 11. 3 sigma of output in each track

the simulation results are reliable. Table. II shows simulation parameters. In this simulation, we used PID controller which is well tuned for following mode control.

We explain about how to do the simulation without FF input. First, we run the simulation and store the data, namely output data and PES data. It corresponds to the first servo track. Second, we use the output which we got in the first simulation as reference (in case of the simulation with FF input, FF input should be inputted) and run the simulation. We also store the output data and PES data. It corresponds the second servo track. Third step is the same as the second step. By repeating this step to the target tracks, we finally get a simulation result.

B.3 Simulation Results

Simulation results are shown in Fig.8∼10. Fig.9 shows that servo tracks diverge rapidly without proposed feedforward input. According to Fig.9 and Fig.10, servo tracks become more stable by adding the feedforward input. In order to observe the effectiveness of this feedforward input, Fig.11 shows a 3 sigma of output in each track. Judging from this figure, it diverges exponentially if we do not add FF input. On the other hand, 3 sigma is suppressed if we add FF input. However, servo tracks still diverge gradually with FF input. We think that the cause of this result is in sensor noise.

In order to verify this assumption, Fig.12 is shown. This simulation has done without adding any sensor noise. As a result, Fig.12 is exactly the same figure as Fig.8. It means that the servo track does not diverge without sensor noise. Therefore, we conclude that the cause of divergence is sensor noise.

Analyze this phenomenon using some equations. Transfer function of input in n+1(th) track is written as eq.(13).

$$y_n = \frac{P}{1+CP}d_n + \frac{1}{1+CP}SPM_n + \frac{CP}{1+CP}\Sigma_{k=1}^{n}\xi_k \tag{13}$$

Furthermore, transfer function of feedforward input in n+1(th) track is written as eq.(14).

$$y_{FFn+1} = \frac{P}{1+CP}d_n + \frac{1}{1+CP}SPM_n - \frac{1}{1+CP}\Sigma_{k=1}^{n}\xi_k \tag{14}$$

Subtract u_{FFn+1} from y_n, then eq.(15) is obtained.

$$y_n(=ref) - y_{FFn+1} = \Sigma_{k=1}^{n}\xi_k \tag{15}$$

In eq.(15), right term makes servo tracks diverge. In order to maintain servo tracks stable, right term should be 0. Therfore, we should redesign feedforward input. Our idea is described as eq.(16).

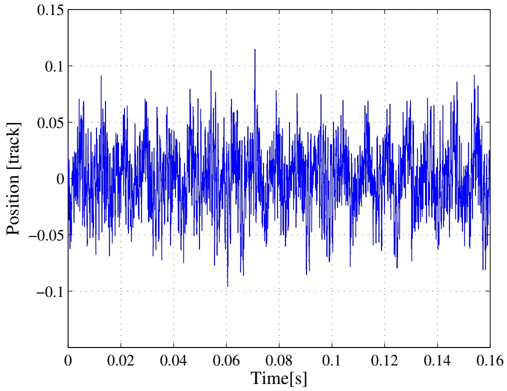

Fig. 12. Time series of output with FF input (20th track, gain of sensor noise = 0)

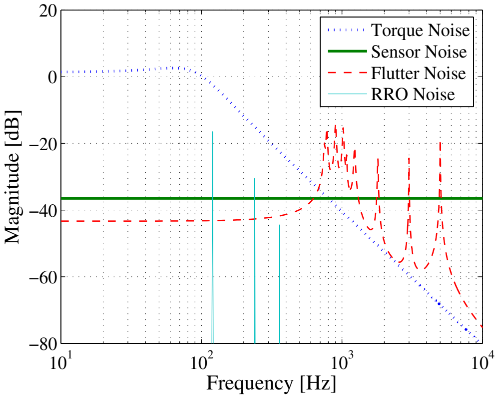

Fig. 13. Noise data in frequency domain

$$y_n - k(s) \cdot y_{FFn+1} = 0 \tag{16}$$

Eq.(16) is described as eq.(17).

$$\begin{aligned}
& y_n - k(s) \cdot y_{FFn+1} \\
&= \frac{P}{1+CP} d_{n+1} + \frac{1}{1+CP} SPM_{n+1} + \frac{CP}{1+CP} \xi_{n+1} \\
&-k(s) \cdot \left(\frac{P}{1+CP} d_{n+1} + \frac{1}{1+CP} SPM_{n+1} + \frac{CP}{1+CP} \xi_{n+1} \right) \\
&= (1-k(s)) \frac{P}{1+CP} d_{n+1} + (1-k(s)) \frac{1}{1+CP} SPM_{n+1} \\
&\qquad + \left(\frac{CP}{1+CP} + \frac{1}{1+CP} k(s) \right) \xi_{n+1}
\end{aligned} \tag{17}$$

We have two ideas how to design the parameter $k(s)$. Details are explained as following.

- $k(s) = \alpha$, where $0 < \alpha < 1$
  If we define $k(s)$ as α, we can reduce the influence of sensor noise. However, the first term and the second term of eq.(17) are not equals to be 0. It means that d and SPM, which are completely suppressed when $\alpha = 1$, should be considered. By selecting proper α, we assume that we can achieve better performance.

- $k(s)$ is filter
  In order to design filter $k(s)$, we need to think about each disturbance. Fig.13 shows the noise data in frequency domain. According to this figure, d, torque noise, mainly has 10∼100 [Hz] disturbance. Therefore, first term of eq.(17) should be 0 in this frequency area. SPM, namely RRO noise and flutter noise, has its peak around 120, 230, 360, 800, 900, 1000, 2000, 3000, 5000 [Hz]. Similarly, second term of eq.(17) should be 0 around these peaks. These are the conditions in designing filter $k(s)$.

In both cases, it is important to define the optimal $k(s)$. How to design the optimal parameter is our future work.

IV. Conclusion and Future Work

In this paper, we have found out the reason why servo tracks diverge gradually when servo track writing proceeds. We concluded that the reason of this phenomenon is measurement noise. Therefore, we should redesign the feedforward input considering the noise. Then, we assume that it is effective to introduce prameter $k(s)$. It can reduce the influence of white noise. However, it also means that parameter $k(s)$ increases the influence of the other disturbances. Therefore, we should select proper $k(s)$. Our future work is to propose how to find out the optimal $k(s)$ and search the other mehod to design a feedforward input.

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