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A Survey of Control Issues in Optical Data Storage Systems ⋆

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Abstract: This paper presents a survey of control issues in optical storage data systems. Servo control has the important role of moving the optical pick to a track and regulating it to read and write data along the track. The performance of the servo system determines total system performance, such as access time, data rate, and latency. In this regard, we review servo control systems and walk readers through key issues of servo control technology. We also discuss servo control issues in some new storage technologies, such as near-field recording systems. Although optical data storage systems are highly precise mechatronic systems, they have not yet been considered extensively in the literature of the control engineering society. This review provides a description of servo control issues in optical data storage systems from specification to implementation of control theory. We thus believe that this paper will be useful for readers practicing control theory both in academia and in industry.

Keywords: Optical data storage, servo systems, robust control, tracking systems

1. INTRODUCTION

This paper presents a survey of control issues in optical data storage systems (ODSSs). The optical data storage industry first introduced the compact disk (CD) to the consumer market almost three decades ago in 1982 (Pohlmann [1992], Stan [1998]). To date, optical disk drives such as CD-ROM and DVD are the most widely used data storage systems. Blu-ray discs, which have greater data storage capacity than CD and DVDs, have recently become popular. Blu-ray discs can record high-definition videos without any quality loss. Moreover, from a servo control point of view, Blu-ray discs overcome DVD readability issues with a closer lens to medium distance, thus eliminating the problem of disk tilt, which causes birefringence. Servo control technology is at the center of optical data storage systems that are evolving for greater data capacity. In the case of optical discs, servo control plays the important role of moving the optical pick to a track and regulating it to read and write data along the track. The performance of the servo controller also determines the performance of the optical data storage system, such as access time, data rate, and latency. In this regard, we review servo control systems by describing actuators, sensors and sensor signals, specifications, servo control structures, and key issues of servo control technology such as focus servo, track servo, seek operation, and robust control against periodic and nonperiodic disturbances, including fault detection and shock disturbances. We also discuss servo control issues in some new storage technologies such as near-field recording systems, in which significant technical progress in development has recently been made. Although optical data storage systems are highly precise mechatronic systems, they have not yet been considered extensively in the literature of the control engineering society (Chaghajerdi [2008]). This survey paper contributes a description of servo control issues in optical data storage systems from specification to implementation of control theory. We thus believe that this paper will be useful for readers practicing control theory both in academia and in industry.

The rest of this paper is organized as follows. In Section 2 we review the general architecture of ODSS and the general sequence of a servo system to help readers understand how the servo system reads (or writes) data from (or to) a disc. Section 3 introduces signal processing for control and reviews the basic principles of signal detections for focus and track servo. Section 4 reviews the basics of control systems, such as focus and track servo and robust control in order to illustrate control issues. Section 5 reviews emerging issues in optical data storage, such as near-field recording systems, and Section 6 provides our conclusions.

2. GENERAL ARCHITECTURE OF OPTICAL DATA STORAGE SYSTEMS

2.1 System Architecture

This section illustrates the generic architecture of ODSSs and the servo system. Fig. 1 shows a typical example of

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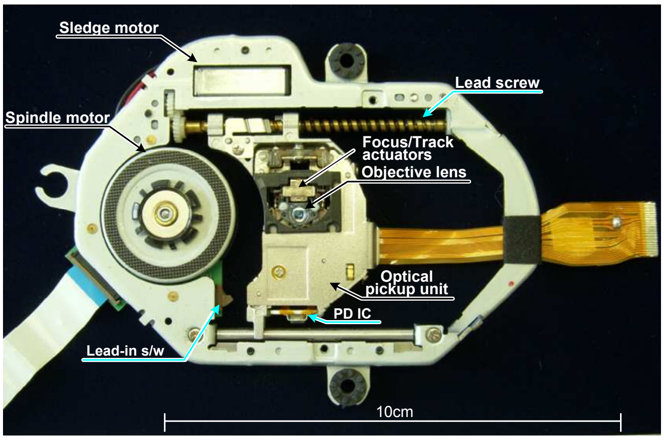

Fig. 1. An example of a mechanism assembly with a DVD pickup.

an ODSS, consisting of an optical pickup unit (OPU), a sledge motor, and a spindle motor (see e.g. Pohlmann [1992], Steinbuch et al. [1994], Stan [1998], Chaghajerdi [2008], and the references therein). An OPU is composed of several components:

- Servo components: focus actuator, track actuator, and spring supports for holding an objective lens.
- Optical components: laser diode, collimation lens, polarizing beam splitter, objective lens, and so on.
- Electric components: monitoring photo-detector (MPD), photo-detector for channel signals, and so on.

The laser diode emits red lasers with wavelengths of 780 nm and 650 nm for CD and DVD systems, respectively. Also, a blue laser with a wavelength of 405 nm can be used for Blu-Ray (or HD-DVD) systems. Note that the emission efficiency of a laser is sensitive to the ambient temperature. Hence, the emission power of a laser should be controlled by a feedback loop in order to obtain the optical signals uniformly against temperature variations. For the feedback, the MPD indicates how much power is emitted from the laser. Since the life cycle of a laser depends on the amount of current supplied to it, a current limiter should be placed along with the feedback loop to avoid damage to a laser diode. The focus and track actuators move the objective lens in the focal and radial directions, respectively. The objective lens supported by springs with light damping can be moved by electromagnetic forces from the actuators. Once the objective lens is placed at a focal length from a disc and the laser power is stably controlled, the photo-detector generates the channel signals and a high frequency (HF) signal. Position error signals (servo errors) of a beam spot can be obtained by combining the channel signals.

Observe that the OPU is movable along with the lead screw, which is rotated by a sledge motor. The sledge motor can be designed by either a DC motor or a stepper motor depending on the target applications (see e.g. Liao [2005]). If fast data access is needed, a stepper motor can be used. A DC motor is a better choice if silent movement is required rather than fast data access, as in a CD player. Overall, a sledge and a track actuator can be viewed as a *dual stage* actuation system for track servo. The sledge motor moves the OPU as a course actuator, and the track actuator finely adjusts the location of an objective lens.

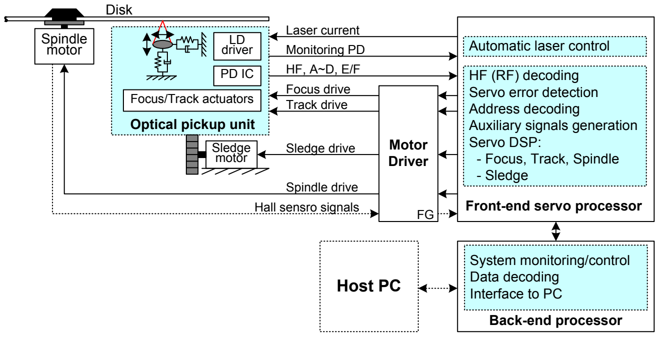

Fig. 2. The typical architecture of an optical data storage system.

To read data from or record data to an optical disc, the so-called *servo system* should control the OPU, the sledge motor, and the spindle motor in the correct sequence. To this end, the block diagram of the servo system is shown in Fig. 2. In general, the *front-end servo processor* handles the channel signals, performs the servo control, and decodes the data (or sector address). The back-end processor may be a microprocessor or a multimedia processor that can supervise the front-end processor, enable the communication protocol to the host PC, and conduct data decoding (e.g., MPEG decoding in the case of a DVD player). More recently, the marketplace has favored one chip semiconductor solutions that combine the front-end servo processor and the back-end processor to reduce the system cost (Okamoto et al. [2003]). Further details on the functionality of the control loop in commercial optical disc drives (ODDs) can also be found in other studies (Pohlmann [1992], Stan [1998], Akkermans [2001], Bittanti et al. [2002]).

The general sequence in which a servo system reads data from a disc is as follows:

(1) Offset calibration of signals after power-on; the channel signals from a photo-detector contain a certain amount of electrical offsets. These offsets should be measured and compensated first.
(2) Laser turned on and disc search process; once a disc is loaded, it should be checked to verify that it has sufficient reflection. To this end, the objective lens is moved from the bottom position up to a maximum position with the laser turned on. The HF signal is generated when the objective lens passes across the focal depth area around the focal length distance. By detecting this, the existence of a *playable* disc can be determined.
(3) Focus error and HF signals calibration; regardless of constant laser emission power, the intensity of reflection varies through discs, which results in different signal levels. To avoid this, the magnitude of the focus error (FE) is measured during the disc search process, and the amplifier gains of channels (e.g., the analog amplifiers or the digital gains along A$\sim$D signals from the photo-detector) should be correctly adjusted.
(4) Spindle rotation started.
(5) Focus servo turned on.

(6) Track error calibration; once the focus servo is stably working, the magnitude of sub-channel signals (or the differential phase detection signal for a DVD) should be appropriately adjusted to obtain a specified magnitude of track error.
(7) Track servo turned on.
(8) Automatic gain adjustment of the focus and track servo loops; even with the initial calibration process, the closed-loops for the focus and track servo involve significant parameter uncertainties caused by the non-unique reflectivity of a disc, track pitch variation, and the uncertainties of OPU. To guarantee uniform servo performance, the loop gain (i.e., the DC gain of an open-loop system that uses an injected disturbance) should be automatically adjusted (Kim and Rew [2007]).
(9) Identifying the current address and seeking; when the focus and track servo are stable, the data is restored through the data phase-lock loop (PLL) process from the HF signal. The current position in an address format is then identified, and the beam spot of a pickup should be moved to reach a target address, which is called the *seeking* operation.

Steps (1) through (8) are necessary for a newly loaded disc, and they consume a certain amount of time at the beginning stage of reading a disc. This initial startup time is considered one of the major drawbacks of ODSSs. Only when the calibration and gain adjustment processes are completed can the uniform performance of ODSSs be achieved.

2.2 Servo Actuators in OPU

The main performance of ODSSs comes from the control performance of the focus and track servo systems; thus, the design parameters of an OPU can be a major concern. In general, the servo actuators can be modeled by a mass-spring-damper system (Bittanti et al. [2002], Hock and Li [2000], Filardi et al. [2002]), and the actuation to an objective lens for focusing (or tracking) is achieved by a voice-coil actuator: $F = BLN \cdot i$, where B, L and N are the magnetic flux density, the length of coil, and the number of coil-turns, respectively, and i is the amount of current flowing through the coil. The actuation force moves the objective lens of mass m, with a spring support that has stiffness k and damping d, which leads to the transfer function from the current $I(\cdot)$ to the displacement $X(\cdot)$ as follows

$$\frac{X(s)}{I(s)} = \frac{BLN/k}{\left(\frac{s}{\omega_n}\right)^2 + \frac{1}{Q}\left(\frac{s}{\omega_n}\right) + 1} \tag{1}$$

where $\omega_n = \sqrt{k/m}$ is the natural frequency, and $Q = \sqrt{mk}/d$ is the Q-factor. Thus, with the electrical components of the actuator with resistance R and inductance L, the overall transfer function can be described by

$$\frac{X(s)}{V(s)} = \frac{1}{R + Ls} \cdot \frac{BLN/k}{\left(\frac{s}{\omega_n}\right)^2 + \frac{1}{Q}\left(\frac{s}{\omega_n}\right) + 1} \tag{2}$$

where $V(\cdot)$ is the input voltage (Bittanti et al. [2002]). Hence, the major design parameters for a servo actuator are the first natural frequency, Q-factor, the low-frequency gain (i.e., the DC gain: $BLN/(kR)$ at $s = 0$), and the coil resistance and inductance. For example, the design parameters of a focus servo actuator in an OPU for a CD-player are a low frequency gain of 1 ±0.5 mm/V, a first natural frequency of 25 ±4 Hz, a Q-factor of less than 20 dB, and a resistance of 11 ±1.5 Ω.

Note that the simplified modeling of an OPU in (2) does not describe *generically hidden* issues in practice. First, the actuators in an OPU have the second resonant frequency, which should be far from the closed-loop bandwidth of a servo system (Hock and Li [2000]). For example, the closed-loop bandwidth of a focus servo is usually designed to be less than 2 kHz (in a high speed ODSS). Also, the second resonance may exist over 10 kHz as a result of an OPU design specification. Since they may not be sufficiently separated, for a certain sample, the high frequency components of the feedback control input may excite the second resonance and cause structural vibration, which degrades the control performance and also results in a high-frequency noise. A similar spillover effect has been reported in an OPU design with flexible supports in Choi et al. [2001]. Second, in the case of the focus servo, gravity may cause a steady deflection of an objective lens from the center position. This phenomenon worsens at high temperatures, a fact that should be considered in the mechanical and control design. Third, the deviation of an objective lens from the nominal position (due to the mismatch of the sledge and desired track positions) induces a nonlinear effect that degrades the control performance. Fourth, the design parameters addressed above may be defined and measured at room temperature. This implies that there should be a great amount of parameter variation when the OPU is used at high or low temperatures. Measuring the characteristics of the OPU in an open-loop is generally difficult without using a laser Doppler vibrometer (LDV). However, open and closed-loop parametric system identification can be performed by measuring the current through the actuator (Vidal et al. [2001c]).

3. SIGNAL PROCESSING FOR CONTROL

3.1 Specifications

In order to specify the servo system for the optical data storage system, focusing, axial, and radial tracking need to be considered. Specifications are given for each servo controller, and are determined by the maximum vibration error and maximum acceleration. The specifications for CD, DVD, and Blu-ray differ because they allow different readout/recording conditions.

In designing a servo system, time-domain and frequency-domain specifications are needed. The time-domain specifications denote seek and settle times, while the frequency-domain specifications represent the steady-state response of the servo system. The frequency-domain specifications include disturbance attenuation properties at certain frequencies, which can be depicted in a sensitivity curve plot. Given values of the maximum error and acceleration, one can compute conditions in the sensitivity curve plot. However, it is typical to specify open-loop gain conditions to meet such sensitivity curve requirements, which is much

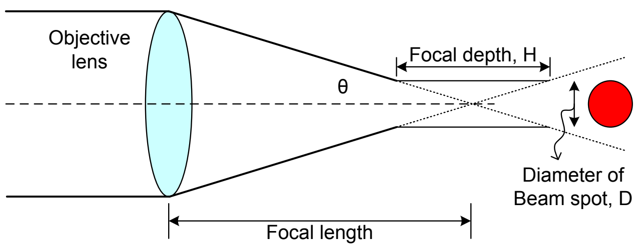

Fig. 3. The principle of focusing.

easier to plot. A requirement for the open-loop gain that meets the sensitivity curve specifications with some margins can be found. Such open-loop gain specifications are given for each servo.

For example, in order to specify the servo system for axial and radial tracking in DVD specifications (DVD [2003]), the following function of $G(s)$ in (3) is used:

$$G(j\omega) = \frac{1}{c}\left(\frac{\omega_o}{j\omega}\right)^2 \times \frac{1 + \frac{j\omega}{\omega_o} \times c}{1 + \frac{j\omega}{c\omega_o}} \tag{3}$$

where $\omega = 2\pi f$ and $\omega_o = 2\pi f_o$, and f_o is the crossover frequency of the open-loop transfer function. The constant c provides the crossover frequencies of the lead-lag network of the servo, the leadbreak frequency $f_1 = f_o/c$, and the lag frequency $f_2 = f_o \times c$. The constant c is set around 3. It specifies the nominal values of the open-loop transfer function $G(s)$ of the reference servo(s) in the pertinent frequency ranges (e.g., 100 Hz to 10 kHz for DVD). Using the steady state output for a given sinusoidal input $u = \delta \sin \omega t$ (which shows $\ddot{u} = -\delta\omega^2 \sin \omega t = -\omega^2 u$, a slope of -40 dB/dec), we find $\delta_{\max} = c\omega^2\alpha_{\max}$ where $\delta_{\max}$ is the maximum vibration error, $\alpha_{\max}$ is the maximum acceleration, and c is the gain of the stable controlled loop. Given that $\alpha_{\max}$ and $\delta_{\max} \approx 0$ dB, a crossover frequency f_o can thus be obtained from

$$2\pi f_o = \omega_o = \sqrt{\frac{\delta_{\max}}{c\alpha_{\max}}} \tag{4}$$

at which the sensitivity curve should be below $\delta_{\max}$. Additional sensitivity requirements at corresponding frequencies can be similarly determined. In the case of the DVD axial tracking, $\alpha_{\max}$ shall be 1.5 times the expected maximum axial acceleration of 14 m/s^2, and $\delta_{\max}$ shall not exceed ± 0.08 μm. Assuming $c = 3$, the sensitivity curve should be below 0.08 μm at the crossover frequency $f_o = 4.5$ kHz. The condition -40 dB/dec should be satisfied at frequencies below f_o up to 100 Hz. For the radial tracking, the condition $|\delta_{\max}| < 0.014$ μm and $|\alpha_{\max}| = 1.5 \times 3.0$ m/s^2 requires a sensitivity value less than 0.014 μm at $f_o = 4.9$ kHz. Specifications for focusing are similarly determined.

3.2 Focus Error Detection

Fig. 3 shows the basic principle related to the formation of a *focused* beam spot on the reflective layer on a disc. Once an objective lens is located at a focal length from the reflective layer, the beam spot can be generated within a focal depth range with a certain diameter due to the spherical aberration of the objective lens. The numerical aperture (NA) of an objective lens is defined by $NA = n \sin\theta$, where n is the refraction index. Then, observe that

Table 1. Comparison of optical parameters

Parameters	CD	DVD	Blu-Ray (BD)
λ	780nm	650nm	405nm
NA	0.45-0.5	0.6−0.65	0.85
D	1.56-1.73μm	1.00-1.08μm	0.476μm
H	3.12-3.85μm	1.54-1.81μm	0.561μm

$$D = \frac{\lambda}{NA}, \quad H = \frac{\lambda}{NA^2} \tag{5}$$

where λ is the laser wavelength, and D and H are the diameter of a beam spot and the focal depth, respectively. Table 1 summarizes the optical parameters for each of the different media. Fig. 4 illustrates key properties of CD, DVD, HD DVD, and Blu-ray recording, and Fig. 5 shows a comparison of pit shapes.

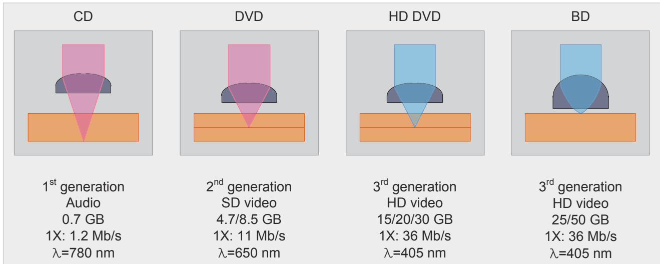

Fig. 4. Key properties of CD, DVD, HD DVD and Blu-ray recording (source: Philips) (Sarid and Schechtman [2007]).

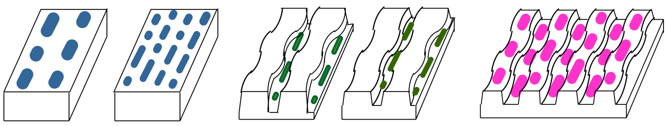

Fig. 5. Pit shape comparison.

Also, we refer to Milster [2005] for further discussions. Note that the focal depth is less than a few micrometers, and the accuracy of the focus servo should be much smaller than that. Hence, accurate detection of the focus error is critical to achieve stable control performance. Several methods of focus error detection have been described in the literature (see e.g. Pohlmann [1992], Stan [1998], Chaghajerdi [2008], Kinnstatter et al. [1990], Nakai et al. [2006], and many others). In this paper we introduce the *astigmatic method*, which is the most popular method in practice thanks to its simplicity and accuracy.

Fig. 6 shows a typical example of focus error and HF signal generation using the sub-signals of a *main* photo-detector. The photo-detector is composed of 4 sub-components: *A-channel, B-channel, C-channel and D-channel.* When the objective lens is far from a disc, the beam spot shape becomes an ellipsoid oriented through B-D channels, and its size decreases. On the other hand, the beam spot is oriented through A-C channels when the objective lens is close to the disc. If the objective lens is located exactly at the focal length from the disc, then the beam spot is evenly distributed over the four channels. In this instance, note that the sum of the channel signals becomes the maximum.

Considering that each of the sub-channels may have different sensitivity, the signals should be calibrated appropriately with some gains. Let us define an HF signal:

$$HF = k_a \cdot A + k_b \cdot B + k_c \cdot C + k_d \cdot D \tag{6}$$

where k_i $(i = a, b, c, d)$ are the calibration coefficients that should be determined during the initial calibration processes. A, B, C, D are the levels of signals from each channel. From Fig. 6, observe that the focus error is detected linearly within a certain range. The linear range can be determined by measuring the HF signal. Note that the linear range of the focus error is guaranteed only when the HF signal is greater than a threshold value. Based on these characteristics, one may define the focus error as follows: when $HF \geq HF_{thres}$,

$$FE = k_1 \{k_a \cdot A + k_c \cdot C - (k_b \cdot B + k_d \cdot D)\} \tag{7}$$

where k_1 is a calibration coefficient and HF_{thres} is a threshold value. The focus error was calculated using analog amplifiers until the beginning of the year 2000. However, fast AD conversion techniques are now available, so the calibration of channel signals and the computation of focus error are conducted by DSP signal processing (Okamoto et al. [2003]).

As the object lens moves up and down, the FE is expected to have S-curve behavior around the focal length, as shown in Fig. 6. The error is linear with respect to distance within a range of a few microns (e.g., about 10 μm for CD). Beyond this point, the reflected signal becomes diffuse and the FE signal goes back to zero (Pohlmann [1992], Stan [1998]). When a disc is first inserted, the servo system does not have information about the distance of the focal length and the number of data layers on the disc. By sweeping through all focus values and examining zero crossing points, the number of layers and their focus points can be determined (Hwang [2000]).

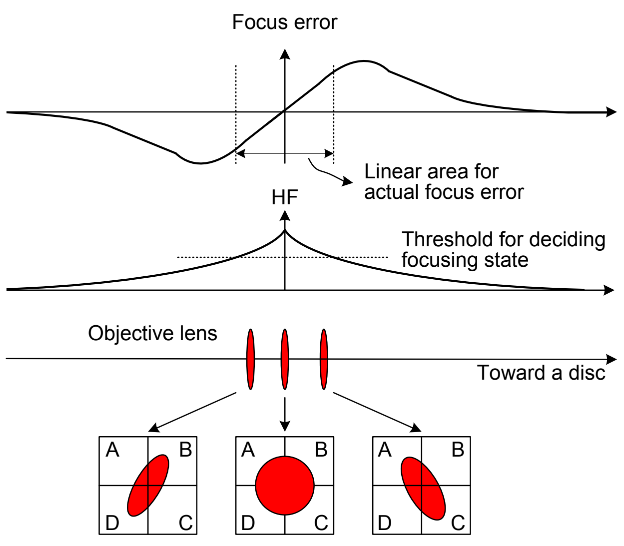

Fig. 6. Focus error detection based on an astigmatic method.

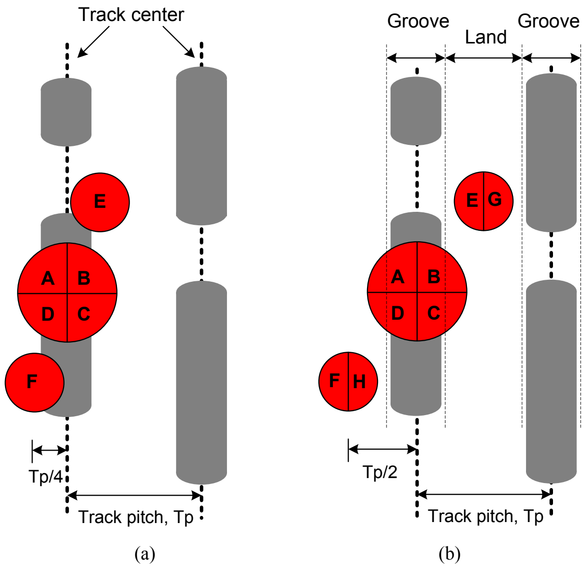

Fig. 7. Track error detection by (a) the 3 beam method and the (b) differential push-pull method.

3.3 Track Error Detection

There have been several methodologies for track error detection for different disc media (Chaghajerdi [2008], Peng et al. [1998], DeVore [1986]). In this paper we introduce major methods in practice - the *3 beam method*, the *differential push-pull* method, and the *differential phase-detection* method. The 3 beam method has been developed for a CD-ROM, or more strictly speaking, CDs with data pits (or marks). The method cannot be used for unrecorded CDs. Hence, the 3 beam method is only applicable to CD-players for audio playback or CD-ROM drives without a recording function. In a CD OPU, the laser can be split into 3 beams through a refraction grate plate as shown in Fig. 7(a). The reflected beam from the main beam generates the channel signals by a photo-detector (as illustrated in Section 3.2). At the same time, two sub-beams produce E- and F-channels in a photo-detector. Since they are separated from the track center by the distance of a quarter of a track pitch (i.e., 1.6 μm/4=0.4 μm), the two beams are reflected with different intensities due to the existing data pits when the center of the beams deviate from the track center. Therefore, the track error can be defined as

$$TE = k_2(k_e \cdot E - k_f \cdot F) \tag{8}$$

where k_i $(i = 2, e, f)$ are the calibration coefficients. Note that the 3-beam method is only available when there are data pits on a data track.

The differential push-pull method was devised for CD media with the *land-groove* architecture, such as CD-Recordable (CD-R) or CD-Rewritable (CD-RW) discs. As shown in Fig. 7(b), the sub-beams are located at a distance of half of the track pitch (i.e., 1.6 μm/2 = 0.8 μm). The height gap between the land and groove and the inclination of the land-groove connecting area result in a difference correlated to the track deviation in a main beam push-pull signal,

$$PP = k_a \cdot A + k_d \cdot D - (k_b \cdot B + k_c \cdot C). \tag{9}$$

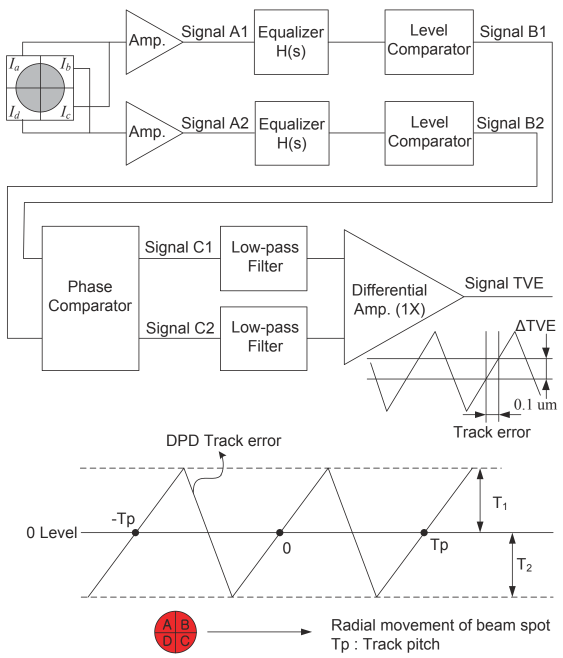

Fig. 8. Track error detection by a differential phase detection method (ECM [2001]).

However, this push-pull signal is highly sensitive, particularly to the disc inclination (sometimes called disc-tilt). Hence, the push-pull signal generally cannot be used alone to detect a track error. An attractive remedy for this matter is to use four additional channel signals obtained from two sub beams. That is, the side beam push-pull signal,

$$SPP = k_e \cdot E + k_f \cdot F - (k_g \cdot G + k_h \cdot H) \tag{10}$$

may contain the offset component, which makes the main beam push-pull signal equally sensitive. Thus, one may define a *differential push-pull* signal as follows:

$$TE = PP - k_{dpp} \cdot SPP \tag{11}$$

where k_{dpp} is a calibration coefficient.

The differential push-pull method is highly robust to the disc-tilt. Also, note that the differential push-pull method is best suited for CD-R or CD-RW media. Hence, in a CD-RW drive (which allows a CD recording function), the reading capability for the CD recorded media is generally satisfactory. However, even for a CD-ROM, which lacks a land-groove structure, the differential push-pull method should be used so that the reading capability is not degraded compared with the 3 beam detection method.

Differential phase detection (DPD) is a track error detection method devised for DVD-playback. The differential push-pull method can be extended for use with DVD-Recordable (or -Rewritable) media with the land-groove structure. However, a DVD-ROM (without the land-groove structure) needs a different track error generation method. To resolve this, the DPD uses 4 main channel signals (i.e., A∼D channels) to detect the phase difference (Peng et al. [1998], ECM [2001], Shiraishi et al. [2007]). Fig. 8 shows the standard block diagram used to compute the DPD error signal. In case of DVD 1X playback, the equalization is given by

$$H(s) = \frac{1 + 1.6 \times 10^{-7} s}{1 + 4.7^{-8} s}, \tag{12}$$

which should be adjusted accordingly for other playback speeds. Although DPP with three spots is known to effectively eliminate the offset of tracking error caused by the objective lens shift or the radial skew of the disc, it is impossible to align three spots on the track boundary for different track pitches of a multi-type DVD, so phase-shift DPP (PS-DPP) is used for precise alignment of the three spots on the track (Koide et al. [2002]). The cross-coupling between focus and tracking servo systems is also important. The optical model of a CD player was investigated in Odgaard et al. [2003b]. The general principle of the three beam focus and radial detection system was introduced with a nonlinear static model of the relationship between the detector signals as outputs and focus tracking error as inputs.

4. CONTROL ISSUES AND METHODS

4.1 Focus Servo

A focus servo is a feedback control loop designed to keep the objective lens in a focal length with respect to the disc surface (more strictly, the reflective layer with data pits). As long as the variation in the gap between the lens and the reflective layer is much less than the focal depth, the focus servo is stable. The focus servo is the first feedback control loop established among several feedback loops in an optical data storage device. Hence, achieving reliable focus control is a key factor for data reading (or recording) performance (Lim and Jung [1999], Yang et al. [1998], Yockyama et al. [1994], Odgaard et al. [2004]).

One of the major difficulties of focus control comes from the vertical deviation of a disc from the objective lens of a pickup. In practice, there could be two reasons for this vertical deviation: i) the disc itself is warped due to inaccurate manufacturing of the disc substrate; and ii) inaccurate assembly of the spindle-turn table that holds the disc. As shown in Fig. 9, the disc can be maximally deviated from the objective lens at the outermost location, and the deviation is synchronized with the rotational frequency. In general, the amount of vertical deviation of a disc should be less than ±1 mm, which implies that the pickup should be designed to allow a working distance of ±1 mm. Moreover, the gain of the focus controller $C_{fcs}(s)$ in the low frequency band covering the rotational frequencies should be increased appropriately to suppress the effect of vertical deviation as follows:

$$|C_{fcs}(j\omega)| \geq \frac{1}{G_{fcs}(j\omega) Kopt_{fcs} \delta_{allow}} \tag{13}$$

at $\omega \leq \omega_{rot}$, where $G_{fcs}(\cdot)$ and $Kopt_{fcs}$ are the focus system (plant) and the optical gain, respectively. δ_{allow} is the allowable amount of vertical position error given by the specification, and ω_{rot} is the rotational frequency of the disc.

Some CD/DVD players are used in automobiles. For automotive use, environmental conditions such as the working

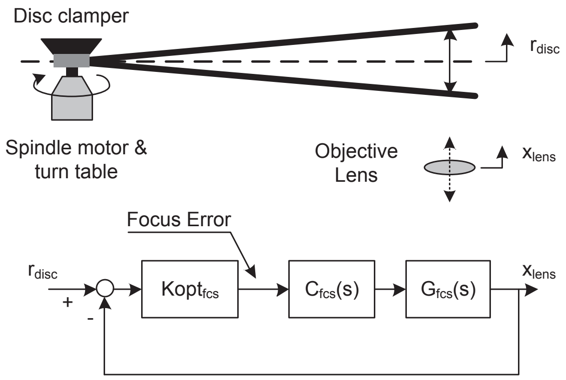

Fig. 9. Vertical deviation of a disc (top) and a focusing control loop (bottom).

temperature range of -40 ^oC to 85 ^oC and the ground vibration over 1.5 g (i.e., 1 g=9.81 m/s^2) should be considered for focus control design. The wide temperature variation causes *non-negligible* system parameter uncertainties, particularly in the stiffness of a spring supporting the objective lens. Also, severe vibrational disturbance weakens the focus control performance (Yockyama et al. [1994]). Hence, the bandwidth and gain of the focus servo should be determined with respect to target applications.

4.2 Track Servo

Once the focus control is stably achieved and the disc is rotating with an appropriate angular speed, the track servo is needed to read the data from a spiral track (Filardi et al. [2002], Chaghajerdi [2008]). To accomplish the track following operation in an optical data storage system, the *pull-in task* and the *steady track following task* should be performed reliably (Kim [2003, 2005]). As shown in Fig. 10(left), the eccentricity is defined by the mismatch of a rotational center with respect to the geometrical center of the data tracks. The main sources of the eccentricity are inaccurate formation of tracks on a disc and inaccurate disc clamping. In the case of CD-ROM discs, an eccentricity of 210 μm may be the allowable limit that can be coped with by a track servo. Under a certain amount of eccentricity, rotating a disc results in a relative trajectory of the beam spot (emitted from an objective lens) on a disc, as shown in Fig. 10(left). As a beam spot crosses data tracks, the sinusoidal track error is generated as shown in Fig. 11(left). However, note that the speed of a beam spot with respect to data tracks varies, and is calculated by the radial velocity such that

$$v_{rad} = \epsilon\omega_{rot}W_k \tag{14}$$

where $W_k := \sqrt{(2-k/N)\cdot k/N}$, $(k = 0,\cdots,2N)$, is a geometric weighting factor (Kim [2005]), as shown in Fig. 10(left). Given an integer number $N = fix(\epsilon/Tp)$ for an eccentricity ϵ and the track pitch Tp, the beam spot crosses 2N tracks during a half cycle of a rotation. The index of k=0 denotes the C_0 location of the beam spot on a disc in Fig. 10(left). As a result, during a half cycle of a rotation, the typical shape of track error can be observed as shown in Fig. 11(right). Note that the track error appears dense as v_{rad} increases.

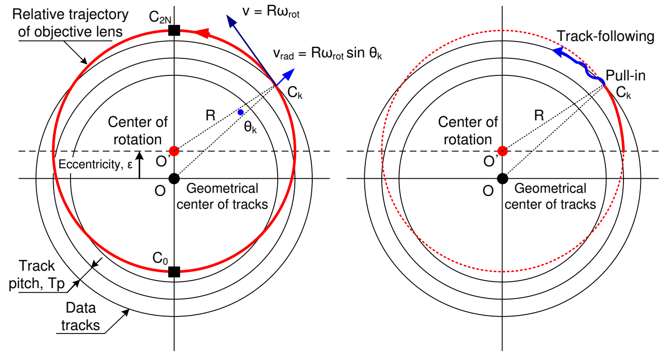

Fig. 10. Effect of eccentricity during the *free-running* state (left) and the tracking control (right).

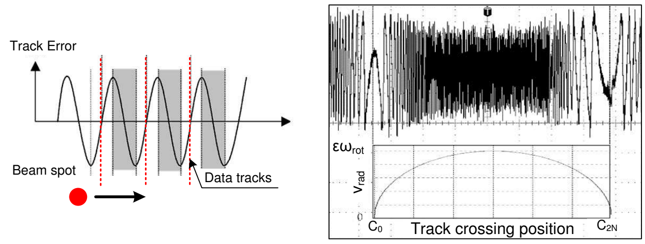

Fig. 11. Track error (TE) signal (left) and a typical TE in the free-running state (slightly modified from (Kim [2005])) (right).

To follow a data track, the track servo or track controller should be turned on at the moment a data track is crossed, which is denoted by C_k. As shown in Fig. 10(right), the track controller should be able to suppress the radial velocity v_{rad}, and stably *pull in* the beam spot onto the data track. After the pull-in phase, the track servo should sustain the track following operation. At this point, two conflicting requirements for the track servo arise: i) fast settling against the initial velocity (i.e., v_{rad}) for a reliable *pull-in* operation, and ii) robust track following capability against the corrupted track error (due to scratches or black-dots). The radial velocity is proportional to the eccentricity, the rotational speed, and the geometric position of the beam spot, which are the major factors considered to improve the pull-in capability. In general, to enhance the pull-in capability, the track servo may impose high damping requiring the phase-lead action (or simply the derivative control). On the contrary, the steady track following needs to be robust against faults in track error detection, which implies the *averaging* action rather than the derivative action. Therefore, in many applications the track servo employs two or several sets of control parameters in order to cope with the pull-in and steady track-following operations.

The eccentricity also affects the track following performance, particularly at high rotational speeds. Note that the tracking servo in an optical data storage system is formulated by an unknown reference tracking problem, and the unknown reference fluctuates with the amount of eccentricity synchronized with the rotational frequency. Thus, the unknown reference can be treated as an unknown disturbance, which may be handled by increasing the low-frequency gain of a track controller. In general, a lead-lag compensator is adopted, and its gain at the low-frequency band (including the rotational frequency) is *boosted* to suppress the disturbance of eccentricity. Note that Filardi et al. [2002] does introduce a simplified lead-lag compensator derived from a PID control structure, which may have been commercialized in an LSI. Also, a notch filter may be effectively adopted (Bittanti et al. [2002]). It is necessary that at $\omega \leq \omega_{rot}$,

$$|C_{trk}(j\omega)| \geq \frac{1}{G_{trk}(j\omega) Kopt_{trk} \delta_{allow}^{trk}}, \quad (15)$$

where $C_{trk}(\cdot)$, $G_{trk}(\cdot)$ and $Kopt_{trk}$ are the track controller, the track system (plant), and the optical gain of the track error, respectively. Also, the allowable amount of track position error δ_{allow}^{trk} should be defined by the specification. However, boosting the low-frequency gain of the controller may weaken the phase-lead property around the cutoff frequency, and thus degrade the *dampening* property. To avoid this difficulty in designing a nominal track servo, several approaches have been proposed based on the disturbance observers (Kim [2002, 2003], Kim and Hong [2002], Shim et al. [2003, 2004]), the repetitive control (Doh et al. [2006], Steinbuch et al. [2007], Doh et al. [2002], Dong et al. [2003]) or a nonlinear control (Heertjes and Sperling [2003]).

In addition to generic issues such as the eccentricity, black-dots, or scratches on a disc, the robustness of the track (or focus) servo is one of the major issues. With a single set of control parameters, a large number of optical data storage devices (sometimes over a million sets) should be manufactured. Also, all of them can be operated at different temperatures and with various discs. Academic efforts have been made to achieve robustness against the system parameter variations (see e.g. Vidal et al. [2003]). However, automatic feedback loop gain adjustment methods have been widely adopted in practice (Kim and Rew [2007]).

4.3 Seeking Operation

Track seeking is a sequence of tasks that are carried out to find a specific sector of a target address. That is, given a target sector address, the following tasks are completed: i) calculate the number of tracks to move (by considering the current and target sector addresses and the track pitch (Stan et al. [1998])); ii) turn off the track servo and move the pickup head unit (consisting of a sledge motor and a tracking actuator) as much; iii) restore the track servo and check the sector address at the new location; and iv) repeat steps i)∼iii) until the target sector is reached. In practice, there are several critical issues related to the control during these operations.

First, considering that the track pitches of CDs and DVDs are 1.6 μm and 0.74 μm, respectively, the accuracy of sledge movement can be of concern in the case of a *long* jump operation, which is required for a long distance movement. To move a sledge holding an optical pickup, either a stepper motor or a DC motor have been adopted. The jumping accuracy can be remarkably increased with the micro-stepping technique of a stepper motor, while the motor is more expensive than a DC motor. In the case of a DC motor-based sledge, the calibration of friction is crucial to enhance the jumping accuracy (Han et al. [2000], Hsu and Fu [2004], Helwegen [2005]).

Second, sledge movement affects the *focal stability* and the *seek time* of the objective lens. Since the objective lens is supported by a spring fixed at the pickup base on the sledge, the sledge movement causes vibration during (and after) the movement. Due to the induced vibration of the objective lens, the focusing control becomes unstable. Also, the residual vibration after the movement prohibits fast restoration of the track servo, which extends the seek time. The so-called *center error control* is an effective method (Kim and Hong [2001]) to avoid this induced vibration. Typically, the track servo is de-activated during a long jump. However, with the center error control method, the track servo controller is used to stabilize the vibrant objective lens. An effective alternative is to generate a motion profile instead of employing the active feedback control. The input shaping technique can also be adopted to suppress the vibration of the objective lens (Kim and Rew [2010]).

Third, the track servo instability after jumping less than several hundreds of tracks (*short* jump) can be a major issue. For a short jump, the objective lens should be pushed away while the number of tracks to move is counted. The jumping speed should be controlled in order to meet a speed profile (Akiyama and Ishikawa [1993], Ryoo et al. [1999]), with the speed measurement taken by counting the time period of a sinusoidal track error; Fig. 11(left) shows a typical track error. Thanks to this control, the speed of the objective lens at the final stage is slow enough that the pull-in performance of the track servo becomes stable. However, the speed control is often poor because of faults (e.g., scratches) in the detected track error and the eccentricity. Therefore, the pull-in capability of the track servo is the most important factor to avoid *serious* track slips for seeking operations in general, and it has not been addressed adequately in the literature to our knowledge.

Last, aside from the above issues, several issues such as focusing failure during a short jump and PLL failure (or spindle control failure) after a long jump may arise. Rewritable (or recordable) optical discs involve *land-groove* structures. During the short jump, these land-grooves cause a sinusoidal error in the astigmatic detection of focus error synchronized with the jump speed. This detection error may lead to a failure of focusing control during the jump, which has not been reported in literature, but occurs frequently in practice. The PLL failure may be caused by the spindle speed error, particularly after a long jump under a constant linear velocity (CLV). The constant angular velocity (CAV) mode has been developed for fast data access.

4.4 Robust Control

This subsection introduces robust control methods applied to ODSSs. ODSS has various disturbances due to disk imbalance, eccentricity, windage, external shock, and resonances caused by the actuator itself. These disturbances contain significant periodic components that appear at a known fundamental frequency corresponding to the disk rotational velocity and higher harmonics. Disturbance observers (DOB), repetitive control, and iterative learning control (ILC) have been successfully applied to ODDs to reject periodic disturbances or disturbances at low frequency ranges.

Disturbance Observers DOB is used to enhance system performance by observing and eliminating undesirable disturbances in the low-frequency range. Since it was reported that DOB is effective at rejecting these disturbances in ODD systems (Fujiyama et al. [1998]), various types of DOBs have been applied to ODDs. Doubly coprime factorization and Youla-parameterization are used together to design robust DOBs in the presence of plant input multiplicative uncertainties (Ohishi et al. [1996]). Improved performance of a tracking servo system is achieved in Arai et al. [2000] by using a feedback controller and a feedforward controller, which employs a zero-phase error tracking (ZPET) method (Tomizuka [1987]). The feedback controller was designed based on coprime factorization to guarantee robust stability against multiplicative perturbation (Zhou and Doyle [1998]). Since only the tracking error signal is available in optical drive systems, a modified estimation method is used and performance is improved (Ohishi et al. [2001]). In Ohishi et al. [2006], this idea is applied to an optical disk recording system based on the prediction of tracking error. There is another approach to guidelines for the design of DOB with respect to plant modeling uncertainty (Ryoo et al. [2004]). In the paper, a graphical design guideline for frequency response analysis is used. In DOB, the disturbance rejection performance depends on the order of the Q filter and its coefficients. Its robustness also depends on the relative degree and denominator order of the Q filter (Choi et al. [2003]). Additional loops enhance the perturbation attenuation of disturbances, but the robust stability margin on the modeling error becomes stricter (Kwon and Chung [2002]). Recently it was demonstrated that multi-loop DOB improves the sensitivity function at low frequencies without increasing the peak of the sensitivity function (Lee and Chung [2009]),

Tracking control performance can be addressed in terms of pull-in capability and steady track-following ability using an add-on compensator in the form of DOB designed in state-space (Kim and Hong [2002], Kim [2005]). The add-on compensator enhances the tracking performance by suppressing the eccentric disturbance. The compensator can boost open-loop gain in a low-frequency range without affecting the closed-loop characteristics. Modifications to conventional DOBs are also considered to improve the performance of conventional DOBs at high rotational frequencies (Ryoo et al. [2003], Koide et al. [2007]).

Repetitive Control Repetitive control has been shown to be effective for rejecting repetitive disturbance (Hara et al. [1988]). Repetitive controllers employ the internal model principle (Francis and Wonham [1976]), and consist of a periodic signal generator that enables perfect (asymptotic) rejection of periodic disturbances. The advantages and disadvantages of repetitive control are summarized in Kempf et al. [1993] based on four different algorithms used for cancellation of periodic disturbance. A tutorial for iterative learning control and repetitive control for compensation of repeatable runouts (RROs) was recently introduced in the hard disk drive industry (Chen et al. [2008]). One of the drawbacks of repetitive control is the requirement of exact knowledge of the period time of the external signals. Practical applications require either a constant period time or an accurate measurement of the periodicity (Steinbuch [2002]). Another drawback is due to the Bode sensitivity integral: perfect reduction at harmonic frequencies is counteracted by amplification of noise at intermediate frequencies. Various approaches have been reported to address this problem (Steinbuch et al. [2007]). Two types of linear digital repetitive control systems were designed and analyzed to reduce the error spectrum, including both harmonic and nonharmonic components (Chang et al. [1995]). This result was extended to show that it can be cast into a convex optimization with application to ODSS (Steinbuch et al. [2007]). Furthermore, by using appropriate weighting functions, the same problem formulation yielded the results in Steinbuch [2002]. Although the method (Steinbuch [2002]) requires an increased number of memories, it is effective for rejecting disturbances when the period varies within a narrow range.

The performance and robustness of repetitive control also depend on the cutoff frequency of a Q filter included in the repetitive controller. The bandwidth of the filter needs to be sufficiently higher than the disturbance frequency. However, the high bandwidth is undesirable since unmodeled dynamics at high frequencies may be excited. For these reasons, various methods have been introduced for robust control against model uncertainties. The use of a graphical design technique based on the frequency domain analysis of a linear interval system was proposed in Moon et al. [1998]. In the presence of plant uncertainties, a sufficient condition for robust stability of the repetitive control system is derived in the form of linear matrix inequality (LMI) by using the Lyapunov functional for time-delay systems (Doh et al. [2006]). In Leyva-Ramos et al. [2010], a modified repetitive compensator uses notch filters with feedforward gain.

Iterative Learning Control The goal of ILC is to generate a feedforward control that tracks a specific reference or rejects a repeating disturbance. A feedback controller reacts to inputs and disturbances, and therefore always lags in transient tracking. Feedforward control can eliminate this lag, but only for known or measurable signals, such as the reference, and typically not for disturbances. Recently, a survey of ILC was reported regarding analysis, design, time, and frequency-domain system representation in a well summarized form (Bristow et al. [2006]). Iterative learning control was also successfully applied to ODDs. In Moon et al. [1996], the convergence of the learning algorithm was proven in the presence of the plant uncertainty, and the effects of the initial state errors on the tracking performance was analyzed. Two types of ILC schemes - previous cycle learning (PCL) and current cycle learning (CCL) - are used to eliminate RRO disturbance in hard disk drive (HDD) servomechanisms. The convergence conditions of two learning control schemes have been explored in detail (Xu et al. [2001]).

Frequency Adaptation The tracking problem can be formulated into a regulation problem with unknown disturbance. Based on a simple disturbance observer that effectively estimates the low frequency components of disturbance, the feedforward compensation is then added to the conventional feedback control (Kim and Hong [2002]). Shim et al. demonstrated that the add-on type of output regulator can reject sinusoidal disturbance at a known frequency when applied to the track following problem of an ODD (Shim et al. [2003, 2004]). The add-on output regulator preserves the same performance of the predesigned feedback controller, even in the presence of the parametric uncertainty of the plant model. This approach is extended to an adaptive output regulator in order to reject the sinusoidal disturbance of unknown bias, magnitude, phase, and frequency (Kim et al. [2010]). The adaptive output regulator consists of an add-on type output regulator and the modified adaptive algorithm proposed in Brown and Zhang [2003]. A novel frequency adaptive control technique (FACT) was proposed in order to deal with the RRO cancellation for both CAV and CLV spindle modes in ODDs (Liu and Yang [2004]). This control method depends only on the disk position, so it is independent of the playing speed of the disks. The FACT controller is equivalent to a linear time-invariant controller, and the upper bound of adaptation gain is determined according to system dynamics for the attenuation of periodic disturbances. Its convergence property is shown through the Lyapunov function approach (Liu and Yang [2005]).

Fault Detection and Shock Disturbance In addition to periodic disturbances, non-periodic disturbances exist, which are divided into surface defects and external shocks. Surface defects include scratches, fingerprints, and dust that exist on the disk surface. Surface defects distort tracking error signals reflected by the disk surface, and cause it to obtain false information and deteriorate the track-following performance. The robust controllers introduced in the previous subsections have shown good performance during periodic disturbances caused by eccentricity, but have been unable to effectively eliminate non-periodic disturbances such as surface defects and external shock (Miyazaki et al. [2004], Zhou et al. [2004]).

A comprehensive study on the surface defects of compact disks is reported in Vidal et al. [2001a]. A different approach to disc defect classification based on hierarchical clustering of measured signals that are affected by disc defects was recently addressed in van Helvoirt et al. [2005]. Fault detection and accommodation with an observer and a linear quadratic regulator (LQR) was shown to enhance playability (Vidal et al. [2001b]). Tracking errors due to surface defects are false errors that should not be followed. Therefore, lowering the closed-loop bandwidth of the system so that the optical pickup does not follow false errors has been studied (Odgaard et al. [2004]). Moreover, studies have been conducted using estimators to obtain accurate tracking error information when the optical pickup passes surface defects (Vidal et al. [2001b], Odgaard et al. [2003a]). Increasing the loop gain commonly improves system performance with regard to shock, but deteriorates performance with regard to disk defects. Thus, the conventional trade-off between disturbance rejection and measurement noise sensitivity is needed. In Heertjes and Sperling [2003], disturbance rejection is improved by using a nonlinear dynamic filter, which is an additional gain to the feedback controller, and the small gain theorem is used to guarantee absolute stability. Performance is also quantified using a measure derived from the linear sensitivity functions (Heertjes and Steinbuch [2004]). Heertjes and Steinbuch [2004] considers nonlinear performance in terms of time-domain responses. This result is extended in Heertjes et al. [2006], in which an experimental performance analysis based on frequency-domain measurements is conducted. A combined describing function and swept-sine measurement approach was shown to offer a tool that is both efficient and sufficiently accurate for studying global qualitative nonlinear behavior. The approach not only efficiently reveals both the amplitude and frequency dependency under different levels of shocks and vibrations, but also provides measured amplitude and phase characteristics. Switching control using an observer is known to be effective in tracking following in the presence of disk scratches or heavy finger prints (Heertjes and Leenknegt [2010]). Addressing non-stationarity of disturbances in the control design significantly improves servo performance. The observer is based on a linear time-invariant part and a nonlinear part consisting of a dead-zone based switching gain.

Mechanical shock is another type of disturbance. A simple additional current measurement providing positive feedback effectively eliminates disturbance, and thus attenuates high frequency disturbance (Stoustrup et al. [2000]). Unlike surface defects, tracking errors formed by shock should be eliminated. Therefore, the closed-loop bandwidth of the system should be increased so that the optical pickup eliminates the errors caused by disturbances. However, when the closed-loop bandwidth is increased, shock immunity is increased, but the optical pickup follows surface defects. Consequently, a controller design that considers only closed-loop bandwidth is inadequate. There have been various studies that have aimed to design robust control over shocks. Zhou et al. [2002] presents a robust servo control system using observer-based sliding mode control to handle shock. Also, in Miyazaki et al. [2004], a feedback controller using coprime factorization and a feed-forward controller using ZPET were employed together to eliminate periodic disturbances. Although the systems in these studies (Zhou et al. [2002], Miyazaki et al. [2004]) enhance anti-shock performance, the control structures are complicated. In a recent study of anti-shock controllers (Zhou et al. [2004]), a nonlinear anti-shock controller with a simple control structure (a dead zone in this case) was developed. The dead zone was simply added parallel to the original linear servo control loop in order to improve the anti-shock performance by virtually boosting low-frequency gain. A dead-zone with saturation improves the stability margin without degrading tracking performance (Baek et al. [2006]). Application to automotive systems can be found in Yockyama et al. [1994], where acceleration disturbance suppression control in the focus actuator was implemented using a disturbance observer providing a wide range of detection.

Other Methods In conventional ODSSs, the range of fine seeking is limited in order to avoid the risk of misalignment between an objective lens and a laser beam axis, which causes the access time to increase enormously. In Ryoo et al. [1999], a new fine seek algorithm extends the applicable range of fine seeking without maneuvering a sledge actuator. A seek control system can be designed such that its performance is guaranteed for a set of plants with parameter perturbations. The performance of the seek control system was formulated in linear fractional transformation (LFT) and improved, and robust performance was confirmed by experiments using a 24 x CD-ROM drive (Jin et al. [1998]).

5. FUTURE TREND IN OPTICAL DATA STORAGE: NEAR-FIELD RECORDING SYSTEMS

As long as we maintain the structure of the conventional optical disc system, which has a laser with optics and a rotating medium, the fundamental means of achieving large storage capacities is to increase the data density recorded on the medium. However, the data density of an optical recording medium depends on the focused laser beam spot size. The beam spot size can be reduced by using a shorter wavelength laser or a larger NA objective lens (Table 1). The optical far-field technology cannot present more than 20 to 30 GB in a 12 cm disc. In the case of CD media, we have a 780 nm laser and 0.45 NA (0.7 GB). For DVD media, we have 650 nm and 0.6 NA (4.7 GB), and for Blu-Ray media we have a blue 405 nm laser and 0.85 NA (25 GB). However, several new approaches to further increase the recording density based on far-field optics, such as magnetic super-resolution (MSR) and optical super-resolution (OSR) technologies, cannot achieve more than 100 GB (see e.g. Milster [2000], Tominaga and Nakano [2005]).

Beyond optical diffraction limit In the case that a focused laser beam is used for high-precision readout of recorded pits in an optical disc system, the real cut-off frequency is determined by the spatial cut-off frequency $(2\mathrm{NA}/\lambda)$ $\times$ the disc rotation speed. If we apply a much higher frequency to the disc readout and recording, no readout signal is observed. This is called the *optical diffraction limit*. The diffraction limit thus determines the data storage capacity of the disc. This is the critical issue in developing super-high-density, next generation optical data storage systems. Available technologies so far depend on the development of new shorter-wavelength semiconductor lasers and sophisticated lenses. However, such far-field optics-based approaches have reached theoretical and technological limits because of the diffraction limit.

Near-field is a prospective technology that provides a significantly reduced beam spot to overcome the resolution limit with the help of new technology. The optical near-field is a special electromagnetic field that presents a significantly reduced laser beam spot size to overcome the resolution limit, but cannot propagate over a long distance (unlike optical far-field waves). In order to overcome the technical limitations in optical far-field data storage due to the diffraction limit, near-field optics and its related application have been proposed for decades (see e.g. Terris et al. [1996], Ichimura et al. [1997], Milster [2000], Peng et al. [2005], Tominaga and Nakano [2005]).

Properties of optical near-field recording In optical far-field recording, the size of the optical spot is proportional to λ/NA where λ is the wavelength and NA is the numerical aperture. The minimum wavelength is 405 nm with the blue laser, and the maximum NA is 0.85 (in the case of Blu-ray). The minimum resolution is determined by $\lambda/(2\mathrm{NA})$ because of the diffraction limit. The Blu-ray has a resolution of 140 nm, which is considered the practical limitation of optical far-field recording. On the other hand, in near-field optical recording, a source and receiver smaller than the wavelength are introduced, and the distance to the medium is made shorter than the wavelength in order to attain a higher resolution beyond the diffraction limit (see e.g. Milster [2000], Tominaga and Nakano [2005]). The evanescent wave, which is detectable in the case of a source smaller than the wavelength, makes the laser beam spot size smaller than its wavelength. Near-field optics can thus overcome the limitations of the focused spot size of a laser beam, which is determined by the wavelength and lens numerical aperture. In principle, we can use the optical near-field to read out very small marks beyond the diffraction limit of the far-field optics.

The optical near-field recording (NFR) terminology refers to the extremely short distance (called the *air gap*) between the read/write head and the disc surface. The roughly 25 nm gap is directly comparable to the flying height (distance between the head and the disk surface) in hard disk drives. The gap is shorter than that of CDs and DVDs (roughly 1 mm) and even BD (1 mm). Much smaller marks (<100 nm) are recorded and read out by several different optical probes, presenting more than 100 GB in a 12 cm disk. The optical near-field cannot propagate beyond 100 nm, however, and the intensity decreases exponentially against the distance. Accordingly, the medium surface has to ultimately be flat in comparison to the current removable DVDs or CDs. Flying height control (also called air gap control) is important. NFR will not be achieved until this issue is technically addressed.

Practical methods of NFR How can we control the near-field light in data storage? The development of a high NA lens system combined with a low-hovering recording head is challenging. A promising method is the use of a blue laser to write and read data through a *solid immersion lens* (SIL) or *solid immersion mirror* (SIM) as illustrated in Fig. 12. The SIL/SIM significantly reduces the spot size of the focused beam at the bottom of that lens (see e.g. Mansfield et al. [1993], Ichimura et al. [1997], Peng et al. [2005], Tominaga and Nakano [2005]).

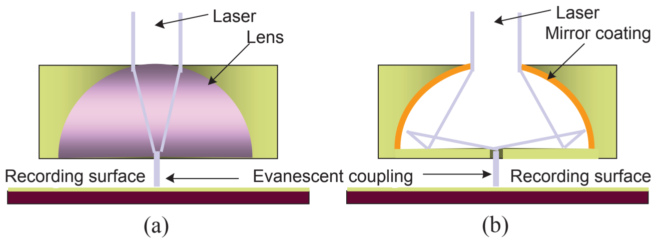

Fig. 12. Optical near-field recording: (a) SIL and (b) SIM.

Other methods proposed for optical NFR have some practical limitations. A thin-film technique called *Super-RENS* (see e.g. Tominaga et al. [2000]) has a low signal-to-noise ratio. All NFR systems based on scanning probe microscopes (SPM) (see e.g. Kim et al. [2001]) have common fatal disadvantages of slow recording speed (10 μm/sec) and a limited scanning area ($100 \times 100\ \mu m^2$). Data transfer rates of more than 20 Mbit/sec are required to record and reproduce actual movie pictures in DVD. High data rates require high speed disk rotation, which causes run out and thus causes the gap to vary with rotation angle. After achieving the high NA, the laser head needs to made to hover accurately at roughly 25 nm above the medium surface. Earlier development of optical near-field recording systems used a slider that is found in hard disk drives. The slider relies on an air-bearing surface with positive and negative pressure pockets to build up the air pressure on which the slide floats. This approach was unsuccessful due to contamination in those pockets.

A new technology involves the introduction of an actuator and the control of the read/write head position. Trials by Philips and Sony have shown that actuators are more robust than sliders, even at extremely short distances. Ishimoto et al. [2002] introduced a gap servo using a PZT actuator, which requires a high control voltage and a short working distance with hysteresis. An optical head with a biaxial device (i.e., mounting the lens in a conventional DVD actuator, which is currently used for focusing and tracking) has been shown to be the most promising; it requires a low control voltage and has a long working distance without hysteresis. Moreover, a gap error signal (GES) can be determined optically without an additional sensor. In active air gap control there are no pockets in which contamination can build up. Moreover, the hinges of an actuator are much more robust than the thin metal suspension (gimbal) that holds a slider. If a slider hits the disk, the slider itself usually survives the crash, but the gimbal generally does not. It has been shown that nothing happens to the actuator if the lens in the actuator collides with the disk (Zijp et al. [2005]).

Accordingly, a practical near-field readout system can be attained with a system similar to the conventional optical disc, in which a biaxial device is used as an optical head actuator and the gap error is detected optically. A gap servo is required to maintain a constant air gap between the SIL/SIM bottom and the disc surface in a near-field position where the evanescent wave is detectable. A biaxial device can be used as an optical head actuator with the gap error signal detected optically. The air gap servo controls the air gap from a far-field initial position to a near-field target position without the head colliding with the disc.

Control issues in NFR Although the system structure appears similar to that of conventional optical disc systems, there is a significant difference in the air gap width. The final air gap, which is typically 25 nm to 30 nm, is much smaller that that of conventional optical disc systems. Moreover, the gap error signal cannot be detected in the far-field.

Servo technology becomes important as it is required to maintain the air gap between the head and the medium to generate the optical near-field, and to accurately track significantly reduced bits. A much smaller track pitch will definitely make the control problem more challenging in the case of optical NFR systems. However, tracking and seeking control methods will not differ much from that of the conventional optical far-field recording systems discussed in Section 4. In the optical NFR, the recording bit size becomes 100 nm; therefore, the required positioning control accuracy is much less than 100 nm, which may not be attained using the current optical far-field device control technology.

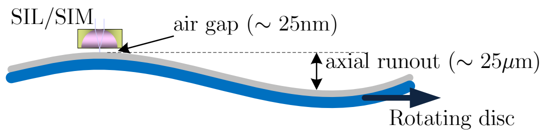

Fig. 13. Air gap control - disc moves due to its non-flat shape and clamping.

An air gap controller is used to control an air gap between the lens and the disc surface, which moves due to its non-flat shape and clamping (Fig. 13). Mode switching, an open-loop approach mode and closed-loop air gap control mode, is widely used in the air gap servo control because the GES is available only in the near-field distance. The (open-loop) approach mode brings the lens head from a remote distance in the far-field to the near-field distance. The sequence of the approach mode brings the lens subsequently closer to the surface. When the lens enters into the near-field range at one of the approach instants, the air gap controller is switched to closed-loop mode. When the air gap controller cannot mitigate the effect of different initial conditions, it is often useful to introduce a hand-over mode between the two modes to avoid overshoot, which may cause the SIL to hit the rotating medium. Although an overshoot of less than one micron may be a trivial problem for an optical far-field system, it could cause the optical head to collide with the disc in a near-field system. The air gap control becomes even more challenging when disk warping and eccentricity, which occur during the manufacturing process, cause run-out motion of the disk surface. Surface vibration also occurs due to disk misalignment in the drive set. In this regard, Sony demonstrated 20 ± 1 nm at a 150 rpm (Ishimotoa et al. [2003]), and recently Philips demonstrated a 20 ± 1 nm air gap for a 3500 rpm polycarbonate disc (Zijp et al. [2005]).

For track seek and tracking, the conventional methods can be used, though a more challenging servo control specification is required. Track seek servo is similar to that of the conventional optical disc systems discussed in subsection 3.3. During track seek servo, the head should be set as far as possible (the maximum working distance of the biaxial device) from the disc to avoid collision between the SIL head and the disk. The power reflected at far-field before operation of the air gap servo is constant, which may make the track seek servo design more difficult. The aforementioned issues also exist in the track seek servo of conventional optical disc systems to a greater extent.

The gap servo system provides an open-loop control signal to the head actuator in order to make the head approach the disc (see e.g. Ishimoto et al. [2003], Zijp et al. [2005], Kim et al. [2007, 2008b]), possibly along a certain profile to reduce pull-in time while avoiding overshoot. An air gap error signal is generated to detect the distance between the SIL and the disc surface. However, the air gap error signal is available only in a near-field region of approximately 50 nm. Due to the late appearance of the air gap error signal and in consideration of the problem of overshoot, introducing an appropriate open-loop control signal is desirable to avoid the problem of overshoot and reduce pull-in time. A pull-in procedure that ensures smooth air gap servo start-up without lens-disc collision is necessary (Lee et al. [2005]). A DOB was used to reduce the overshoot at the switching point between open-loop and closed-loop modes (Kim et al. [2008a]).

Status of NFR Some companies have been active in near-field studies for many years. Sony demonstrated a SIL-based optical NFR system using blue lasers and a NA of SIL at 1.84 with a gap of 20 nm (Ishimotoa et al. [2003]). They also revealed recording densities of 80.6 Gbits/square inch and one-layer capacities of about 112 GB. Philips recently developed a SIL-based optical NFR system for high density recording under the near-field recording concept using a blue laser beam focused by a pair of special lenses that offer a NA of 1.5. They revealed recording capacities of 150 GB or more on two layers (Zijp et al. [2005]). By raising the numerical aperture to 1.61, a single layer can accommodate 125 GB on a 120 mm diameter disc, and as many as four layers can be used to create a single disc capacity of 500 GB. Samsung and LG are also developing optical NFR systems based on SIM and SIL, respectively.

6. CONCLUSIONS

In this paper we have examined the control issues of ODDS from system and control engineering points of view. We have described the basic architecture of servo systems, including actuation, sensing, and control in optical storage. In addition, we discussed key servo loops, including focus and track servo, seek operation, and robust control against periodic and non-periodic disturbances. The speed and quality of the read and write processes depend on how well these servo systems perform. After the successful introductions of CD and DVD media to the data storage market, advances in optical storage technology have also succeeded in commercializing Blue-ray disc players using blue lasers, the smaller wavelengths of which enable the detection of smaller pits and the use of smaller track pitch, thereby increasing the capacity of optical drives. The new needs of the market in consumer products such as high-definition content (e.g., 3D HDTV) increases the likelihood that high density optical storage will become more prevalent in the near future.

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