Lecture 5

Part I: DVD focus control[1]

Imagine the following: You are traveling at half the speed of light, along a line from which you may only deviate 1 m. The line is not straight but oscillates up to 4.5 km sideways, 23 times per second.

This is a scaled version of the control task in a DVD player, where the pick-up head needs to follow the bit-track. The real numbers are 3.5 m/s, with maximally 0.022 μm deviations from the track. A disk is always slightly asymmetric, causing it to oscillate up to 100 μm per rotation, and the rotation speed is up to 23 Hz (for *single* speed).

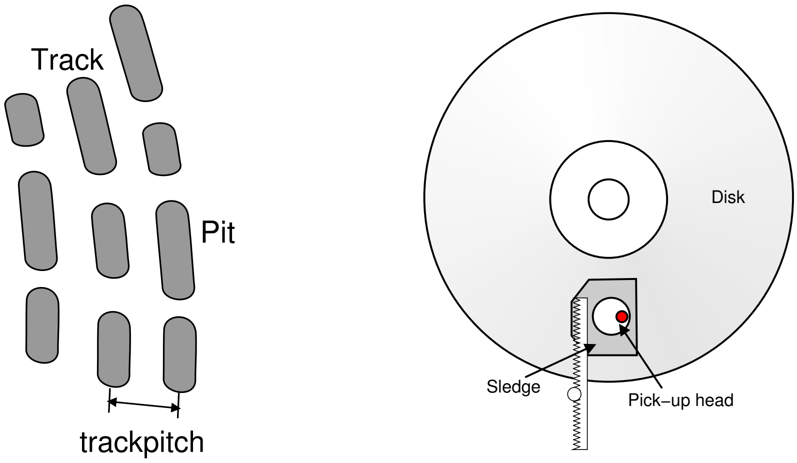

Figure 5.1 Pits forming tracks on DVD surface (left). Larger radial movements are taken care of by the sledge (right).

The surface velocity is constant (about 3.5 m/s), meaning that the disc should rotate at different speeds depending on the current reading position.

5.1 The DVD player

A typical DVD player has a pick-up-head consisting of a laser, an astigmatic lens, and a light detector with four fields. See Figure 5.1.

The lens is mounted on springs in the axial (focus) and radial direction, and can be moved by electromagnets. This way, the laser spot can be moved very fast in a small range (a few hundred tracks sideways). The lens and laser are mounted on the *sledge*, which can move over the whole disk (in radial direction), but with much less precision and speed. As the disk rotates, the track moves both radially and axially because of asymmetries, so feedback control is needed for both the radial and the axial position of the lens.

Light is emitted by the laser, focused through the lens onto the disk surface. The disk surface is reflective, so that laser light is reflected back. Data bits are

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[1] This text is based on an original manuscript by Bo Lincoln

represented by pits of different lengths in *tracks* on the disk. The “image” of the surface is reflected back through the lens and read by a set of four photo detectors. These pits make the laser beam interfere destructively with itself, and therefore the pits look black to the detector.

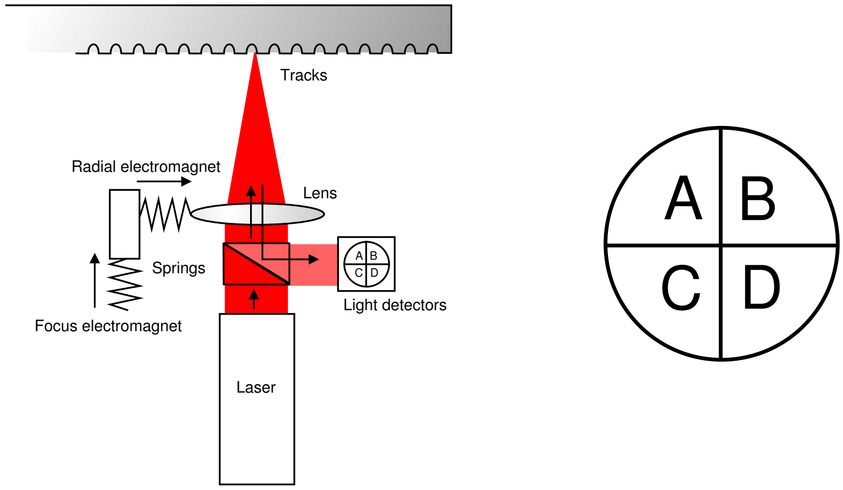

Figure 5.2 The pick-up-head has two electromagnets for fast positioning of the lens (left). The four photo detectors $A - D$ (right).

The photo detectors

The photo detectors sense the reflected laser light from the disk. It can be thought of as a very simple camera with only four pixels (see Figure 5.2). This information is enough to sense position radially (are we to the left or right of the track?), axially (thanks to the astigmatic lens) as well as the current bit. *There are no other sensors in the pick-up head to help keep the laser in the track.*

Focus error

The pick-up lens is astigmatic diagonally, so bad focus results in brighter light in either detectors $A + D$ (too high) or $B + C$ (too low). Therefore, the focus error (FE) can be calculated as

$$FE = A + D - (B + C)$$

which gives a surprisingly good result. Sweeping the focus lens from low to high usually results in an FE as in Figure 5.3. There is a linear range in the center where the FE signal is useful to control the lens around the correct focus. The slope of the curve depends on the reflectivity of the disc.

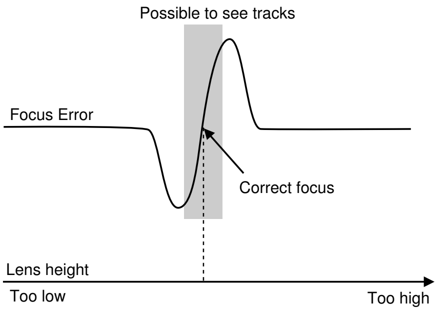

Figure 5.3 Sweeping the lens axially from low to high results in a curve like this.

Radial error

The radial error (RE), meaning sideways deviation from the track center, can be measured in two ways using the photo detectors. The simple way is to let

$$RE = A + C - (B + D),$$

i.e., use the difference in light from the left and right pair of detectors. For example, if the reflected light is brighter to the left, the radial error is positive, and we should move right. This measurement method is called radial push-pull (PP). See Figure 5.4.

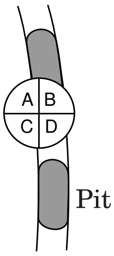

Figure 5.4 Push-pull: Calculating radial error as $RE = A + C - (B + D)$..

There is a second measurement method (DPD), which usually gives better result, but requires the disk to have pits. This is not true for a non-written DVD-R (writable), for example. The signals $f_1 = A + D$ and $f_2 = B + C$ are created, and phase compared (see Figure 5.5). For example, if f_1 comes before f_2 the lens is too far to the right. The time difference forms the error signal RE.

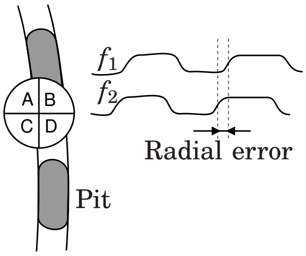

Figure 5.5 DPD: Radial error from phase difference between f_1 and f_2.

According to the DVD specification, DPD should be used whenever possible. Sweeping the lens radially over the disk creates an RE as in Figure 5.6 for PP and DPD.

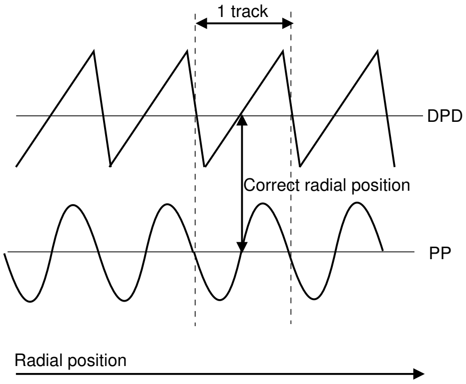

Figure 5.6 DPD- and PP-signals as the disk rotates and the lens is swept over the tracks radially. As can be seen, DPD is linear in a larger range.

5.2 Dynamics

The DVD player system can be viewed as a two-input, two-output dynamical system. The main dynamics are due to the springs and masses in the lens system. The inputs are voltages to the electromagnets moving the lens, and the outputs are voltages corresponding to FE and RE. See Figure 5.7.

Figure 5.7 The pick-up head and disk seen as a two-input, two-output dynamical system.

The department has a "raw" DVD player without any controller. Using system identification techniques, the transfer function $P_f(s)$ from u_{focus} to FE and the transfer function $P_r(s)$ from u_{radial} to RE have been estimated. The cross-coupling between inputs and outputs have been ignored for simplicity. The resulting Bode diagrams can be seen in Figure 5.8.

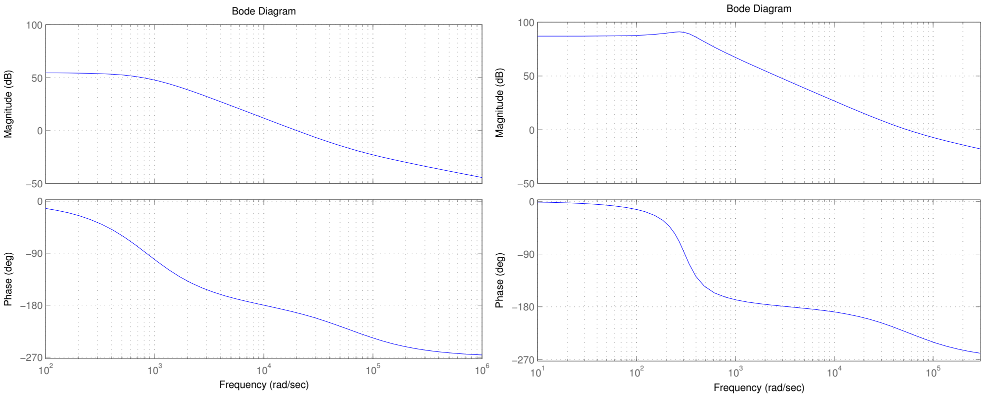

Figure 5.8 **Left:** Transfer function estimate for the focus servo. The model is of second order. **Right:** Transfer function estimate for the radial servo.

5.3 Specifications and control structure

The control structure is simple: the focus and radial parts are separated (see Figure 5.9). The task of the focus controller C_f is to keep the disk sufficiently in focus for the system to see the tracks, and the task of the radial controller C_r is to keep the laser spot in the track.

In the DVD specification, bounds on the open-loop transfer functions for both the focus and radial loops are given. The open-loop transfer function is (as you know) the product of all elements in the control loop: $L_r = C_r P_r$, $L_f = C_f P_f$. The control specifications in the DVD standard are as follows:

$$\begin{aligned} |C(i\omega)P(i\omega)| &\geq 1000 && \text{for } \omega \leq 23.1 \text{ Hz} \\ |C(i\omega)P(i\omega)| &\leq 1 && \text{for } \omega > 2 \text{ kHz} \end{aligned}$$

The first specification is chosen to remove enough of the disk oscillation disturbances to stay in track. The second specification is chosen to reduce the effects of measurement noise and small disturbances (dirt and scratches).

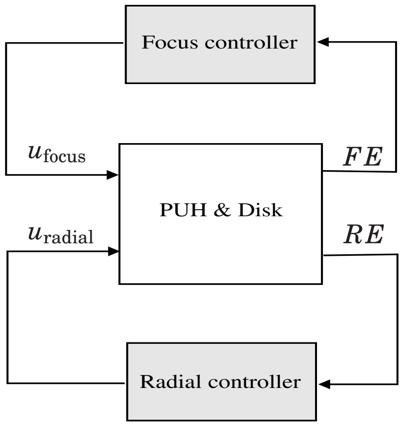

Figure 5.9 The control structure.

Meeting these specifications is not a trivial task. In fact, most DVD readers probably don't! Instead, the manufacturers modify the specifications according to the circumstances. For example, a CD player for a car would need very good disturbance rejection (high gain at low frequencies) and this is obtained at the expense of high gain also at high frequncies, which gives less robustness to disc scratches.

The goal of this lecture is to design the focus controller according to the specifications and try it on the experimental setup.

5.4 Design of the Focus Controller

The specifications require that the magnitude of the loop transfer function decreases by a factor 1000 in the frequency interval between 23.1 Hz and 2.0 kHz. Without compensation, the magnitude decreases only by a factor 200. See left plot in Figure 5.10. A proportional controller with gain 0.4 satisfies the amplitude specification at 2.0 kHz (right plot). However, the phase at 2.0 kHz is $-184°$, so the gain has to be even smaller in order to keep the closed loop stable. Hence, a dynamic compensator is needed.

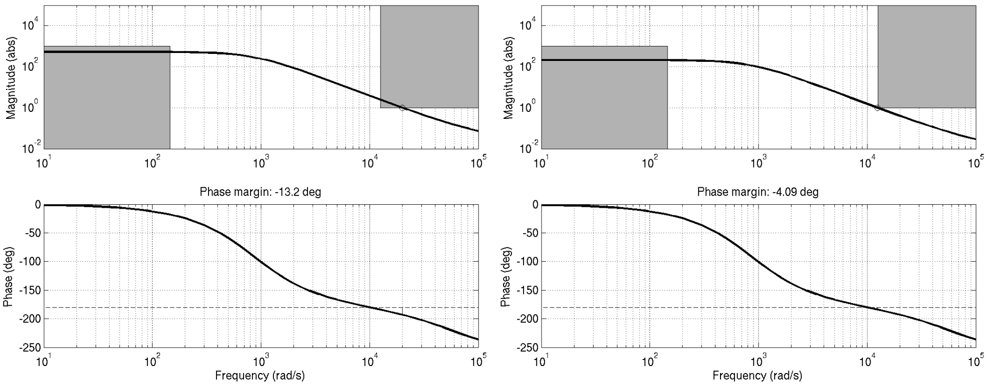

Figure 5.10 Uncompensated system (left) and with proportional gain 0.4 (right).

It is natural to introduce lag compensation to increase the gain at low frequencies. However, the break points need to be at frequencies well below 2 kHz in order to avoid additional phase lag at the cut-off frequency. Using a lag filter $C_1(s) = 0.4\frac{s+600}{s}$ gives the modified plots in Figure 5.11 (left).

However, the closed loop system is still unstable, so further compensation is needed. Hence, we add a lead filter to increase the phase near 2 kHz; $C_2(s) = \frac{1+s/5000}{1+s/50000}C_1(s)$ (right plot).

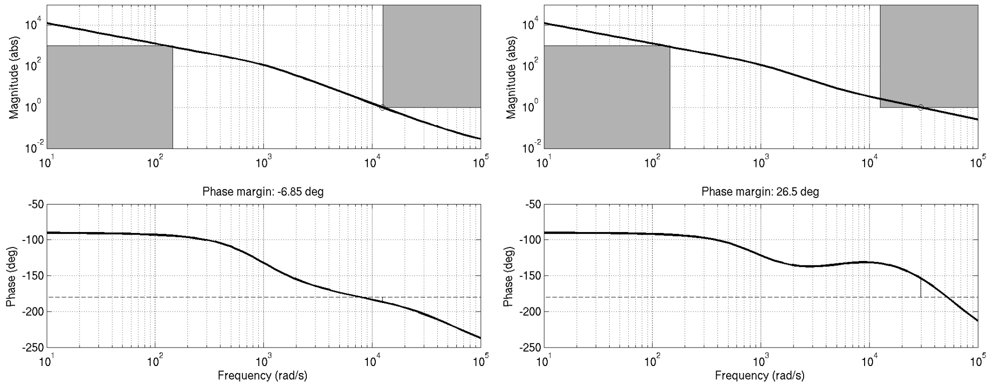

Figure 5.11 A lag filter has been used to increase the gain at low frequencies (left). A lead filter improves stability by increasing the phase near 2 kHz

The gain needs to be adjusted to keep the cross-over frequency unchanged. See Figure 5.12 (left). Now the closed loop system is stable with good margins, but the gain at 23.1 Hz is still too low, just 100 instead of 1000. This can be corrected by modifying the break point of the lag filter to get the final controller $C(s) = 0.15\frac{s+1600}{s}\frac{1+s/5000}{1+s/50000}$. See Figure 5.12 (right).

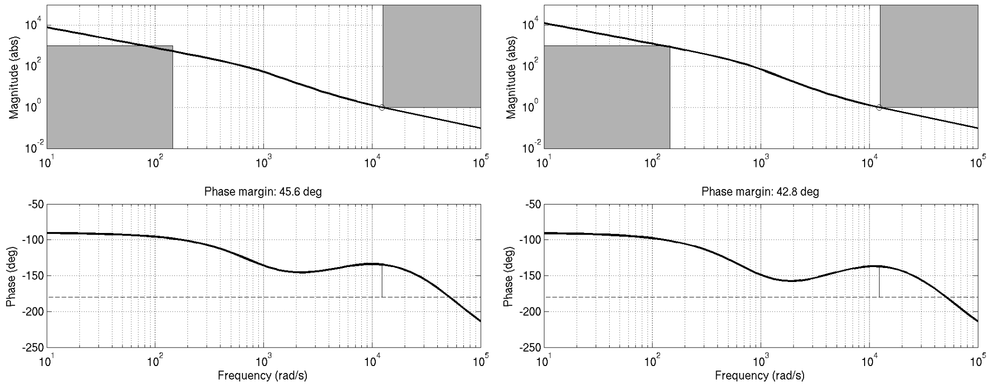

Figure 5.12 Lead-lag compensation with correct gain at high frequences is shown left. After modifying the lag-filter, the final controller gives the plot to the right.

The controller is verified by experiments done in the lecture. Notice that the final design is very similar to a PID controller of the form $C(s) = K\left(\frac{1}{sT_i} + \frac{sT_d}{1+sT_d/N}\right)$.