CONTROL STRATEGIES FOR WRITING SERVO TRACKS 
NARROWER THAN 5 MICRO INCHES

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ABSTRACT

Hard disk drives have crossed the 90,000 tracks-per-inch mark in year 2002 without using the much desired dual-stage actuators. In this paper, we will discuss some possible problems facing the servo system design in servo track writer for achieving narrower than 5 micro-inch track width. Problems such as feedback information configuration, control system structure, servo problem formulation, and servo loop shaping, will be discussed.

1. INTRODUCTION

The areal density of hard disk drive (HDD) products is keeping at the 100% compound annual growth rate (CAGR) curve although the laboratory demonstration of areal density has slowed down to about 60% CAGR in year 2002-2003 [1]. To sustain the areal density growth, the track density, measured by track per inch or TPI, should grow faster than the linear density, measured by bit per inch or BPI. Higher TPI places a big challenge on the read/write head design to achieve smaller critical dimensions, as well as the servo-mechanical system to support the positioning of the R/W head with a standard deviation of a few nano meters.

Traditionally, achieving higher position accuracy for higher TPI has been realized by scaling. Advancement in component designs as well as HDD mechanical system design have resulted significant reduction of vibrations induced by electromagnetic force, disk-spindle pack imbalance, ball/liquid bearing [5], air-flow [3, 7, 18], electronics and servo control schemes [4, 9]. Structural vibrations have been reduced via alternative material/structure in disk, actuator assembly, as well as feedback control using instrumented suspension, active damping with sensor buried on the arm, feed forward control accelerometers mounted on HDD housing, as well as sensor assisted disk vertical vibration control [13]. Furthermore, the ever-lower flying height might cause more friction in the head disk interface, and hence there is a need for an effective servo to deal with frictions.

Now that HDD TPI has been growing so rapidly, so are the requirements on the servo track writing (STW), the process to define the servo tracks on the disk surface [10] [12] [14]. Since the tracks are defined at the STW, any misalignment will limit the TPI achievable As well as the repeatable runout (RRO) written on the disk. More RRO means the HDD servo loop needs to have more effort on it, and thus there is less power for the non-repeatable runout, or NRRO.

Since the STW servo shares a lot of similarity with the HDD servo, in what follows, we will examine the basics of servo limitations, and then move on to the discussions of servo strategies for writing servo tracks narrower than 5 micro inches.

2. LIMITATIONS OF CONTROL

High bandwidth actuation has always been desirable for achieving higher positioning accuracy. Increase in the servo bandwidth has been achieved by stiffening the actuator via change actuation structure [17], alternative actuator material, weight reduction, active damping, instrumented suspensions for vibration attenuation and even simply by increasing the position error signal (PES) sampling frequency [16].

![HDD servo loop block diagram.](image)

When pushing the performance of the servo system, it would be interesting to know what are the limitations to the control. Assume that the actuator model and servo controller are represented by \( G(s) \) and \( C(s) \), the disturbance and noise models are \( S_P \) and \( S_N \) respectively (Fig. 1). The sensitivity and complementary sensitivity transfer functions \( S(s) \) and \( T(s) \) could be represented as:

\[
S(s) = \frac{1}{1 + G(s)C(s)}, \quad (1)
\]

\[
T(s) = \frac{G(s)C(s)}{1 + G(s)C(s)}
\]

Hence the PES(s) can be described as following:

\[
PES(s) = T(s)S_N(s) + S(s)S_P(s)
\]

Before we discuss the limitation of control, let's visit the Bode Integral Theorem [15, 19]:

A continuous SISO linear time-invariant system has a
stable transfer function \( G(s)C(s) \). When the closed-loop system is stable and \( k_c = \lim_{s \to \infty} sG(s)C(s) \), then

\[
\frac{1}{\pi} \int_{-\infty}^{\infty} \ln |s(j\omega)| \, d\omega = -\frac{1}{2} k_c
\]

(3)

where \( S(s) \) is the sensitivity transfer function. This theorem explains the existence of waterbed effect in most servo loops.

Fig. 2. Illustration of the waterbed effect.

**Waterbed effect in single stage servo**

The single stage actuator employs a voice coil motor having a slope of \(-40 \text{ dB/decade}\) and hence a \(1/s^2\) behavior. Typical PID type controller will add one more \(1/s\) section in the open loop transfer function. Applying (3), it is easy to see that \( k_c = 0 \), and hence

\[
\frac{1}{\pi} \int_{-\infty}^{\infty} \ln |s(j\omega)| \, d\omega = 0
\]

(3)

meaning that at some frequencies if \(|s(j\omega)| < 1\), it is necessary that at some other frequencies \(|s(j\omega)| > 1\). With such a relationship, vibration rejection at some frequencies will cause vibration amplification at other frequencies.

In case the integral action in the controller is not needed and a pure velocity, or acceleration feedback is available by adding additional sensors, then \( k_c \) might be greater than 0, resulting in more vibration attenuation than amplification with a continuous time controller. With limited sampling frequency, a digital servo loop will have more vibration amplification than a continuous time servo loop of the same bandwidth.

**Waterbed effect in dual-stage servo**

In dual-stage servo, the secondary stage actuator helps to achieve higher servo bandwidth but not necessarily lower sensitivity peak.

MEMs based micro-actuators having a \(1/s^2\) type frequency response will produce the same bode integral, and hence the water bed effect. Similar to the discussion on VCM, MEMs actuators having velocity and/or acceleration sensor can help to achieve a lower Bode integral value, and hence, more vibration rejection with the same servo bandwidth.

PZT actuated suspensions and sliders have a flat frequency response in a wide frequency range. In case the resonant modes are very high, a pure gain can model the actuator model fairly accurately [23]. In this case, the secondary stage actuator loop can bring down the sensitivity transfer function peak to practically close to 0 dB [24].

4. DEFINING THE SERVO TRACKS

Servo Track Writing (STW) is the process to fill the servo pattern on the disk platter so that the HDD servo system can later retrieve and calculate the relative position of the reader relative to the track center. Comparing with the HDD servo system, the requirements on the accuracy of the bursts will be more stringent because the non repeatable vibration during the STW process will later appear as RRO, and cause a lot of stress to the servo system to follow later.

Over the years, there has been a focused interest on patterned media (and thus eliminates the need from the STW) using technologies such as nano-imprint. However, such kinds of approaches potential to achieve minimum dimensions of less than 100 nano meters will have to resolve issues like throughput and so on to produce the patterned media cost-effectively [20, 21]. Next we will compare the STW technologies, namely (1) conventionally STW, (2) media STW, and (3) self STW, and see the control limitations when writing servo tracks of less narrower than 5 micro inches.

**Conventional STW**

Traditional STWs use absolute position signal provided via contact pushpin or non-contact way of optical pushpin [10].

Using the notation in Fig. 1, conventional STW's feedback is the absolute head or arm position depending on where the sensor is placed. As such, even if the feedback sensor is non-contact sub nano-meter resolution offered by the digital laser vibrometer, and the control system is of higher bandwidth such that the head position is controlled accurately, the disk and motor radial vibrations will still move the track center around. Currently, the radial NRRO of spindle motors is in the micro-inch range. Disk vibration is extra. These two factors together cause the movement of the target track center that is not included in the feedback control and thus cannot be corrected by position feedback control using an external position sensor.

To see how the disk-motor movement affects the STW process, consider a track width of about 5 micro inches.
A motor with an NRRO of half a micro inch will cause a vibration of 10% of the track width. As such a gap of about one micro inch has to be left between the neighboring two tracks so that the disk vibration will not cause the neighboring tracks being erased.

Media STW

Fortunately, STW can be done in the factory production line, and thus, one can invest in tooling and equipments, and use alternative process to perform the servo writing.

Media servo track writers use air-bearing spindles to reduce the spindle induce vibration. It further improved the throughput by writing multiple disks simultaneously. Since it is a dedicated system for STW, various ways of vibration reduction such as different types of shrouding or alternative STW spindle speeds that are not economical in HDDs can be implemented here.

Nevertheless, air bearing spindle motors have a NRRO of about 10 nm (3σ). Considering the disk NRRO, there will be more than 10 nm of track center movement that cannot be compensated for. Alternative ways still need to be sought after to compensate for the disk and motor vibrations to improve the STW quality.

Self-Servo Track Writing

Self-servo track writing (SSTW) uses the read/write head to sense previously written tracks to place the next track, and thus the feedback signal is the head’s relative distance from the previously written track [11, 12]. Such a structure includes the disk and spindle vibrations in the servo loop, making it possible for the servo loop to compensate for the vibrations.

SSTW is easier to work in small form factor HDDs, such as 1 inch HDDs, than in large form factor HDDs such as 3.5 inch primarily due to the fact that large form factor HDDs have higher level of vibrations, and thus have more error sources to prorogate from one track to another. Efforts have to be made to contain the error propagation via algorithms, or different configurations to reset the errors, so that the whole disk can be written instead of stopped half way due to missing of previously written track information, or accumulated position errors.

To place narrower servo tracks closer without being limited by the spindle motor runout, next we will show a hybrid type STW which can be viewed as a combination of conventional STW and the SSTW.

4. HYBRID STW FOR TRACKS NARROWER THAN 5 MICRO INCHES

Fig. 3 shows the configuration of our hybrid STW. In the experimental setup, we used a fluid bearing spindle motor which rotates a 2.5 inch glass disk of 1.27 mm thick at 5,400 rpm. As shown in Fig. 3, a MicroE micro positioner rotates an actuator arm embedded with a PZT chip (“A” in the figure) so that arm can be deflected and hence the head (“B”) moved. With such a micro actuation, we have the flexibility to control the fine movement of the commercially available head-suspension outside the MicroE loop. We note here that actuated suspension or slider or head is more preferable for the fine positioning than the “PZT actuated arm”. A clock head (“D”) and a VCM assembly (“C”) are also available in the setup. The spacer ring (“E”) provides the features for perfectly balancing the disk-spindle pack.

The control block diagram is shown in Fig. 4. Here $P_1(s)$ is the MicroE arm model, $C_1(s)$ represents the controller available in the MicroE, $K(s)$ represents the model (scaled to 1 for simplicity) of the optical sensing device, $n_1$ is the noise in the sensing loop. The PZT actuator loop in the MicroE arm is modeled as $P_2(s)$, with its controller represented as $C_2(s)$. $n_2$ represents the R/W head position. $n_{nf}$ represents the n-th track written on the disk, $v_1$ represents the suspension and slider vibrations, $v_2$ represents the spindle and disk vibrations, $y_{nf}$ represents the track center of the n-th track, $y_2$ represents the measured difference between the track center of the n-th track and the track to be written, $n_3$ represents the measurement noise using the R/W head. Two feed-forward signals, $u_3$ and $u_4$, are employed. $u_3$ is the measured previous track RRO signal (i.e., $T_{n-1}$) with $C_2(s)$ cut open, $u_4$ is the filtered value of $y_1$.

Fig. 3. Experimental setup.

Fig. 4. Block diagram of the control system.
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\[ C_2(s) \] is designed such that the PZT loop compensate for the vibrations between head and media, i.e., the head position \( Y_2(s) \) follows \( V_2(s) - V_1(s) \), to minimize written-in error. The reading element is used as the sensor to measure the vibrations. We note that taking out \( T_{n,1} \) from the loop (by injecting \( u_t \)) relaxes the error propagation problem and reduced the written-in error compare with the self-servo track writing method \([12]\).

In view of Fig. 4, we have

\[ Y_1(s) = \frac{P_1(s)C_1(s)}{1 + P_1(s)C_1(s)} R(s) \]  \hspace{1cm} (4)

By ignoring \( T_{n,1}, n_2 \) and \( u_e \), we also have:

\[ Y_1(s) = \frac{1}{1 + P_1(s)C_1(s)} [V_2(s) - V_1(s)] \]  \hspace{1cm} (5)

As such, the PZT actuator can attenuate the head and disk vibrations by including them in the feedback loop, using the R/W head as the sensor instead of the external optical sensor. Furthermore, the selection of controller \( C_2(s) \) for vibration \( V_2(s) - V_1(s) \) rejection and noise \( n_2 \) attenuation can follow the same way as in HDD servo design as shown in Fig. 1.

Since our “actuated arm” has a prominent resonant mode at 1.1 kHz, we only achieved an open loop cross over frequency of 400 Hz. With such a feedback loop, vibrations below 200 Hz can be attenuated. After the servo writing process, we’ve measured the NRRO with a \( \sigma = 4.97 \) nm. Fig. 5 shows the PES spectrum with and without the PZT loop. As shown in the figure, the PZT loop effectively rejected the vibrations below 200 Hz.

**Fig. 5.** PES spectrum with and without PZT loop.

Using the vibration model obtained with the setup, simply elevating the bandwidth to 1.2 kHz in simulation which is only half of the bandwidth achievable by an actuated suspension can bring down the \( 3\sigma = 13.6 \) nm. Further increasing the open loop bandwidth to 2.2 kHz resulted in a \( 3\sigma \) of 12.8 nm. Assuming that a 10% track width is required of the \( 3\sigma \), such a STW configuration can easily support writing servo tracks of about 5 micro inches on the fluid bearing motor.

In the above discussion, we only explored the extension the servo bandwidth without carefully looking at the servo loop shaping. As discussed in Section 2, PZT actuators with substantially high resonance or microactuators with velocity sensing can help to bring down the sensitivity transfer function peak such that more vibration attenuation and less amplification can be achieved. With these control, actuator and sensor technologies, we can expect the PES spectrum with the control loop on to be lower than the case without control, and those spikes at 1.7 and 2.7 kHz in Fig. 5 attenuated as well, and thus hybrid servo track writing for lower than 5 micro inch tracks achievable.

**5. CONCLUDING REMARKS**

In this paper we discussed some basic issues in servo systems for servo track writing. Due to the lack of disk and motor NRRO information, STW using absolute head position will inevitably be limited by the motor and disk NRRO level. SSTW, on the other hand, inherently has the information structure to attenuate the disk and spindle NRRO without using high quality external position sensor. We further show a hybrid STW example, in which optical position feedback loop determines the average track center whereas the previously written servo information determines where the next servo burst is laid. The control design philosophy for the PZT actuator loop follows that of HDD servo control design. Limited by the head width and the PZT actuator bandwidth, we only achieved a PES \( \sigma \) of 4.97 nm. With a right R/W head and proper actuated suspension, we project that the system can perform STW of tracks narrower than 5 micro inches. We further pointed out that sensor and actuator technologies can help to alleviate or eliminate the waterbed effect, and help to achieve servo track writing at even narrower track width.

**REFERENCES**


