Precision Control of Hard Disk Drives

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Imagine that you are flying an airplane at a speed of 1,500 miles/s, 1/16 in above the ground, on a highway with 100,000 lanes, each of which is only 1-in wide. Moreover, you are expected to change lanes frequently and then follow the new lane with the same precision. The lanes are not straight but wavy. You cannot see continuous lane markings as markings appear only at regular intervals. If you can visualize the problem of controlling such an airplane, you can comprehend the task of the head-positioning servomechanism of a hard disk drive (HDD). Scaling down the size of the airplane scenario by a factor of 10^5 results in the control problem found in an HDD. From the earliest days of HDDs, accessing data on rotating disk media has provided a wealth of control challenges with practical and economic implications. Reference [1] provides a fascinating journey through the history of HDD control explaining the interaction between the development of components and the control loop.

In an HDD, data is recorded on concentric tracks of a disk spinning at a speed of at least 6,000 rev/min (100 rev/s). These data tracks are far from perfect circles due to the lateral and vertical motion of the disk, imperfections in the bearings of the spindle motor, and disturbance forces acting on the read/write actuator arm while creating the data tracks. The distance between two adjacent tracks is typically 10 μin or 250 nm. In other words, track density (the number of tracks created per unit length along the disk's radius) is 100,000 tracks/in (TPI). Figure 1 shows a small segment of a track.

The data tracks are defined by prerecorded magnetic reference patterns called servo sectors, which are spaced several degrees apart. All of the tracks in a drive have the same number of servo sectors, usually between 100 and 150. The servo sectors of one track are aligned with those of the adjacent track, forming a radial pattern that resembles the spokes of a bicycle wheel. The track segments between servo sectors are used for storing data. The HDD spins at a constant angular velocity, and therefore the time needed to scan between two consecutive servo sectors is constant. This scanning time, which is about 50 μs in most commercially available 3.5-in drives, is the sample interval for the head-positioning servomechanism. Specifications for the servomechanism demand a position error of less than 10% of the track pitch, which corresponds to less than 1 μin or 25 nm in today's drives. Track density is projected to reach 500,000 tracks/in in 2007, particularly for small form factor drives (HDDs with disks of diameter 2.5 in or smaller). Specifications for such drives require an error tolerance of 0.2 μin or 5 nm.

Although the HDD market is currently dominated by products having a 3.5-in form factor, smaller form factors have recently shown a growth potential comparable to those of the 3.5-in drives in the early 1990s. Starting in 2003, the growth in production volume of 2.5-in, 1.8-in, and 1.0-in drives has been 36%, 380%, and 55%, respectively. Global shipment of small form factor drives (2.5 in and below) was 50 million units in 2003 and is projected to reach 100 million units in 2006. The insatiable demand of laptops and consumer electronics such as MP3 players and video cameras is the main driving force behind this growth. Although increasing track density requires tighter error tolerance for the servomechanism, stringent specifications are also necessary due to the diversified applications of HDDs. For example, a drive used in a camcorder must be able to withstand much larger vibration than a drive in a desktop PC.

The read/write head is positioned through a voice coil motor (VCM) actuator to which the heads are attached using a thin stainless steel suspension. Stringent control specifications must be met in the presence of various factors such as 1) bounded control signal, 2) friction of the actuator pivot reducing low frequency gain, 3) structural vibrations of the actuator arm, suspension, and head-slider assembly, 4) vibration induced by the air flowing at high speed around the suspension arm, 5) lateral and vertical motion of the disks (runout), and 6) external shock and vibration. The servomechanism is expected to move the read/write head from one track to another in minimum time (track-seek mode) and regulate head position precisely on the center of the track during track-following mode. Near time-optimal control is widely used for the seek mode, while linear control such as proportional-integral differential (PID) plus loop-shaping compensation is used for track following. Advanced compensation techniques have also been suggested for enhancing the performance of the servo controller [2]–[4].

Dual-Head Actuation

It is remarkable that HDD specifications have so far been met with a cost-effective solution using a single VCM actuator. However, the trend of decreasing error tolerance has motivated researchers to search for alternative technologies that can meet the challenges of future disk drive generations. The distance between the point of actuation and the point of control (that is, the read/write head) is large compared to the precision demanded of a VCM actuator. Moreover, energy from the lightly damped

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modes of the arm and suspension is transmitted to the point of control. A secondary stage actuator placed near the head-slider can provide a solution to these problems. Several possibilities have been suggested to realize this secondary actuation, including 1) a piezoelectric actuator on the suspension arm, 2) a microelectromechanical system (MEMS) actuator between the suspension and slider, and 3) a MEMS actuator as an integral part of the head-slider. Although these options have been tested in laboratories, a drive with secondary actuation has yet to reach the market. Cost and fragility of the secondary stage are critical factors delaying the commercial production of such drives. Physical size of the drives and ruggedness of the components are more important than ever before. In view of the efforts of researchers in industry, universities, and research institutes, it may not be long before HDDs will perform track following with a dual-stage actuator. A list of these efforts is given in [5].

A lightweight, secondary-stage actuator placed close to the point of control performs better than a single-stage actuator in regulating the position of the read/write head above the center of the track. A commonly used criterion for evaluating the performance of the track-following controller is the standard deviation σ_{pes} of the position-error sensing (PES) signal. Achievable track density is related to this standard deviation, and $3\sigma_{\text{pes}}$ is widely regarded in the HDD industry as a measure of the track pitch. Histograms of the PES signals for two configurations, namely, servo control using VCM alone and servo control using a dual-stage actuator with piezoelectric secondary stage, are shown in Figure 2. The standard deviations of the two configurations are 0.015 μm and 0.010 μm, respectively. While the tracking performance is slightly improved using the dual-stage actuator, the secondary stage also helps to significantly reduce the time taken to move the read/write head from one track to another during a short seek. The step response of a dual-stage actuator is shown in Figure 3. With a step command applied at $t = 1$ ms, the head-slider reaches the target in about 1 ms. Although the VCM response is sluggish (requiring about 2 ms), the overall response is improved. However, this improvement in response time is significant for small step commands only. Since the maximum deflection of the secondary stage is restricted to less than a few microns, maneuvers for large step commands are dominated by the VCM's response, in which case the secondary stage provides negligible improvement.

The performance shown in Figures 2 and 3 is obtained using a piezoelectric secondary stage fabricated as part of a suspension arm. A secondary stage mounted on the head-slider or between the suspension and head-slider is expected to perform better during the track-following mode. This further reduces the $3\sigma_{\text{pes}}$ and, thus, enables higher track density. References cited in [5] report successful realizations of MEMS-based secondary actuation in an HDD.

Another trend in the HDD industry is the reduction of the flying height, the gap between the head-slider and disk. In the near future, we expect to see drives supporting flying heights of less than 10^{-12} m. At such low flying heights, the fluid-dynamic forces acting on the slider become a dominant source of disturbances. In addition, nonlinear friction of the ball bearings in the actuator pivot will be significant for the servo loop aiming to meet an error budget at subnanometer scales. To address these issues, development is required in all aspects of the servo loop, including actuation, sensing, and control algorithms. Efforts are underway in industry and in many research organizations to find solutions that can help sustain the growth rate of track density.

References

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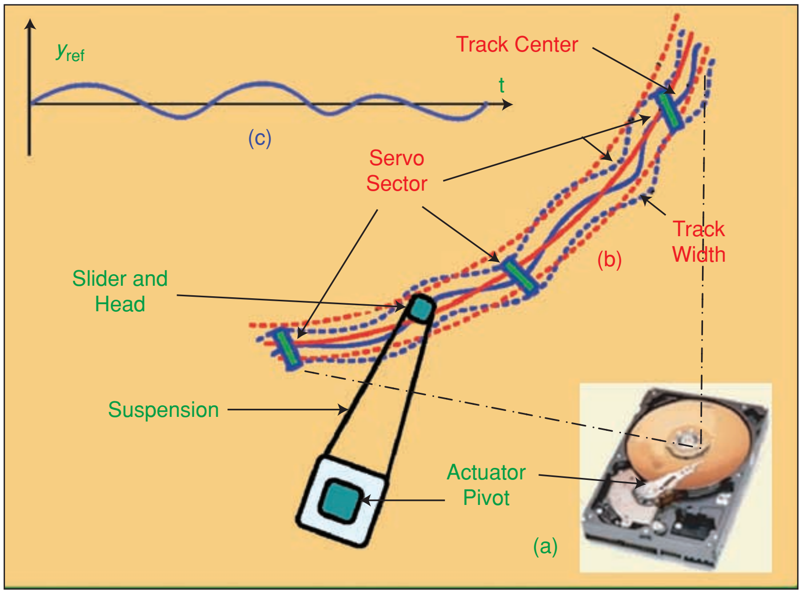

Figure 1. *Data tracks in a hard disk drive, which are anything but perfect circles. (a) A hard disk drive. (b) Graphical representation of a small segment of a data track. The solid lines represent the center of the track. Red denotes the ideal circular track and blue denotes the actual track. The dotted lines are the track boundaries. (c) The reference signal* y_{ref} *for the head-positioning servomechanism, which corresponds to the center of the track, is wavy in accordance with the noncircularity and imperfect nature of the track. These effects are due to imperfections in the process used to create the reference signal, called servowriting. Furthermore, this reference signal cannot be measured directly. The feedback signal in a hard disk drive servomechanism is the error between the position of the head and* y_{ref}*. In the servowriting process that occurs at the time of manufacturing, magnetized spatial patterns are created in each servo sector for use as a reference for the track center. The off-track displacement of the head modulates the amplitude of the voltage waveforms when the read head scans these patterns. These short-span voltage waveforms are known as servo bursts. The position-error sensing signal, which is proportional to the error between the head and the track center, is obtained by demodulating the servo burst waveforms.*

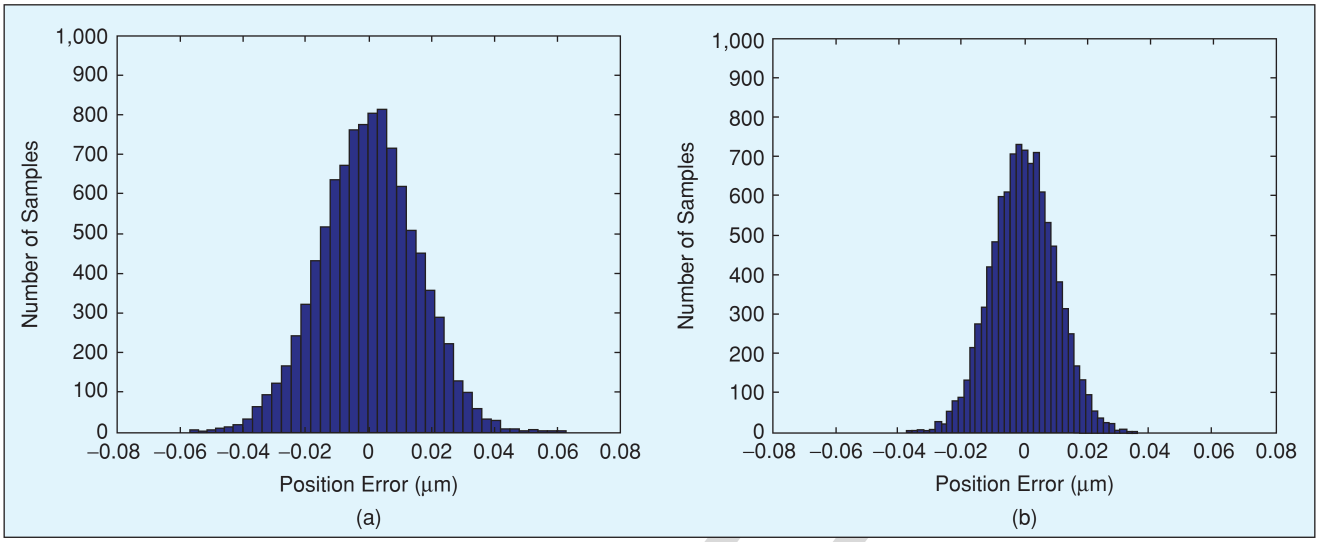

Figure 2. *Position-error sensing signal histogram. These plots show the effectiveness of a dual-stage servo system over a single-stage servo: (a) VCM only,* $\sigma_{pes} = 0.016\ \mu m$*, and (b) VCM plus piezoelectric secondary stage,* $\sigma_{pes} = 0.010\ \mu m$*. Courtesy of the Mechatronics and Automation Laboratory, National University of Singapore.*

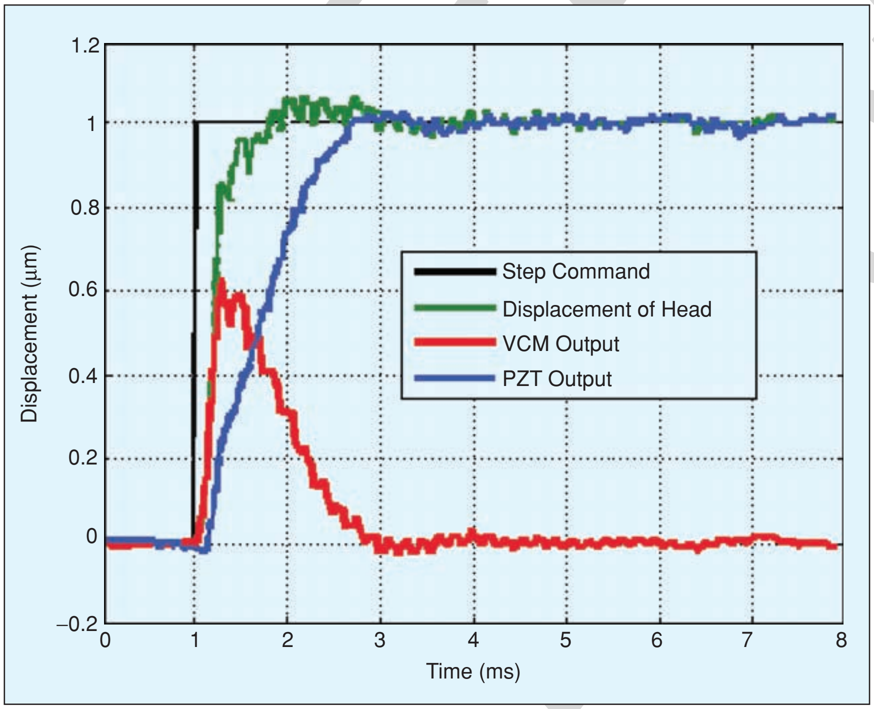

Figure 3. *Step response of a dual-stage actuator. This actuator uses a voice coil motor as the primary stage and a piezoelectric actuator as the secondary stage. The green line shows the combined head displacement response for the reference step command. The red curve is the response of the voice coil motor, while the blue curve shows the response of the piezoelectric actuator. The combined response is faster than the primary actuator alone. Courtesy of the Mechatronics and Automation Laboratory, National University of Singapore.*