Chapter

6.6

Compact Disk Recording and Reproduction

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6.6.1 Introduction

This chapter describes the digital format of the compact-disk (CD) digital audio system, its basic specifications, and the process by which audio signals are converted into digital signals and recorded on the disk. In addition, subcodes that can be put to a variety of uses are described.

6.6.1a Basic Specifications

Audio specifications, signal format, and disk specifications are summarized in Table 6.6.1. Pulse-code modulation (PCM) is used to convert audio signals into digital bit streams. Stereo audio signals are sampled simultaneously at a rate of 44.1 kHz. This sampling frequency was chosen for the following reasons:

- From the standpoint of filter design, a 10 percent margin with respect to the Nyquist frequency is required. The frequency of 44 kHz is the maximum sampling frequency required to cover audible frequencies up to 20 kHz (20 kHz × 2 × 1.1 = 44 kHz).
- The frequency of 44.1 kHz was commonly used in digital audio tape recorders based on videotape recorders.

Quantization

Quantization is a key factor in determining the sound quality of a digital system. Sixteen-bit linear quantization was chosen to maintain the same quality as that of master audio tapes being produced when the standard was developed. Coding of 16 bits was also attractive because it provided a theoretical dynamic range for the system at maximum-amplitude input of about 97.8 dB, or substantially greater than that of conventional analog systems. This feature results from a lower noise level. To reduce quantization noise, preemphasis of a 15/50-μs time constant can be used. The coding is two's complement, so the positive peak level is 0111 1111 1111 1111, and the negative peak level is 1000 0000 0000 0000.

Table 6.6.1 Basic Specifications of the CD System

Recording method	
Signal detection	Optical
Linear recording density	43 kbit/in (1.2 m/s)
Area recording density	683 Mbit/in^2
Audio specifications	
Number of channels	2-channel stereo
Playing time	Approximately 60 min
Frequency response	20 ~ 20,000 Hz
Dynamic range	> 90 dB
Total harmonic distortion	< 0.01%
Channel separation	> 90 dB
Wow and flutter	Equal to crystal oscillator
Signal format	
Sampling frequency	44.1 kHz
Quantization	16-bit linear/channel 2′ complement
Preemphasis	No or 50/15 μs
Modulation	EFM
Channel-bit rate	4.3218 Mbit/s
Error correction	CIRC
Transmission rate	2.034 Mbit/s
Redundancy	≃ 30%
Disk specifications	
Diameter of disk	120 mm
Thickness of disk	1.2 mm
Diameter of center hole	15 mm
Program area	50 ~ 116 mm
Scanning velocity	1.2–1.4 m/s, CLV
Revolution speed	500 ~ 200 r/min
Track pitch	1.6 μm
Pit size	0.11 × 0.5 × 0.9 ~ 3.2 (μm)

Signal Format

The error correction technique used in the CD system is the *cross–interleave Reed-Solomon code* (CIRC). CIRC employs two Reed-Solomon codes that are cross-interleaved. The total data rate, which includes the CIRC, sync word, and subcode, is 2.034 Mbits/s.

The modulation method used is 8-to-14 modulation (EFM), and 8-bit data are converted to 14 + 3 = 17 channel bits after modulation. Thus, the channel-bit rate is 2.034 × 17/8 = 4.3218 Mbits/s.

Playing Time

Playing time depends on disk diameter, track pitch, and linear velocity. The CD system was designed for 60 min of playing time, but maximum possible playing time at the lowest linear velocity is 74.7 min.

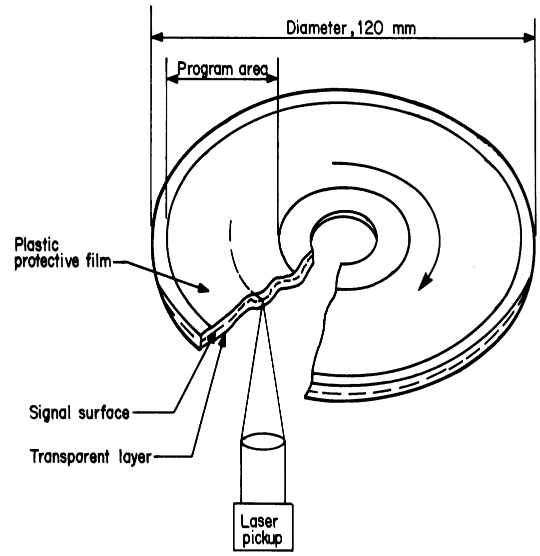

Figure 6.6.1 Construction of a compact disk.

Disk Specification

The diameter of the disk is 120 mm, the thickness is 1.2 mm, and the track pitch is 1.6 μm. The disk rotates clockwise, as seen from the readout side, and the signal is recorded from inside to outside. Because the CD system adopts the *constant-linear-velocity* (CLV) recording method, which maximizes recording density, the speed of revolution of the disk is not constant. The standard linear velocity is 1.25 m/s. Thus, as the pickup moves from the starting area outward, the rate of rotation gradually decreases from 500 to 200 r/min. (See Figure 6.6.1.)

6.6.1b Error Correction and Control Techniques

The CD system employs an optical noncontact readout method. Because the signal surface is protected by a plastic layer and the laser beam is focused on the signal surface, the disk surface itself is kept free from defects such as scratches. As a result, most of the errors which occur at and in the vicinity of the signal surface through the mastering and manufacturing process are random errors of several bits. Even though the CD system is resistant to fingerprints and scratches, defects exceeding the limit will naturally cause large burst errors. A typical bit error rate of a CD system is 10^{-5}, which means that a data error occurs 2×10^6 bits/s $\times$ $10^{-5} = 20$ times per second. Such data errors, even though they may be 1-bit errors, cause unpleasant pulsive noise; so an error correction technique must be employed.

Unlike an error in computer data, an error in digital audio data (if the error can be detected) can be concealed. Indeed, simple linear interpolation is sufficient in most cases. The error correction code used in a CD system must satisfy the following criteria:

- Powerful error correction capability for random and burst errors
- Reliable error detection in case of an uncorrectable error

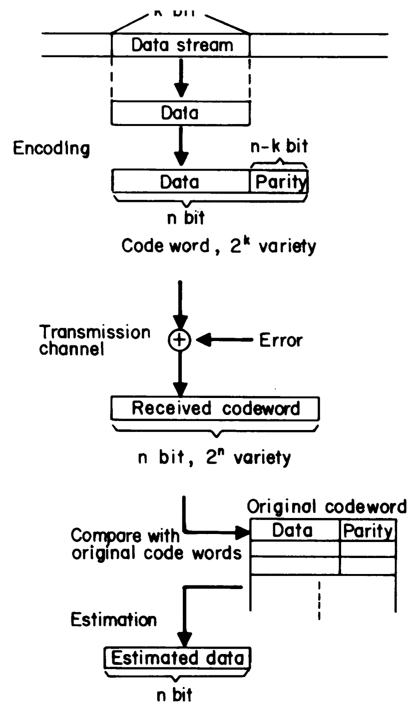

Figure 6.6.2 Basic error correction technique for the CD.

- Low redundancy

CIRC satisfies these criteria and can control errors on the disk properly.

6.6.1c Basic Error Correction Code

The basic error correction procedure is shown in Figure 6.6.2. A group of data is translated into a code word by adding check data and transmitted through the recording channel. At the receiver side, received data are compared with all the code words, and the nearest are selected. If a group of k symbols (the data) is encoded to a longer word of n symbols (the code word) and the code words satisfy special check equations, then this code is called an *(n, k) linear block code*. The encoding process is, in other words, a process of assigning nonparity check data to the original data. For example, suppose $X = (X_1, X_2, ... X_n)$ and $Y = (Y_1, Y_2, ... Y_n)$ are code words, as in Figure 6.6.3, then the Hamming distance between the two code words is defined as the number of different pairs of symbols. If t symbol errors induced in the channel are not to lead to confusion at the receiver side as to whether X or Y was transmitted, X and Y should differ from each other (as in Figure 6.6.4) by at least $(2t + 1)$ symbols. Therefore, a figure of merit of the code called minimum distance d is defined as the minimum distance among all pairs of different code words X and Y.

A code is t-error-correcting if and only if $d \geq (2t + 1)$; and if the locations of the errors (erasure location) are known, $d - 1$ erasure correction is possible. If the number of errors exceeds

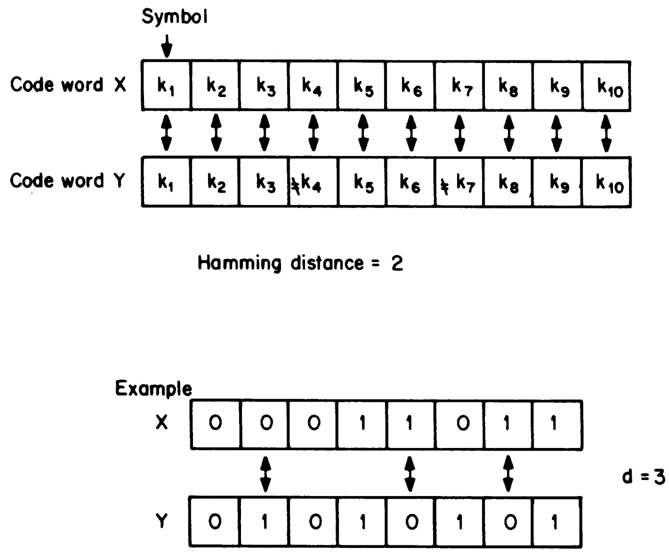

Figure 6.6.3 Illustration of Hamming distance.

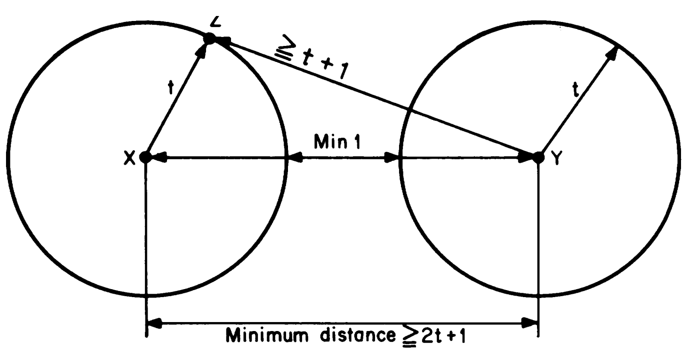

Figure 6.6.4 Minimum distance for *t* error correction.

these bounds, error correction and detection capability are no longer guaranteed and the decoder may make an erroneous decoding.

6.6.2 Fundamental Principles and Specification

The specifications and dimensions of the compact disk are shown in Table 6.6.2 and Figure 6.6.5. The diameter of the disk is 120 mm, and the center hole is 15 mm. The signal is read out through the 1.2-mm transparent disk substrate. The disk rotates counterclockwise as seen from

Table 6.6.2 Specifications for the Compact Disk

Readout mode	In reflections through transparent disk
Track shape	One spiral
Outer diameter of disk	120 ± 0.3 mm
Disk weight	14 to 33 g
Diameter of center hole	15 + 0.1/0 mm
Thickness of disk	1.2 + 0.3, −0.1 mm
Clamping area	26 to 33 mm
Maximum deflection	±0.4 mm
Maximum angular deviation (skew)	±0.6°
Refractive index of substrate	1.55 ± 0.1
Maximum birefringence	100 nm
Reflectivity	70% minimum
Starting diameter of program area	50 mm
Maximum diameter of program area	116 mm
Track pitch	1.6 ± 0.1 μm
Sense of disk rotation	Counterclockwise as seen from readout side
Scanning velocity	1.2 to 1.4 m/s
Maximum vertical acceleration	10 m/s^2 at scanning velocity
Maximum eccentricity	±70 μm
Maximum radial acceleration	0.4 m/s^2
High-frequency modulation amplitude	
I_3/I_{top}	0.3 to 0.7
I_{11}/I_{top}	≧0.6
Track-following signal magnitude	0.04 to 0.07 at 0.1-μm radial offset
Average block error rate	Less than 3%

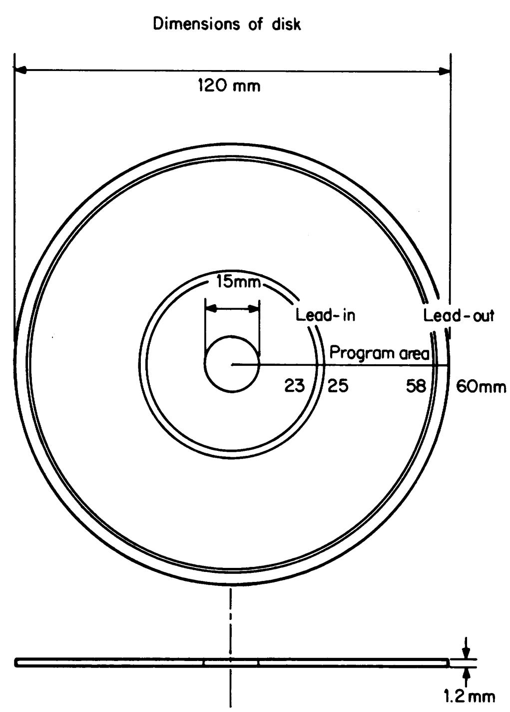

Figure 6.6.5 Dimensions of the program area of the compact disk.

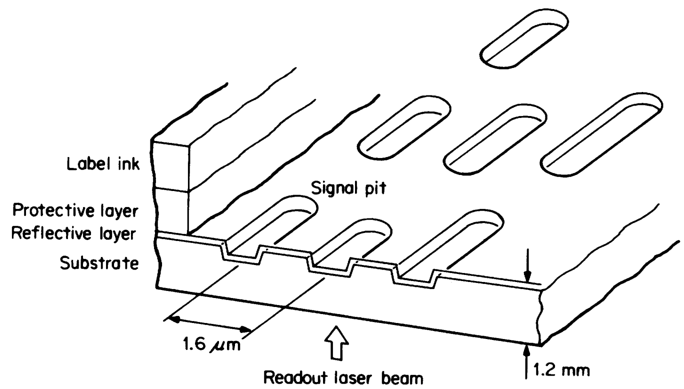

Figure 6.6.6 Cross section of a compact disk.

the reading side. The spiral track pitch is 1.6 μm and is read out from the inside to the outside. Density is about 16,000 tracks per inch. The track length is given by

$$l = \frac{1}{p}\int_{r_i}^{r_o} 2\pi r dr = \frac{\pi}{p}(r_o^2 - r_i^2) = \frac{S}{p} \tag{6.6.1}$$

Where:
p = track pitch
S = area of program zone
r_o = outside diameter of program area
r_i = inside diameter of program area

The program area starts at a 50-mm diameter and ends at a maximum of 116 mm. The total track length derived from Equation (6.6.1) is about 5 km. The lead-in and lead-out zones are used for control of the player system, such as track access and automatic playback. To maximize playing time, the CD is recorded by the CLV method. The scanning linear velocity of the disk (v) is specified as 1.2 to 1.4 m/s. The revolution speed decreases from 500 to 200 r/min. However, the frequency response of the readout signal is the same at any disk radius.

The playing time of a music program (T) is given by

$$T = l/\upsilon \tag{6.6.2}$$

From this equation, the maximum recording time of a CD is about 74 min at 1.2 m/s.

Figure 6.6.6 shows a cross section of the compact disk. The signal is picked up by a focused laser beam through a transparent substrate. Its 1.2-mm thickness prevents signal disturbance by dust or fingerprints. The material of the substrate must satisfy various optical and mechanical requirements such as birefringence, absence of defects, and reliability. Polycarbonates, polymethyl methacrylates, and glass are suitable for disk-production requirements.

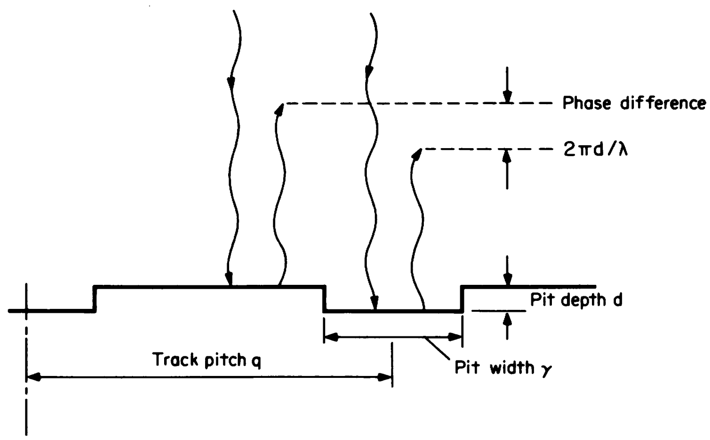

Figure 6.6.7 Phase difference of a reflected beam.

The replicated pits on the signal surface are about 0.1 μm deep, 0.5 μm wide, and several micrometers long. The signal surface is covered with an aluminum layer to reflect a laser beam. This reflective layer is coated with ultraviolet-light-cured resin to protect it from scratches, moisture, and other harmful effects. The label is printed on the protective layer by a silk-screen method.

6.6.2a Pit Profile and Signal Characteristics

The principle of CD signal detection is based on the diffraction phenomenon of a laser spot caused by the *phase pit*. A reading laser beam and pit geometry determine signal performance from an optical pickup. The relation between pit shape and signal amplitude when the phase pit is illuminated by a readout laser beam is reviewed in the following paragraphs.

There is a $2\pi d/\lambda$ phase difference between the reflected light rays from a pit and those from a land (see Figure 6.6.7). When the phase difference is $\pi = \lambda/2$, the modulation index of the reflected beam is at a maximum value by the resultant diffraction. Since a laser beam is reflected from a pit and the pit exists inside the transparent substrate of which the refractive index is $n = 1.5$, the $\lambda/4n$ pit depth gives the maximum high-frequency signal amplitude:

$$\lambda/4n = 0.78\mu\text{m}/4 \times 1.5 = 0.13\mu\text{m} \qquad (6.6.3)$$

On the other hand, the push-pull signal for tracking is at a maximum value when the pit depth is $\lambda/8n$. In view of the performance of high-frequency and push-pull signals, the pit depth of the replica was set at approximately 0.1 μm.

Pit width also affects signal quality; viz., the amplitude, distortion, and frequency response of high-frequency and track-following signals. The pit width is equal to a recording spot size of 0.5 ~ 0.7 μm in mastering. Figure 6.6.8 shows the relationship between the signal amplitude and the square cross-section pit profile.

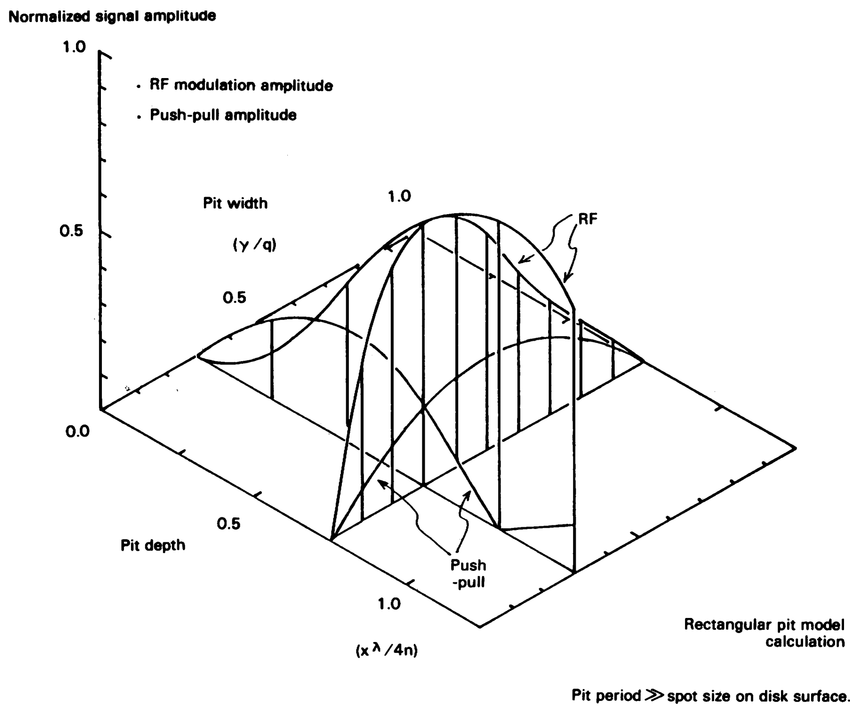

Figure 6.6.8 Normalized signal amplitude versus pit shape.

Pit length is related to the pulse width of the CD signal format. With a scanning velocity of 1.25 m/s, there are nine different pits on the signal surface: 0.87, 1.16, 1.45, 1.74, 2.02, 2.31, 2.60, 2.89, and 3.18 μm. Each pit length is effected by the disk-production processing operation and the readout characteristics of the optical pickup (*asymmetry*). Within a certain range, asymmetry is not a problem because the correction circuit corrects it automatically.

The replicated pit does not have an ideal square cross section but does have a slope of pit edges. This pit shape is called the "soccer stadium" model.

6.6.2b Optical System

The basic optics for reading are shown in Figure 6.6.9. This simple figure consists of a light source, a microscope objective lens to concentrate a spot onto the information layer of the disk, a beam splitter, and a pin diode as a photodetector, which converts to electric current.

The optical principle of noncontact readout is based on diffraction theory. Though this phenomenon by means of a narrow slot is well known, an analogous situation occurs if a light beam impinges on a reflective signal surface with pit-like depressions. In the case of a flat surface (between pits), nearly all the light is reflected, whereas if a pit is present, the major part of the light is scattered and substantially less light is detected by the photodetector (Figure 6.6.10).

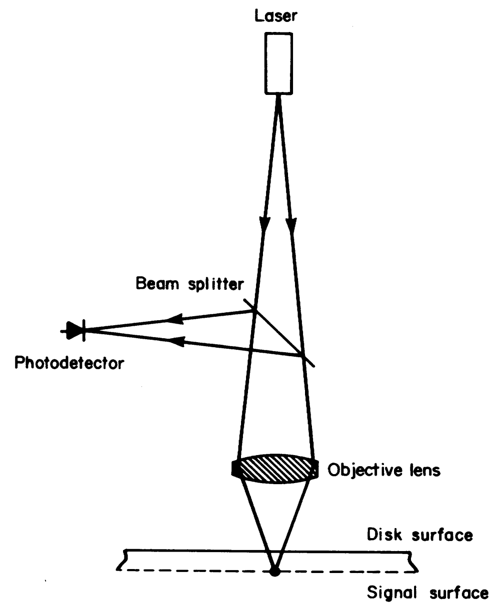

Figure 6.6.9 Basic optics for reading a CD.

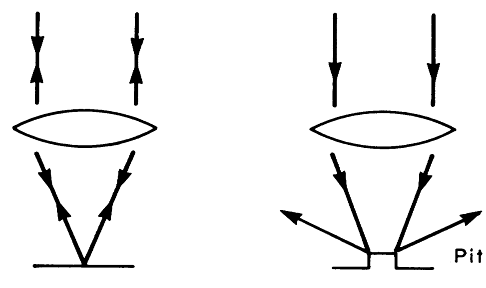

Figure 6.6.10 Principle of noncontact readout.

Laser Diode (LD)

The light source used in the CD system must satisfy the following conditions:

- It must be small enough to be built into the optical pickup
- It uses coherent light in order to focus on an exceedingly small spot
- Enough light intensity for readout must be provided

GaAIAs semiconductor laser diodes satisfy the above requirements. The typical specifications of such an LD include:

- Wavelength = 0.78 to 0.83 µm
- Light power = approximately 3 mW
- Lateral mode = fundamental

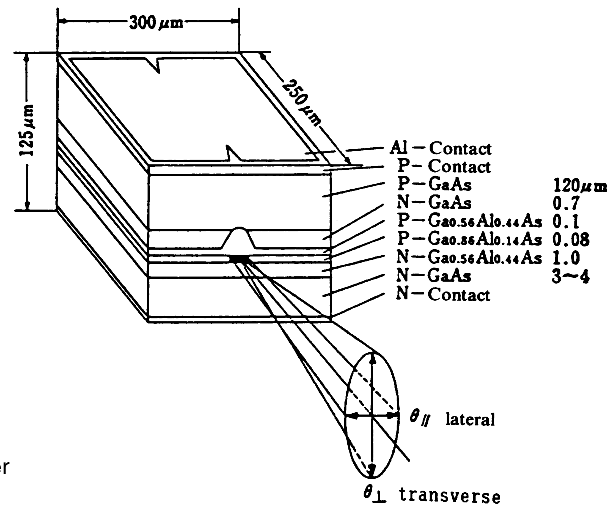

Figure 6.6.11 Structure of the laser diode.

- Transverse mode = fundamental
- Longitudinal mode = multiple

When the light from the LD is returned from the reflective surface of the disk, it has an effect on the light-generating characteristics of the LD and generates large optical noise fluctuations. Thus, a *multiple longitudinal mode* is necessary to prevent the phenomenon. A typical structure and optical and electrical characteristics are shown in Figures 6.6.11 and 6.6.12.

Lens

The lens requirement can be described by means of *numerical aperture* (NA). By using the angle from Figure 6.6.13, it is shown by NA = $n \sin\theta$, where n is the refractive index.

Owing to diffraction at the lens aperture, the light beam has a limited value. It is well known that when a beam with a uniform distribution of flux is incident to a lens, the beam projects a pattern known as the *Airy disk*. The diameter of the first ring, in which about 84 percent of the energy is concentrated, is given roughly by

$$1.22 \times \lambda/\mathrm{NA} \qquad (6.6.4)$$

where λ = wavelength. If the strength is defined as $1/e^2$ (e is the base of the natural logarithm), the effective beam diameter is

$$0.82 \times \lambda/\mathrm{NA} \qquad (6.6.5)$$

From these equations, it can be concluded that to focus on a small spot it is better to have a smaller and a larger NA. But NA also defines the following important factors:

- Depth of focus is proportional to λ / (NA)^2

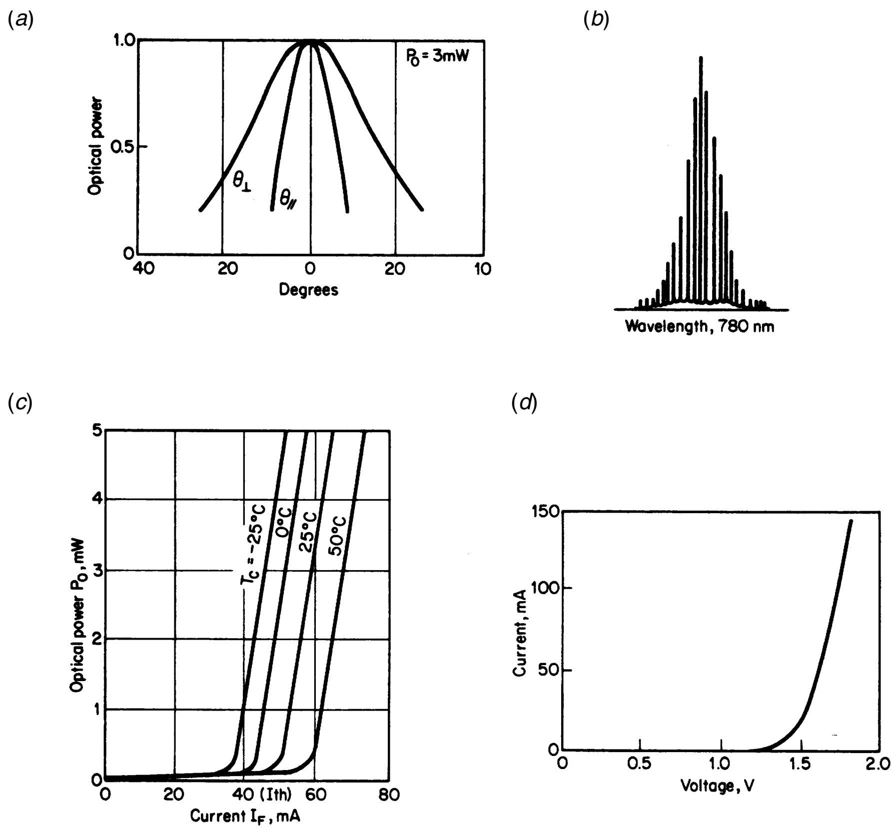

Figure 6.6.12 Specifications of a laser diode: (*a*) far-field pattern, (*b*) longitudinal multimode spectrum, (*c*) *I-L* characteristics, (*d*) *V-I* characteristics.

- Allowance for skew (tilt) is proportional to λ / $(NA)^3$
- Allowance for variations in disk thickness is proportional to λ / $(NA)^4$

For these reasons, an NA which satisfies the following equation is recommended:

$$\lambda/NA \leq 1.75 \qquad (6.6.6)$$

Accordingly, NA must be within the range of 0.45 to 0.50 in combination with the wavelength of the LD.

Modulation Transfer Function

The *modulation transfer function* (MTF) describes the frequency characteristics of the optical channel. In other words, it is the parameter which determines the smallest size of pits that can be

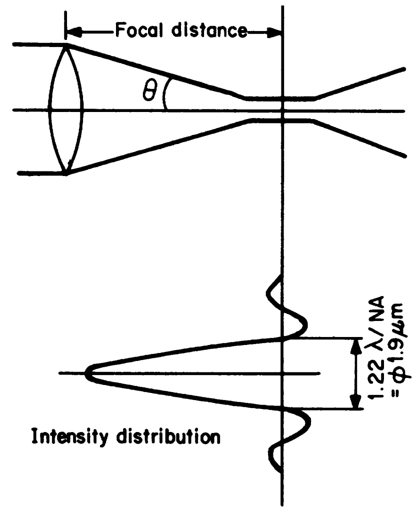

Figure 6.6.13 Numerical aperture of lens and Airy disk.

detected. To make this determination, the *optical transfer function* (OTF) is defined and expressed by a complex number. MTF is the absolute expression of OTF. The phase term of OTF is called the *phase transfer function* (PTF). Generally, OTF is expressed by the cross-correlation function for the input and output apertures. In the case of a CD, a form of reflective optical disk, this becomes the auto-correlation function in the equation

$$F(x) = \frac{2}{\pi}\cos^{-1}\frac{x}{x_o} - \frac{x}{x_o}\sqrt{1-\left(\frac{x}{x_o}\right)^2} \qquad (6.6.7a)$$

where $x = x_o$.

$$F(x) \le 0 \qquad (6.6.7b)$$

where $x > x_o$. Here x shows the spatial frequency and x_0 shows the optical cutoff; x_o is expressed with a given NA and λ as follows:

$$x_o = 2\text{NA}/\lambda \qquad (6.6.8)$$

As shown in Figure 6.6.14, it is a form of low-pass filter. In the case of a CD, λ = 0.78 μm, NA = 0.45, and the optical cutoff frequency is

$$x_o = 1.154 \times 10^6 \qquad (6.6.9)$$

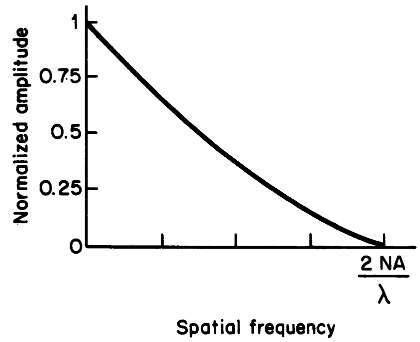

Figure 6.6.14 Modulation transfer function. (MTF)

In other words, this optical system can detect pits as dense as 1154 per millimeter. As outlined previously, the smallest pit of a CD is about 0.87 µm at a linear velocity of 1.25 m/s. If the track were occupied by these pits, the spatial frequency would be

$$1/(0.87\mu m \times 2) \ = \ 0.581 \times 10^6 \tag{6.6.10a}$$

This wideband characteristic facilitates accurate reading of the pit modulation over a wide range. In terms of temporal frequency, the cutoff frequency is

$$\frac{2\text{NA}}{\lambda} \times V \ = \ 1.44 \text{ MHz} \tag{6.6.10b}$$

where the linear velocity $V = 1.25$ m/s.

All the equations are for theoretically ideal optics and ideal conditions. For design and analysis purposes, they must be modified for actual operational conditions and available hardware.

6.6.2c Servo Tracking Methods

For tracking with a light beam, two position controls are necessary, one in the vertical and the other in the radial direction. These controls are called focus- and radial-tracking controls, respectively.

Generally, the servo system is composed of three subsystems, as shown in Figure 6.6.15. The error of position is detected at the first block. The second block is the electronic compensation network, which is necessary for the stability of a closed-loop system. In the last stage, the electronic signal is converted into actual spot displacement by means of the electromechanical system.

Focus Servo System

This system is used to keep the laser beam focused on the reflective layer of the disk within the focus depth of the optical system. The focus depth is

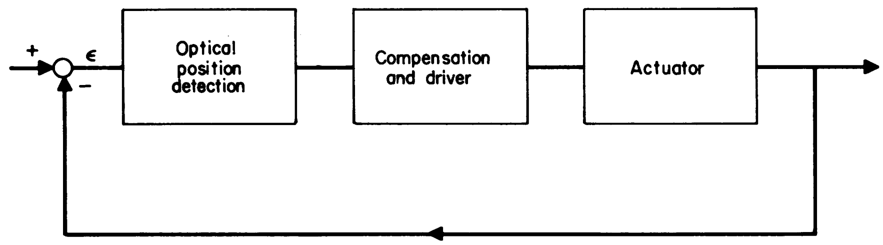

Figure 6.6.15 Block diagram of the servo system.

$$\pm\frac{\lambda}{(NA)^2} = \pm 2\mu m \qquad (6.6.11)$$

where $\lambda = 0.78$ and NA = 0.45. On the other hand, the specified deviation in the vertical direction is:

- Maximum deviation = 0.5 mm
- Maximum acceleration = 10 m/s

This translates into a requirement of more than 48 dB for low-frequency response.

Astigmatic Method

One method to detect the light-beam position in the vertical direction is the *astigmatic* method (Figure 6.6.16). When using this method, it is necessary to modify the basic optics by placing a cylindrical lens between the beam splitter and the photodetector. The photodetector is divided into four segments. When the beam is focused on the disk surface within the focus depth, a circular spot is created on the four-segment detector surface. When the beam is focused before or after that point, elliptic spots are imaged on the detector. If an $(A + C) - (B + D)$ operation is performed, the result is the focus-error signal.

Foucault Method

There are differing forms of this method, one example of which is shown in Figure 6.6.17. In this case, a wedge is used instead of a cylindrical lens, and two-segment detectors are employed. If the beam is in focus, the operation $(A + D) - (B + D)$ is zero. If the disk and lens move closer, the image of the reflected light moves further away. On the other hand, if this distance increases, the resultant polarity of the signal becomes the opposite sign.

Actuator Method

The actuator mechanism is used in the vertical direction in a manner similar to that employed in loudspeakers. For example, as in Figure 6.6.18, an objective lens (or the complete pickup, if possible) can be attached to a voice coil, which moves up and down according to the electronic signal command from the focus-error detector through the phase-lead circuit.

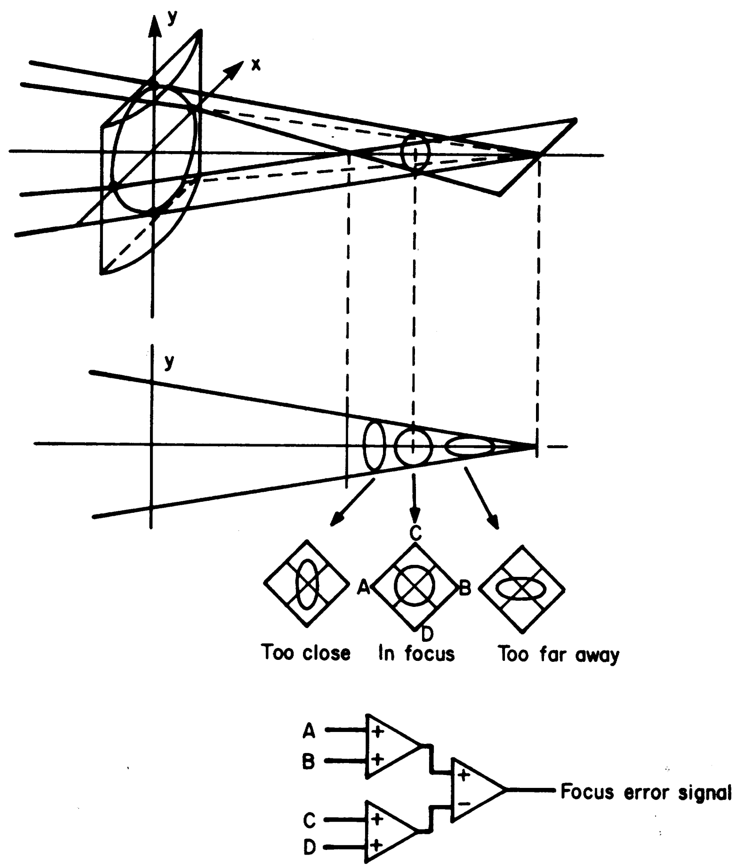

Figure 6.6.16 Astigmatic-focusing servo system.

6.6.3 Compact-Disk Player

A block diagram of the CD player is shown in Figure 6.6.19. The reading beam concentrated onto the information layer detects the signal recorded on the disk in digitally encoded form. The readout signals are processed (added and/or subtracted) and separated into (1) servo status signals and (2) the audio program signal. The audio signal is processed in the decoding block into the conventional but highly precise audio signal waveforms for the right and left channels. Concurrently, the servo status signals drive the servo system, which maintains precise control of spindle speed and laser-beam tracking and focus. The control and display system. using a microprocessor, is a control center; it not only simplifies user operation but also provides a display of visual data (using subcoding Channel Q information derived from the decoding block), which consists of brief notes about the musical selections as they are played.

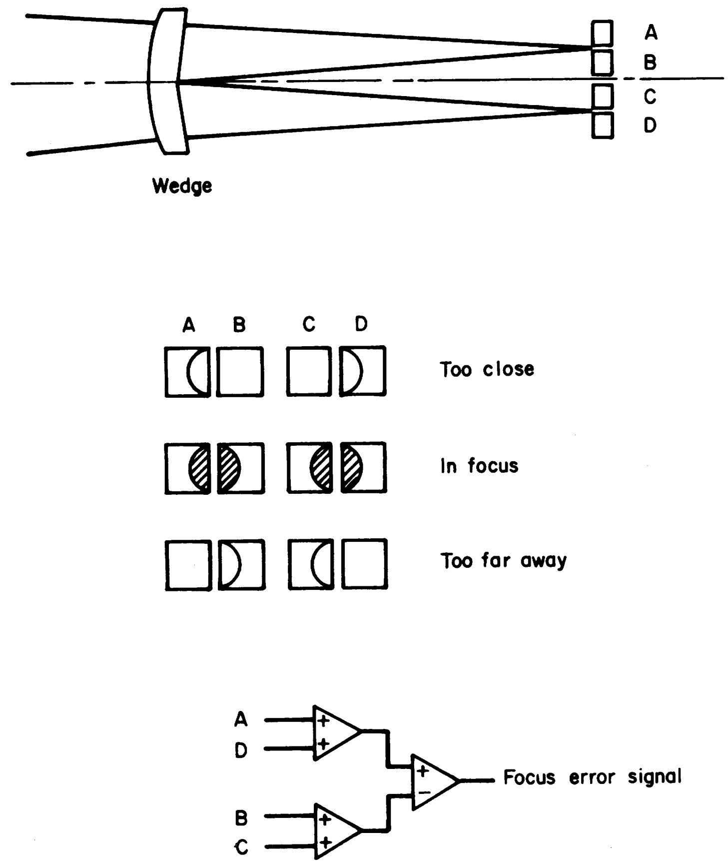

Figure 6.6.17 Foucault method for the focusing servo system.

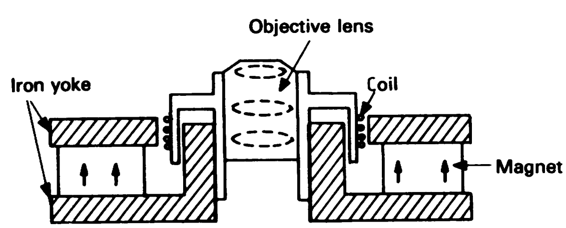

Figure 6.6.18 Actuator system.

6.6.3a High-Frequency Signal Processing

After compensation of frequency response, if necessary, we can obtain the so-called eye diagram, shown in Figure 6.6.20, This is the result of processing by an optical low-pass filter,

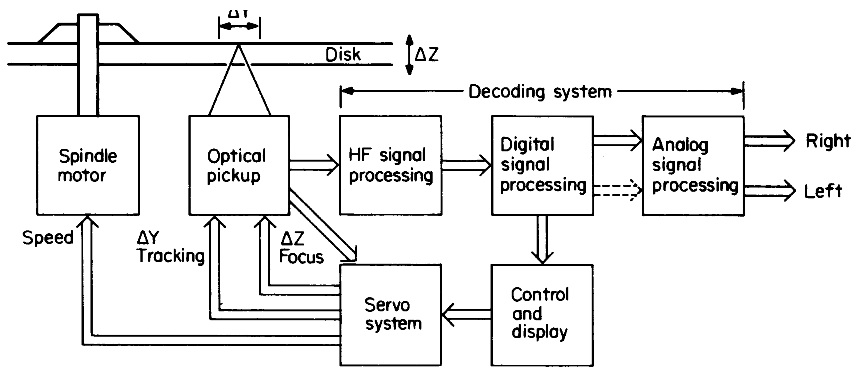

Figure 6.6.19 Configuration of a compact-disk player.

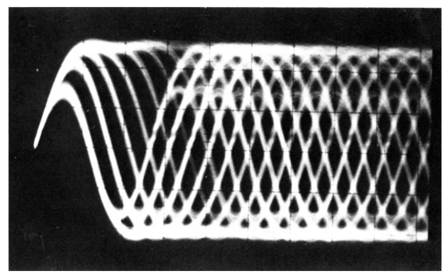

Figure 6.6.20 Eye diagram of the EFM signal.

expressed by MTF.

To convert into a two-level bit stream, it is necessary to take care of the "pit" distortion. By looking at Figure 6.6.20 carefully, it can be understood that the center of the eye is not in the center of the amplitude. This is called asymmetry, a kind of pit distortion. It cannot be avoided when disks are produced in large quantities because of changes resulting from variations in mastering and stamping parameters as well as differences in the players used for playback. Accordingly, a form of feedback digitizer, using the fact that the dc component of the EFM signal is zero, can be used. In addition, the clock for timing signals is regenerated with a PLL circuit locked to the channel-bit frequency (4.3218 MHz).

6.6.3b Digital Signal Processing

Figure 6.6.21 is a block diagram of digital signal processing elements typically used in a compact-disk player. The demodulation of EFM can be accomplished by using various processes to produce the digital audio data and parity values for error correction (CIRC). At the same time, the subcoding that directly follows the synchronization signal is demodulated and sent to the control and display block. The data and parity values are then temporarily stored in a buffer memory (2K bytes or so) for the CIRC decoder circuit. The parity bits can be used here to correct errors or merely to detect them if they cannot be corrected. Although CIRC is one of the

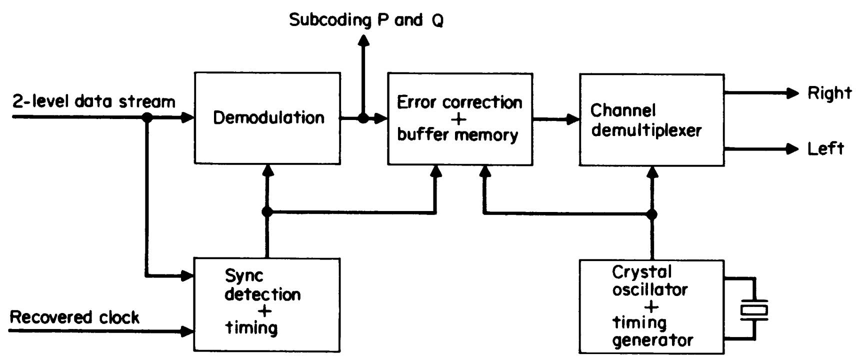

Figure 6.6.21 Block diagram of the compact-disk digital signal processing system.

most powerful error-correcting codes, if more errors than a permissible maximum occur, they can only be detected and used to provide estimated data by linear interpolation between preceding and new data.

At the same time, the CIRC buffer memory operates as the deinterleaver of the CIRC and is used for time-base correction. If the data are written into the memory by means of the recovered clock signal with the PLL and then read out by means of the crystal clock after a certain amount of data has been stored, data can be arranged in accordance with a stable timing rate. In this way *wow* and *flutter* of the digital audio signal are reduced to a level equal to the stability of the crystal oscillator.

6.6.3c Analog Signal Processing

The error-corrected and time-base-corrected digital data must be converted into the analog values that they represent. This is the role of the digital-to-analog converter (DAC), and the necessary conditions for the CD system are:

- 16-bit resolution
- Conversion speed of at least 15 μs
- Low cost (monolithic integrated circuit) implementation

For these requirements, several types of conversion methods have been developed. They are:

- R-2R ladder network
- Dynamic element matching (DEM)
- Integration method using a high-frequency clock

The popular R-2R ladder-type schematic diagram is shown in Figure 6.6.22.

The last stage of analog signal processing is the low-pass filter, used to reduce energy outside the audible frequency range (20 Hz to 20 kHz). Instead of using only an analog filter, the combination of a digital *oversampling filter* with a simple analog filter has become common. A block diagram of such a system is shown in Figure 6.6.23.

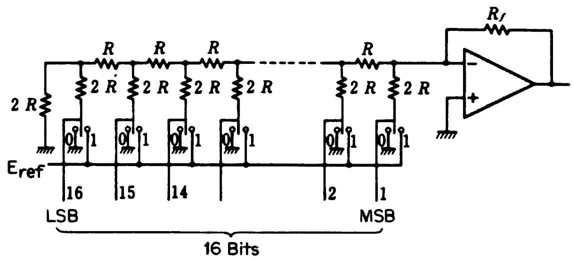

Figure 6.6.22 The R-2R digital-to-analog converter.

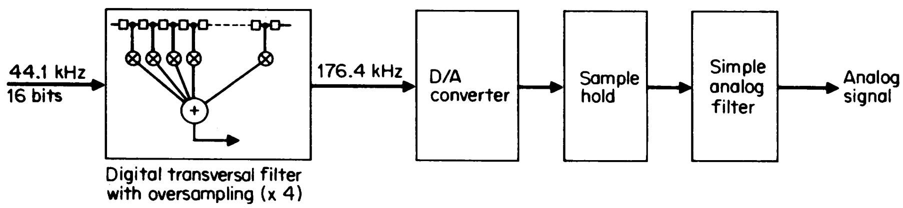

Figure 6.6.23 Digital-to-analog conversion using digital filtering.

6.6.4 Bibliography

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