Chapter 10

The CD player as a measurement system

The CD player has to recover information from a spiral track of small pits which have been formed at a nominal *Information Layer* inside a compact disc. Unlike the old-fashioned vinyl (or shellac!) analog recordings, the CD does not have a ‘continuous' groove and the optical sensor should never touch the disc. Hence the CD player must locate the required information without any mechanical guidance about where the data is to be found. Figure 10.1 illustrates the form of a typical CD surface and the optical beam used to read data from the disc.

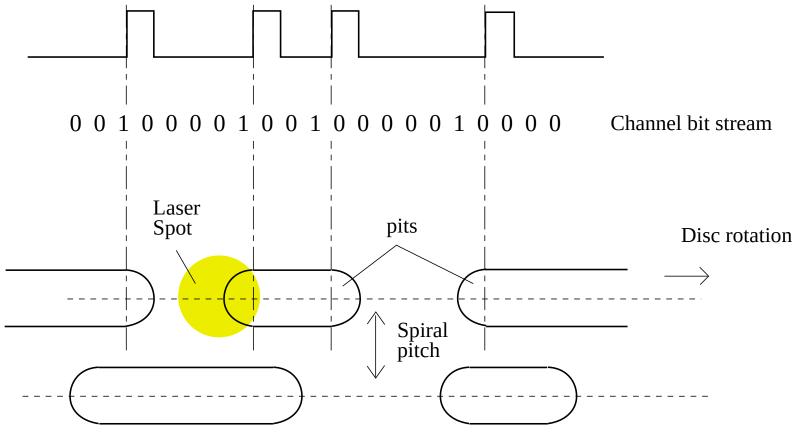

Figure 10.1 Replay of CD pit–land pattern.

Information is recorded on the surface of a CD in the form of a spiral track of pits, and is read using a laser whose wavelength is around 0·7 µm. The spiral pitch (distance between adjacent turns) is 1·6 µm and the disc is rotated so that the position illuminated by the laser spot moves at a constant <u>linear</u> velocity of 1·25 m/s.

Analog disc recordings were normally made at a constant <u>angular</u> velocity. This means that they can be replayed by rotating them at a steady rate. CDs use a constant linear recording velocity in order to maximise the amount of information which can be squeezed onto a given disc diameter. This means that the angular rate of rotation required to play a CD varies as the disc is played. Unlike most analog discs, CDs are recorded 'from the middle, outwards'. The optical sensor used to recover data starts near the middle of the CD with the CD being rotated relatively quickly. As the music plays the sensor moves outwards and the rotational rate is reduced.

CDs can be manufactured in various ways. Many of the first discs were made using photochemical techniques. A light sensitive chemical was coated onto the surface of a disc of plastic. The required pit–land pattern was then 'photographed' onto the disc. The details of this pattern were then etched using appropriate chemicals. More recently, faster, cheaper methods have been developed. For example, many modern discs are produced by *Injection Moulding* — forcing plastic into a metal mould, one wall of which holds a 'negative' version of the required pattern of pits and land. The patterned plastic surface is coated with a thin layer of metal (usually aluminium, but some expensive CDs use gold instead) to make it highly reflective. This is then covered with a protective top coating of transparent plastic.

When using electromagnetic radiation to observe small-scale features, we wouldn't normally expect to be able to measure anything whose size is significantly smaller than the chosen wavelength. In the case of a CD the required bit recovery rate is 4·32 Mbits/s and the the disc velocity is 1·25 m/s. This implies that each bit occupies a track length of just 0·29 μm — i.e. less than half the laser's wavelength! A number of factors help CD players to recover information from such a closely packed surface pattern.

• Firstly, the laser beam is tightly focused to produce a spot whose nominal diameter is typically around 1 μm. This requires an optical system of very high quality.

• Secondly, the encoding system is designed to help the laser sense the surface features. Every stretch of pit or land will be at least 3 bits long. This is a result of the coding requirements that; i) there must always be at least 2 zeros between adjacent ones; ii) pit–land edges represent encoded 1's. This means that pit–land edges will always be at least 0·87 μm apart — i.e. the length of each pit or land feature will always be comparable with the laser wavelength. This means it is possible to ensure that the laser spot will never illuminate more than a single edge at a time.

• Thirdly, the optical system employs a highly coherent light source and the pits are made approximately a quarter-wavelength deep. The readout beam axis is nominally aligned to be perpendicular to the disc plane. When there are no pit–land edges in the spot, all of the reflected beam will share the same phase. The phase of the reflected beam will, however, change by 180 degrees when the spot moves from pit to land, or vice versa.

When the optical spot traverses a pit–land edge the magnitude of the beam reflected back into the sensor optics will momentarily dip almost to zero. The reason for this can be understood by considering what happens if half the spot energy falls upon land, and half into a pit. The reflected beam then consists of two portions, equal in magnitude but opposite in phase. As a consequence the total energy coupled back into the sensor beam would be zero. Of course, the 'missing' energy does not just vanish, instead it is scattered in some other direction, away from the sensor beam.

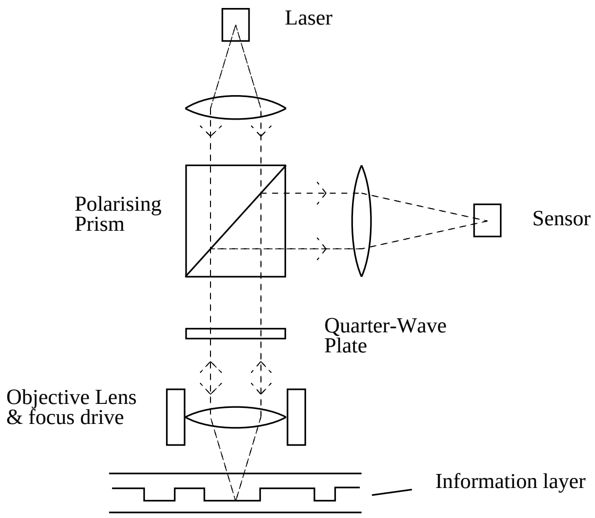

Figure 10.2 Typical CD replay optical system.

Although the details vary a great deal from one manufacturer to another, most players use variations on the system illustrated in figure 10.2. In principle it would be better to employ some form of *Michelson Interferometer* with a pair of detectors. This would enable the player to measure the phase of the reflected signal as well as its amplitude and distinguish pits from land. This would improve the S/N ratio achievable with a given laser power level. However — as will become clear later — the player's optical system is invariably much more complex than implied by figure 10.2. The extra complexity is to allow for the chosen focusing/tracking arrangements. The use of a full interferometer system would require a further increase in player complexity. Fortunately, poor signal to noise ratio need not be a problem with CD players as the manufacturer can generally obtain solid state laser sources which provide ample power levels. Hence the use of a full phase interferometer system isn't usually regarded as necessary. (Although doubtless some manufacturer will eventually make it's inclusion a 'selling point'!)

The system illustrated relies upon detecting the momentary dips in the observed reflected light level which occur at the pit–land edges. Laser light is focused onto the disc information layer via a polarisation prism and a quarter-wave plate. Since this isn't a book on optics we don't have to get into an explanation of just how these items work. For our purposes it's enough to know that a polarisation prism will transmit light with one plane polarisation and reflect light polarised at 90 degrees to the transmission plane. The quarter-wave plate alters the polarisation state of light passing through it. As a result, the light reflected back from the disc is directed onto a sensor, not returned to the laser.

In practice we may find that the reflected energy is not divided exactly 50:50 at the pit edges. The pit depths may also not be exactly a quarter wavelength. This means that the magnitude of the sensed reflection may not dip right down to zero. Despite this practical problem, the power of the replay laser is normally so large that we can obtain a high enough S/N ratio to determine the locations of pit–land edges with an uncertainty considerably smaller than a wavelength.

When the system is working correctly, the laser spot is focused on the information layer which sits in the nominal information layer of the disc surface. (This layer can be defined to be mid-way between the land and pit bottom planes.) Light reflected by the disc will return through the system and be refocused at the required output plane, just in front of the signal detector (or detectors).

Any fluctuations in the distance from the objective lens to the information layer will have two undesirable effects. The beam size at the information plane will become larger, and the output focal spot will shift along the beam axis away from its required position. The CD player must, therefore, be able to continuously adjust the objective lens position to maintain its position at the correct distance from the disc. It must also ensure that the spot tracks the spiral pattern of pits.

Since there is no physical contact, the CD optical sensor system must itself provide signals which can be used to continuously adjust its position relative to the disc with sub-micron accuracy — even when playing a disc which is warped or rotating off centre by over a hundred times this amount. It must also provide a measurement of tracking velocity with enough accuracy to enable the player to vary the disc rotation rate and collect audio data with a channel bandwidth of over 2 MHz. The CD player must therefore contain a highly accurate and responsive position/velocity measurement system.

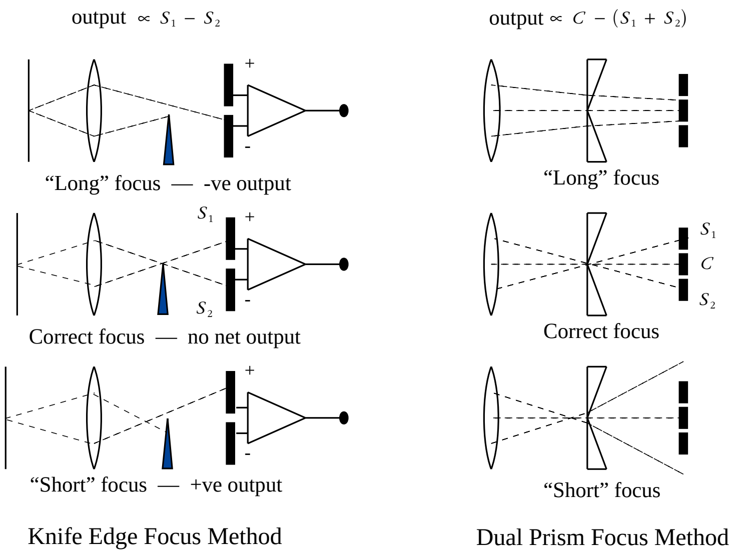

Figure 10.3 CD spot focus mechanisms.

CD player manufacturers have used a variety of techniques to control the optical recovery of information and position the sensor correctly. For the sake of illustration we can examine four techniques:

i) dual-prism focusing   ii) knife-edge focusing
iii) three-spot tracking   iv) dither tracking

Figure 10.3 shows the focusing methods we are considering. In each case the output light level is detected by using more than one sensor. The systems are arranged so that any alteration in objective-disc spacing alters the relative levels seen at the sensors. In the *Knife-Edge* system, an opaque edge is placed near the output focal spot. This stops some of the light from reaching a pair of sensors placed a little further along the beam.

When focused correctly, the output focal spot rests near to the knife-edge and the amounts of light reaching each sensor of the pair of output sensors, S_1 and S_2, are reduced by similar amounts. Any change in the objective-disc spacing will shift the output focal plane along the beam, producing an imbalance in the amounts of light blockage experienced by each sensor.

The output voltages produced by the pair of sensors can be monitored by the CD player. The sum of their voltages, $S_1 + S_2$, can be used to provide audio information. Any difference, $S_1 - S_2$, in their voltages can be used to indicate a focusing error. The sign of this difference voltage indicates the direction of the error. When this difference output is zero the system is ideally focused

The *Dual-Prism* system employs a pair of prisms placed in front of three light sensors. The prisms slightly alter the convergence of the beam, changing the relative levels falling upon three output sensors. The size of the effect of the prisms depends upon the position of the focal plane of the incident beam relative to the prism. As with the knife-edge system, we can use the sum of all the sensor voltages, $C + S_1 + S_2$, to obtain audio information. The difference, $C - (S_1 + S_2)$, between the central sensor and the surrounding ones can be used to indicate any focusing error. As with the knife-edge system a zero difference output indicates when the system is ideally focused. When this happens we can expect about half the light power to be falling on the central detector, C, and the other half on the outer pair. This means that about a quarter of the total falls on each of S_1 and S_2. A focus error in one direction will cause C to rise and $S_1 + S_2$ to fall. An error in the other direction has the opposite effect. Hence, as with the knife-edge system, the sign of the difference output indicates the direction of the error.

However the focusing information is gathered it provides the player with a focus control signal whose magnitude and sign depend upon the amount (and direction) by which the objective-disc spacing differs from the required value. This signal is then amplified and used to drive a motor which changes the objective lens position so as to reduce the error. The overall system acts as a form of *Servo Control Loop* to maintain the required focus.

Figure 10.4 shows the *Three–Spot* method for obtaining tracking measurements. In this system the laser beam is diffracted so as to produce three spots focused on the information layer of the disc. The power reflected at each spot is directed onto a separate light sensor. The spots are arranged to lie in a line at a slight angle to the nominal direction of the information spiral. As a result, when the centre spot is correctly aligned the front and back spots only partly illuminate the spiral.

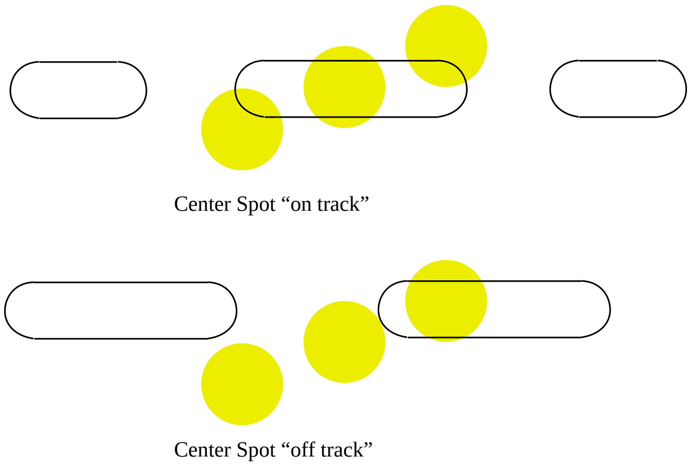

Figure 10.4 Three−spot spiral tracking system.

The CD player monitors the relative levels of light modulation recovered by all three of the spot sensors. When the system is tracking ideally, the centre spot will give a relatively large modulation output. When the spots are slightly off-track the output from either the front or back spot will increase and that from the centre one will fall. The difference in levels between the front and back spot sensors can therefore be used to obtain a measure of any tracking error. As with focusing, any difference signal can be amplified and used to adjust the position of the objective lens so as to maintain good tracking.

A disadvantage of this system is that only about one third of the available laser power will be used to obtain the required audio information. In principle, the player could recover audio information from all three spot sensors. A problem with attempting this is that the spots are looking at different places along the spiral track, and hence at any moment they are recovering different portions of the recorded data. The spots could, if we wished, be placed ‘side by side’ to overcome this problem, but they would then be physically overlapping and — as a result — the sensors would be more likely to see light coming from the ‘wrong’ spots.

The *Dither Tracking* technique makes a single spot do the work of three by forcing the spot to hunt back and forth across the spiral track. This can be achieved by vibrating the objective lens from side to side a very small amount, or by reflecting the laser-sensor beam off a mirror surface whose angle is vibrated. Typical systems employ a sinusoidal modulation with a frequency of a few hundred Hertz. The magnitude of the oscillation is very small and should only move the spot at the disc information layer by a fraction of a micron.

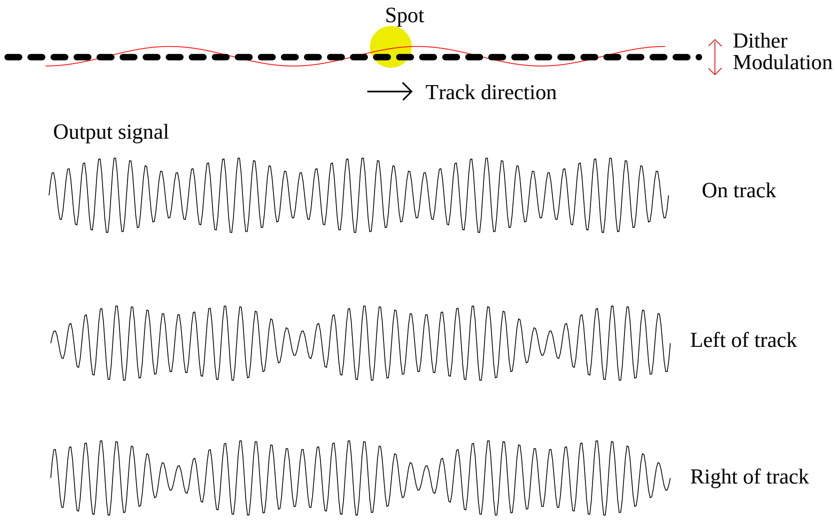

Figure 10.5 Using spot 'dither' to obtain tracking information.

The effect of this deliberate modulation is shown in figure 10.5. The output signal mainly consists of a complex signal with frequency components in the MHz range. When the system is tracking correctly, the dither produces a slight amplitude modulation of this signal at twice the dither frequency. Any tracking error will change the shape of this modulation, producing a shape which contains a component at the dither frequency.

In an earlier chapter we saw that the digital signal recorded on the CD requires a channel frequency range up to at least 2·15 MHz to cope with the required bit-rate. One of the conditions used to select the coding system was that there should never be more than ten ‘0’s between any successive pair of ‘1’s in the data stream. This means that the frequency spectrum of the digital signal won't contain any significant frequency components below about 2·15/10 MHz ≈ 200 kHz. The digital audio data is therefore confined to a frequency band from about 200 kHz to 2 MHz. Since the dither frequency (and twice this frequency) is well below the digital audio frequency range the CD player has no problem separating the dither tracking output from the digital audio information. The player can then compare the magnitudes of the amplitude variations at the dither and 2 × dither frequency, find the phase of these signals relative to the dither modulation it is applying, and use the result as a measure of any tracking error.

The dither technique is, in principle, a very efficient one. Only one spot and sensor are required, and the magnitude and frequency of dither can, if we wish, be continuously altered to suit the difficulty of the task (i.e. less dither on ‘good’ discs and players). Perhaps the main drawback of this method is that its name makes it easily confused with the (quite different!) dither ‘noise’ signal used to suppress quantisation distortion. Various other methods have been devised by manufacturers to recover tracking information. However, as with the choice of focusing technique, what finally matters is the quality of the actual CD player design and manufacture.

Summary

You should now understand how the pattern on the surface of a CD is formed. You should also know how a CD player is able to ‘track’ and recover the spiral of pits in the CDs information layer. In particular, it should be clear how the player can focus and align its laser/sensor system and adjust the rotation rate to recover the required stream of channel bits.