Fuzzy Seeking Control on High Precision Hard Disk Driver

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Abstract -- This paper describes the application of fuzzy logic control on the track-seeking motion in the head-positioning servo mechanism of a hard disk. There are two major operations in the head-positioning servo of a hard disk, *i.e. seeking* and *tracking*. The seeking controller performs minimum-time movement of the read-write heads from their current track position to a target track specified by the file controller. The dynamic behaviors of the head-positioning servo is highly nonlinear, which make the derivations of an analytic model very difficult. Under the circumstances, the increasingly popular fuzzy logic control which does not require an exact mathematical model seems to be a good alternative in controller design. A fuzzy seeking controller is therefore designed and implemented on a high precision hard disk driver, the Zentek ZM3140. The proposed seeking controller can successfully move the read-write head servo mechanism to the desired target track. Our experimental results also show fast responses and robust behaviors of the servo system.

1. INTRODUCTION

To meet requirements of time for smaller, higher performance, and powerful personal computers as well as workstations, hence the Hard Disk Driver (HDD) should have compact, high-speed, and possessing a large amount of storage density and capacity. This is why many researchers dedicated his time to HDD design to keep pace with host computers [1][2][3]. This paper is concerned with the servo side of HDD, that is, head-positioning servo mechanism which provides a means for locating a set of read-write heads in fixed radial locations over the disk surface and allowing the repositioning of these heads from one radial location to another; this servo mechanism also has two major functions, track seeking and track-following. The track-seeking function provides minimum time movement of the read-write heads from its existing track, which is a circular recording band at a specified disk radius, to a different track specified by the file controller. The track-following function maintains the position of the read-write heads exactly over the center of a given track with minimum displacement error in the presence of any possible disturbances. In this paper , we focus on the track-seeking function. The average actuator access time is given by the sum of the average seek time and settling time. The value of average seek time for random seeks is found to be the time to seek to approximately one third of the tracks per recording band. Therefore how to dramatically reduce the average actuator seek time and how to effectively develop a control algorithm is an important work of the research on the HDD.

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Fuzzy has been becoming one of the most famous term in the word, and fuzzy control has been widely spreading its power out in some scientific fields. Fuzzy control is based on fuzzy logic which is very close to human thinking and natural language rather than the two values logic, Basically, it provides an effective means of capturing the approximate, inexact nature of the real world. From a rough knowledge of the system dynamics and input- output relations, we can design a Fuzzy Logic Controller (FLC) having a set of linguistic control rules related by a fuzzy implication rule of inference. Then this FLC convert the linguistic control strategy from experts or operator to an automatic control strategy for the controlled plant. Due to the nonlinear behaviors such as unbalance in the magnetic circuit construction of the actuator, machining tolerances, and unevenness in magnetization of the magnet etc., the analytic model of HDD is variant for every individual track and very difficult to obtain. In traditional control methods, such as Lead-Lag frequency compensator, Hanselmann's LQG/LTR strategy [8], Hasegawa's state feedback method [9], and so on, it needs a mathematical model of system for controller design. On the other hand, approximately reasoning-based Fuzzy Logic Controller (FLC), which have demonstrated a mass of successful applications [4][5], do not require analytic models of controlled plant. We are interested in and motivated by this charming powers, so we decided to use FLC to develop the seeking controller of head-position servo mechanism.

2. SYSTEM DESCRIPTION

2.1 System specifications

The experimental HDD, ZM3140 3.5", 1" height 120 MB is supported by the Zentek Storage Inc., Shin-Chu, Taiwan with the specifications shown in table 2.1. In this head-disk assembly, it is embedded sector servo in which servo information is embedded in the data tracks as prerecorded sectors such that each head provide its own position information. Moreover it has 2 number of disks , 4 number of heads and 1540 number of data cylinders (see Fig. 2.1 and Fig. 2.2).

2.2 Head-Positioning Servomechanism

The head-positioning servomechanism in a hard disk provides a method for locating a set of read-write heads in fixed radial locations over the disk surface and allows the repositioning of these heads from one radial location to another. A block diagram of a typical head-positioning servo with a linear voice-coil motor type, with two arms, 4 heads , and four disks is shown on Fig. 2.2 From the block diagram, we see that the whole controlled plant is composed of the actuator, the amplifier that drives current into the coil, and the position error channel.

The servo system has two primary functions : one is to decide the position of the actuator and the other is to compare the difference of measured and desired position and decide a optimal control to reduce the error as soon as possible [6].

2.3 Position error signal (PES)

One of the important parameters of HDD is the PES ,which is the output of the position error channel and proportional to the relative difference of the positions of the center of the servo head and the nearest track center. Hence the PES is period function of x for stationary and ideal track centers (see Fig. 2.3). The PES results from two sources of motion : motion of the actuator and motion of the disk surface itself. A simple mathematical description of the PES is given by

$$PES = k_x x_e \left\{ MOD[(r-x)+c, w] - \frac{w}{2} \right\}$$

where w = track width

x = radial position of the head

r = track center position reference

c= any constant such that (r(t) -x(t) + c) > 0, for all r, x [6].

2.4 Actuator and Model

As shown in Fig 2.2, actuator prime mover is voice-coil motor (VCM) consisting of a permanent magnet structure and a movable bobbin or coil attached through a T plate to the comb of arms carrying the read-write heads. VCM have antecedents in the motors used in loudspeaker systems. A simple linear model for VCM is a second order system likewise $\frac{J}{s^2}$ where J is a gain constant through a system identification to identify its value. A procedure for identifying our HDD model is to use a white random signal through D/A converter into actuator to move the read -write head reach the target track and then reading the output of position error signal from A/D converter. A collection of input and output data pairs is used in analyzing frequency responses of the system for identifying the gain J. Notice that the gain J is slight varying for different target track. Although FLC is need no any prescribe system model -- this is its main advantage, if we know a approximate rather than precise system model, it would greatly facilitate maters and look insight into the whole system under the development of FLC ,whereas this dependency of operator and expert knowledge is also its drawback.

3. FUZZY SEEKING CONTROLLER

3.1 Structure of Fuzzy Logic Controllers

The basic concept of fuzzy control can be found in many literatures such as [7]. The computational structure of an FLC consists of five major steps which will be sescribed in the following:

1. *Input Scaling* : Basically, it is the multiplication of the physical input value with a normalization factor so that the input is mapped onto the normalized input domain.

2. *Fuzzification* : Let $LE_1^{(i)}, ..., LE_m^{(i)}$ be the linguistic values taken by the process state variables $e_1, ..., e_m$ in the rule-antecedent of the i-th rule. The meaning of each linguistic value $LE_k^{(i)}$ is represented by a membership function defined on the normalized domain ε_n of the process state variable e_k. Thus the meaning of $LE_k^{(i)}$ is given by $\mu_{LE_k^{(i)}} : \varepsilon_n \to [0, 1]$. Let us consider a normalized input vector $e^* = (e_1^*, ..., e_m^*)$, where each of e_k^* is the current normalized measurement. The *fuzification* then consists of finding the membership degree of e_k^* in $\mu_{LE_k^{(i)}}$ this is done for every element of the e^*.

3. *Rule Firing* : For a multi-input/single-output case (MISO) the j-th rule of the set of if-then rule has the form

$$if\ e_1\ is\ LE_1^{(s)} and\ ...\ e_m\ is\ LE_m^{(s)}\ then\ u\ is\ LU^{(s)},$$

where $e_i = x_i - y_i$ is the error with respect to the i-th process state variable x_i, and u is the control output variable, which take linguistic values $LE_i^{(s)}$ and $LU^{(s)}$ respectively. The membership functions of these two linguistic values are denoted by $\mu_{LE_i^{(s)}}$ and $\mu_{LU_i^{(s)}}$ on a common normalized domain. Given an input vector consisting of the normalized measurements of $e_1^*, ..., e_m^*$, the output of the s-th rule is $\mu_{CLU^{(s)}}$ i.e., the clipped membership function for the control output variable u. Then the clipped output fuzzy sets for each rule are combined in the following way :

$$\forall u : \mu_U(u) = \max(\mu_{CLU^{(1)}}, ..., \mu_{CLU^{(s)}}),$$

where μ_U is the membership function representing the value of the overall control output.

4. *Defuzzification* : The result of the rule firing is a fuzzy set μ_U . The purpose of defuzzification is to obtain a scalar value u from μ_U. This is down using the Center-of-Area/Gravity. In the continuous case we have

$$u = \frac{\int_{u \in U} \mu_U(u).udu}{\int_{u \in U} \mu_U(u)du}$$

and for the discrete case

$$u = \frac{\sum_{u \in U} \mu_U(u).u}{\sum_{u \in U} \mu_U(u)}$$

3.2 The seeking Controller

The control law of a conventional PD-controller is

$$u = K_p.e + K_D.\dot{e}$$

where K_p and K_D are the proportional and the differential gain coefficients. While a PD-like FLC consists of rules with the symbolic description is as

if e is <property symbol> and Δe is <property symbol> then u is <property symbol>

where *<property symbol>* is the symbolic name of a linguistic value such as

if e is positive big (PB) and Δe is positive big (PB) then u is negative big (NB) .

In ZM3140 hard disk, the number of tracks in a disk surface is 1560 with 256 units of division between two tracks. The control force is positive if the read-write head seeks in , and vice versa. For practical considerations, the 80196 single chip is used as the computational center of the controller. To reduce the response time of the whole system, we decide to use a look up table for the control implication. However, the trade-off between the hardware memory and the decision table is still required. Therefore to save the hardware memory we perform quantizations on the universe of discourses , and make three decision tables with different input variables under distinct circumstances for the fuzzy seeking controller. The inputs of the fuzzy seeking controller, terr, err_n, tce , and ce_n are defined as:

terr (track error) $\stackrel{\Delta}{=}$ target track - current track

err_n (position error)
$\stackrel{\Delta}{=}$ (target track - current track)* 256 - current PES
= terr*256 - current PES

tce (track change of error)
$\triangleq$ current terr - previous terr
= - (current track - previous track)

ce_n (position change of error)
$\triangleq$ tce*256

Notice that the head position in disk surface is equal to the following:
head position = current track * 256 + PES.

Then three decision tables are constructed and described in the following:

Table 1 is constructed by defining
input variable 1 to be the terr with a universe of discourse of ±600 tracks and a quantization of 12 tracks, and
input variable 2 to be the tce with a universe of discourse of ±10 tracks and a quantization of 1 track.

Table 2 is constructed by defining
input variable 1 to be the terr with a universe of discourse of ± 12 tracks and a quantization of 1 track, and
input variable 2 to be the ce_n with a universe of discourse of ±256 units of division and a quantization of 32 units of division.

Table 3 is constructed by defining
input variable 1 to be the err_n with a universe of discourse of ±256 units and a quantization of 32 units of division, and
input variable 2 to be the ce_n with a universe of discourse of ± 16 units of division and a quantization of 1 unit of division.

Notice that the three tables actually share the same decision table with a properly scaling factor to modify the universe of discourse. The input and output membership function are taken a shape of triangular for each term set (see Fig. 3.2 (a)) and the rule base is also shown in Fig. 3.2 (b). The inference and output defuzification method are max-min implication and center of gravity, respectively.

4. Experimental Apparatus and System Setup

The experimental apparatus and system setup is depicted in Fig. 4.1. The experimental apparatus have the 80196 in circuit emulator, ZM3140 hard disk driver, power supply, 80486 personal computer, shock-resistant pad, oscilloscope and universal counter. The hard disk driver is placed on the shock-resistant pad to avoid unusual vibration. And the connection of devices is through RS232 cable to construct a closed control loop. Furthermore the controlled plant is a voice-coil motor (VCM) which carry the read-write head servo mechanism to move the head to the desired target track as soon as possible and is driven by a VCM driver. The input of controller is the position error signal (PES) with 220 millisecond interrupted period from the position error channel ,and then the controller bases on the PES to get the absolute position in the disk surface. After comparison the target track with the current track number, the controller decide a control force to the VCM driver. Our controller is constructed on 80196 in circuit emulator (ICE) which is a device of emulating a 80196 single chip to help the development of controller during the design period. After the controller design is accomplished, we load the control programs into the Read Only Memory (ROM) rather than ICE such that this control algorithm can implemented on commercial products.

5. Experimental Results

The results of a read-write head moving from the 1500th track to 1000th track is depicted in Fig. 5.1. Fig. 5.1 (a) is a step response of the track number in which the response is no overshoot. In Fig . 5.1 (b), we see that the position error signal (PES) is getting to steady state in about 20 ms. Fig. 5.3 (c) is a state trajectory of error and change of error in phase plane. Finally, Fig. 5.1 (d) is a control force driving the voice-coil motor; With a comparison to the control force of the bang- bang control [2] , we have some advantages such as the control effort in FLC is less than that of a bang-bang control and the temperature on the HDD is also less than a bang-bang control . This is one of reasons that inhere in FLC -- why it is robust with a rejection from temperature and other disturbances.

6. Conclusion

We propose a fuzzy seeking controller implemented on a high precision cpmmercial hard disk driver. The experimental results show that this seeking controller can successfully move the read-write head servo mechanism to the desired target track with fast response seek time and robustness property. Hence we conclude that FLC is able to do a precision motion control on a commercial HDD.

7. Reference

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Number of disks	2
Number of heads	4
Track density (TPI)	1850
Bit density (BPI)	36k
Number of data cylinders	1540
Number of data tracks	6160
Sector size	512 Bytes
Sectors per track (Average)	40
Disk rotation (RPM)	3390

Table 2.1 Specifications of ZM3140 3.5", 1" Height 120MB Hard Disk Driver

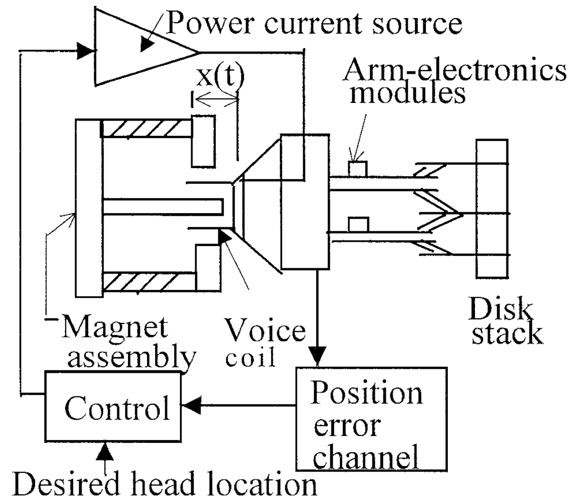

Fig. 2.2 Block diagram of a typical head-positioning servo mechanism

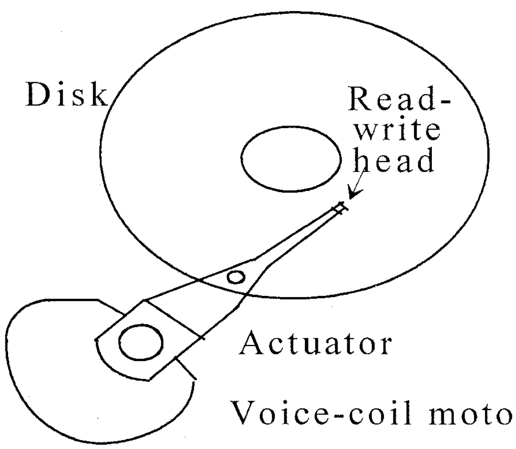

Fig. 2.1 ZM3140 3.5" , 1" height 120 MB HDD

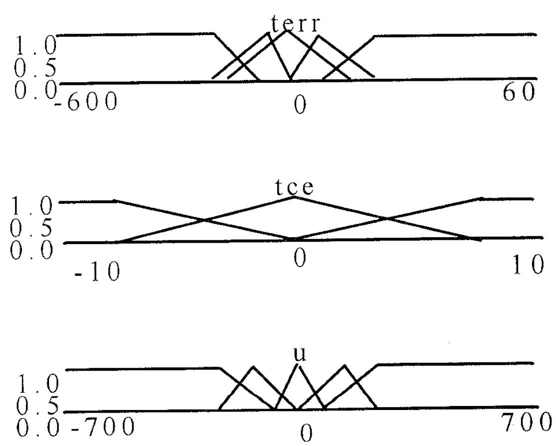

Fig. 3.2 (a) Membership function

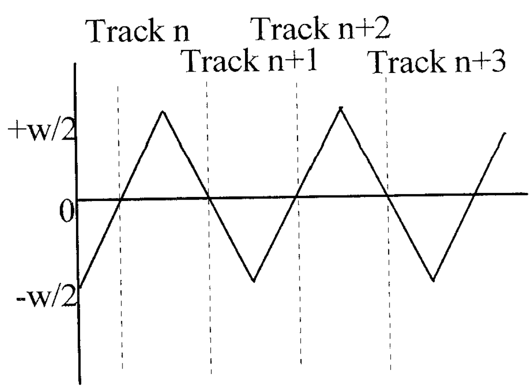

Fig. 2.3 A typical position error signal (PES)

U		TCE NB	TCE ZE	TCE PB
TERR	NB	NB	NB	ZE
	NS	NB	NS	PS
	ZE	NS	ZE	PS
	PS	NS	PS	PB
	PB	ZE	PB	PB

Fig. 3.2 (b) Rule base

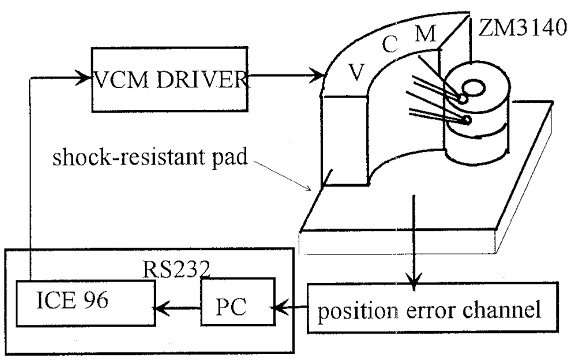

Fig. 4.1Experimental apparatus and setup

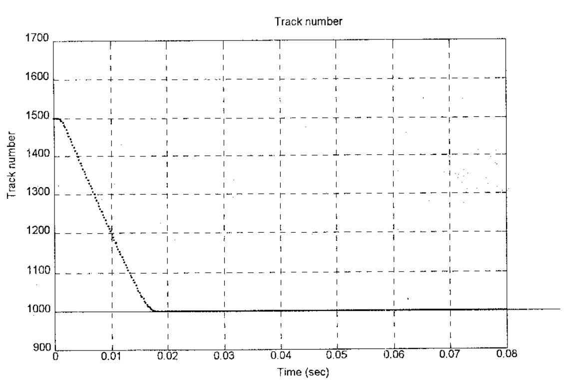

Fig. 5.1 (a) The step response of the track number

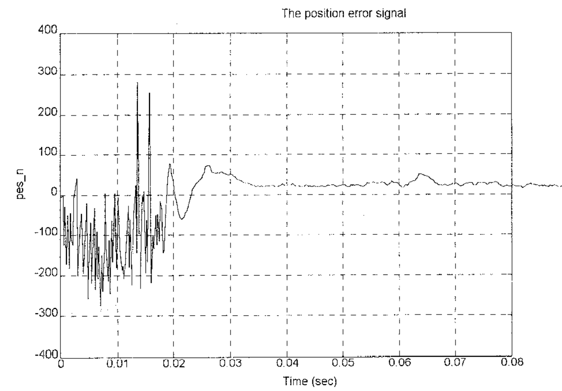

Fig. 5.1 (b) The position error signal

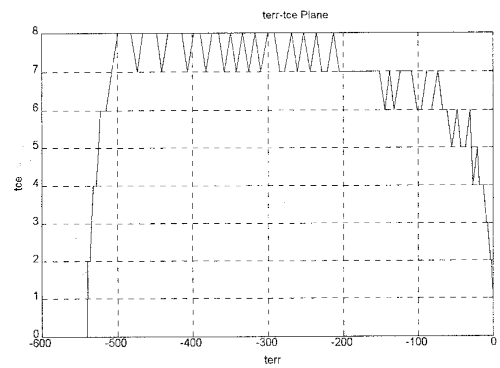

Fig. 5.1 (c) The phase plane of the state trajectory, error (e) and change of error (ce)

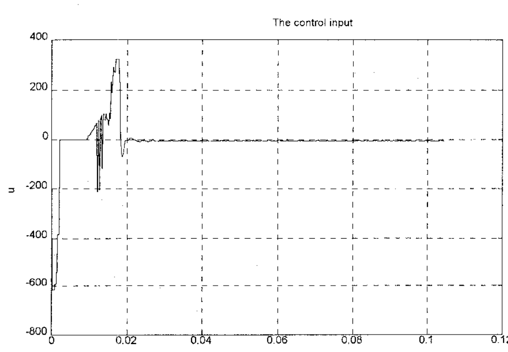

Fig. 5.1 (d) The control force (u)