

# Linear Quadratic Controller with Fault Detection in Compact Disk Players

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## Abstract—

The design of the positioning controllers in Optical Disk Drives are today subjected to a trade off between an acceptable suppression of external disturbances and an acceptable immunity against surfaces defects. In this paper an algorithm is suggested to detect defects of the disk surface combined with an observer and a Linear Quadratic Regulator. As a result, the mentioned trade off is minimized and the playability of the tested compact disk player is considerably enhanced.

## I. INTRODUCTION

At the beginning of the 80's the Compact Disk (CD) was introduced to the market, thereby the era of Optical Disk Drives (ODD) started, which are characterized among other things, by the absence of the physical contact between the pick-up and the disk. Feedback control is therefore necessary to control the position of the lens to be able to read the data from the disk. Two main control loops can be identified: the focus loop which maintains the focus point of the laser on the signal layer, and the radial loop which follows the track.

Due to the different applications where ODDs can be applied in, several challenges emerge. Disturbances can be roughly classified in two groups: external disturbances, like shocks, vibrations, acoustic feedback from speakers and surface defects, like scratches, finger marks and dust. The first group requires a higher closed loop bandwidth than the second group. If the closed loop has a high bandwidth the controller may have a good performance against external disturbances but it might follow the defects of the disk surface, like scratches instead of the track in the signal layer. This imposes conflictive requirements to the closed loop bandwidth of the system. Vigorous work has been concentrated in the first group of disturbances, designing and implementing a disturbance observer, [1], [2], designing a high bandwidth servo with instrumented suspension [3], studying the effects of sound pressure of speakers in CD players [4]. Moderate work can be found in the second group. In [5] a surface evaluation of the compact disk is made. People at their homes may have experienced that the CD player keeps playing a short part of a track repeatedly or that it jumps randomly to another track. In worst case it may even stop playing the CD to a great surprise and irritation of the listener.

This paper suggests a method to detect defects of the disk surface, without additional sensors, combined with an observer. The trade off in the design of the positioning controllers of the pick-up between acceptable suppression of external disturbances and acceptable immunity against defects on the disk is minimized and a Linear Quadratic Regulator is implemented

showing that the playability of the compact disk player is enhanced.

This paper is organized as follows. In section 2, a second order model of the focus and radial loop is presented. The fault detection algorithm is briefly described in section 3. Afterwards the control strategy is described in section 4. In section 5 and 6 an observer and a Linear Quadratic Regulator are designed. Finally the results are presented and discussed in section 7 and 8.

## II. MODEL OF THE FOCUS AND RADIAL LOOP

The optical pick-up is a 2-axis device, enabling a movement of the lens in two axes: vertically for focus correction and horizontally for track following. Two coils which are orthogonal to each other are suspended between permanent magnets. A current through a coil creates a magnetic field which repels with the magnetic field from the permanent magnet. Therefore the coil and consequently the lens will move in the corresponding direction. The relation between the voltage  $u(s)$  applied to the coil and the position of the focus point with respect to the signal layer  $y(s)$  can be described by a second order transfer function [2], as shown in equation 1.

$$\begin{aligned} \begin{bmatrix} \dot{x} \\ \dot{\hat{x}} \end{bmatrix} &= \begin{bmatrix} 0 & 1 \\ -\frac{K}{m} & \frac{-CR-(Bl)^2}{Rm} \end{bmatrix} \begin{bmatrix} x \\ \hat{x} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{Bl}{Rm} \end{bmatrix} u \\ y &= [1 \quad 0] \begin{bmatrix} x \\ \hat{x} \end{bmatrix} \end{aligned} \quad (1)$$

where  $m$  [Kg] is the mass of the moving parts of the actuator,  $R$  [ $\Omega$ ] is the impedance of the voice coil motor,  $C$  [Ns/m] is the viscosity coefficient,  $K$  is the spring modulus [N/m],  $B$  is the magnetic flux density [Wb/m<sup>2</sup>] and  $l$  [m] is the effective coil length.

The absolute distance between the focus point and the signal layer cannot be measured directly. Instead a laser beam is focused on the signal layer and the intensity of the reflected laser is measured by the generated current of two photo-diodes  $D_1$  and  $D_2$ . The difference  $D_1 - D_2$ , is directly proportional to the distance between the focus point and the signal layer in the linear area, see figure 1.

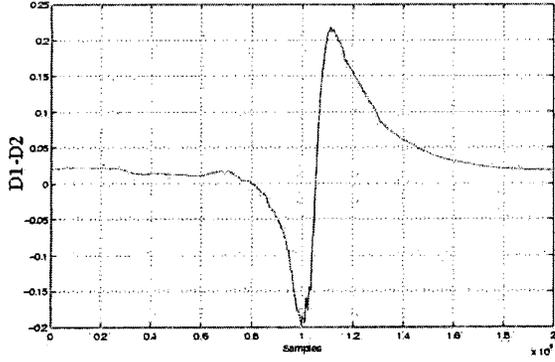


Fig. 1. Measurement of the characteristic of the focus diodes ( $D_1 - D_2$ ).

The disadvantage of considering only the difference,  $D_1 - D_2$ , between the two photo-diode signals is the impossibility of being able to distinguish between the different disturbances like e.g. mechanical vibrations and scratches.

### III. FAULT DETECTION

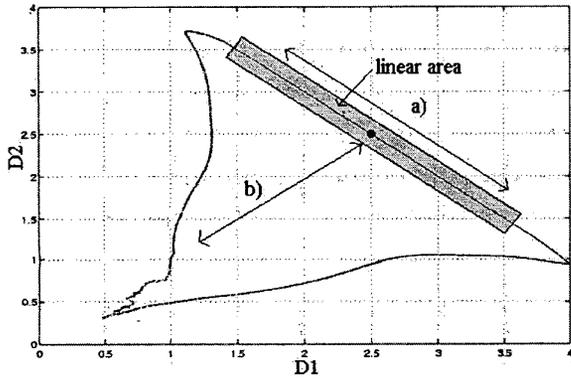


Fig. 2. Measurement of the characteristic of the focus diodes ( $D_1$  versus  $D_2$ ).

By plotting  $D_1$  versus  $D_2$ , see fig. 2, more information can be retrieved. As the information of the defects of the disk surface is present in both focus and radial signals, only the focus signals are used in the detection algorithm. The black spot in the linear area represents the reference position of the focus point. Mechanical vibrations move the optical pick-up from the actual position and results in a real error, oscillating at the reference position. As long as the vibrations are moderate, the oscillations of the signals will remain in the linear area (grey rectangle) shown as case a). The controller must react in a suitable way to suppress the effect of these vibrations. On the other hand the controller must be passive against scratches as they change the reflection properties of the disk resulting in a false error, shown as case b). That is, the further the measurement is from the linear area, the smaller it should be weighted. A detailed description and measurements verifying that defects of the disk surface can be detected by means of  $D_1$  versus  $D_2$  are not shown here as

they are beyond of the scope of this paper. Equation 2 shows how the measurements can be weighted by a factor  $w$ .

$$w = \begin{cases} 1 & \text{for } b < b_{min} \\ \left( \frac{b_{max} - b}{b_{max} - b_{min}} \right)^\alpha & \text{for } b_{min} < b < b_{max} \\ 0 & \text{for } b > b_{max} \end{cases} \quad (2)$$

$b$  is the distance between the actual measurement and the linear area. Mechanical vibrations are fully weighted,  $w = 1$  as they result in a real error which is registered in the linear area where  $b \approx 0$ .  $b_{min}$  is a security margin constant which depends on the measurement noise level. In the case of a scratch, the measurements will move towards origo and are weighted with an exponential function where the exponent  $\alpha$  is chosen empirically.  $\alpha = 4$  for the focus loop and  $\alpha = 2$  for the radial loop.  $b_{max}$  is the limit where the measurements are not weighted at all as the actual defect of the disk surface is too severe to retrieve a valid measurement.  $b_{max}$  is also determined empirically.

### IV. CONTROL STRATEGY

The fault detection can be combined advantageously with an observer and a LQR as shown in fig. 3

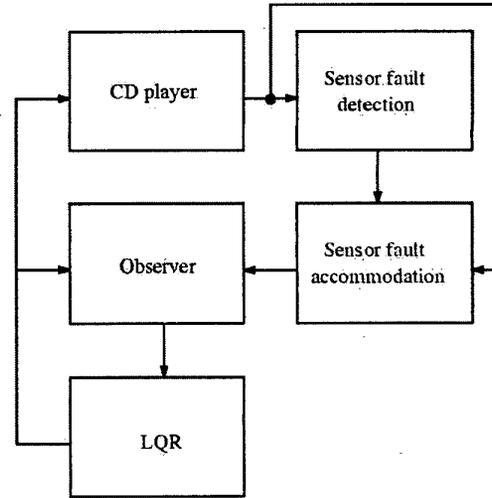


Fig. 3. Control scheme.

The focus and radial loop of the optical pick-up in the *CD player* are controlled by two *LQRs*. In the case the disk has some defects on the surface, the *sensor fault detection* detects the defects, the *sensor fault accommodation* weights the measurements accordingly and the *observer* estimates the position of the optical pick-up. In this way the scratches are filtered out and the controllers will only react against real errors, e.g. mechanical disturbances.

## V. OBSERVER

The major roll of the observer in the suggested control strategy is to estimate the position of the optical pick-up, see equation 3, when it passes e.g. a scratch and no valid measurements can be retrieved.

$$\hat{\mathbf{x}}(k+1) = \Phi \hat{\mathbf{x}}(k) + \Gamma \mathbf{u}(k) + \mathbf{K}w[\mathbf{z}(k) - \mathbf{H}\hat{\mathbf{x}}(k)] \quad (3)$$

The estimation of the position is based on the current estimated state of the plant  $\Phi \hat{\mathbf{x}}(k) + \Gamma \mathbf{u}(k)$  plus a feedback of the difference between the measured output  $\mathbf{z}(k)$  of the plant and the estimated output  $\mathbf{H}\hat{\mathbf{x}}(k)$  multiplied by a fixed feedback gain,  $\mathbf{K}$  and by the time varying weight  $w$  already explained in section III.

Figure 4 shows the observer configuration.

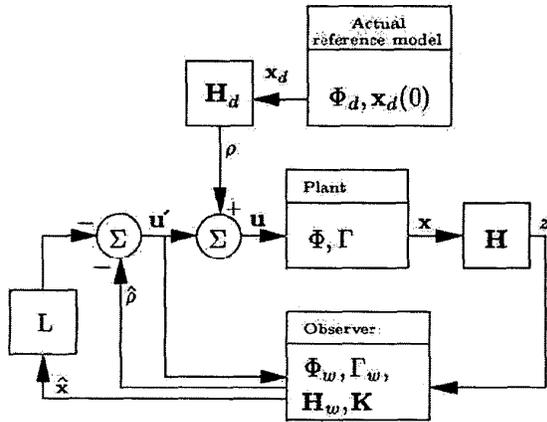


Fig. 4. Observer configuration

It can be seen that the control law is given by,

$$\mathbf{u}' = -\mathbf{L}\hat{\mathbf{x}} - \hat{\rho} \quad (4)$$

and as long as the estimation of the reference model matches the actual reference model,  $\hat{\rho} = \rho$ , the control law is given by  $\mathbf{u} = -\mathbf{L}\hat{\mathbf{x}}$ . It is of crucial importance to include the reference model in the observer as the disks are typically slanted and eccentric, disturbing respectively the focus and radial loop. The disturbance is mainly composed by a sinus which oscillates at the rotation frequency of the disk. When the optical pick-up passes a scratch and no valid information can be retrieved, the positioning controllers must take this disturbance into account in order to follow the track in question.

## VI. LQR DESIGN

The designed LQR is an optimal full state controller, which calculates the best possible control signal to bring the system from an initial state to steady state.  $\mathbf{u}(k)$  is picked up so the cost function shown in equation 5 is minimized,

$$\mathcal{I} = \sum_{k=0}^{N-1} (\mathbf{x}^T(k) \mathbf{Q}_1 \mathbf{x}(k) + \mathbf{u}^T(k) \mathbf{Q}_2 \mathbf{u}(k)) + \mathbf{x}^T(N) \mathbf{Q}_N \mathbf{x}(N) \quad (5)$$

where  $\mathbf{x}(k)$  are the states of the plant and  $\mathbf{u}(k)$  the control signal. Determining the best possible control signal is a trade off between system performance and the effort of the input signal.  $\mathbf{Q}_1$  and  $\mathbf{Q}_2$  are the weights which have influence in the mentioned trade off.  $\mathbf{Q}_N$  punishes large values of the last state.

The cost function is extended as shown in equation 6 in order to introduce an integral effect.

$$\mathcal{I} = \sum_{k=0}^{N-1} (\mathbf{e}^T(k) \mathbf{Q}_{1e} \mathbf{e}(k) + \mathbf{x}_i^T(k) \mathbf{Q}_{1i} \mathbf{x}_i(k) + \mathbf{u}^T(k) \mathbf{Q}_2 \mathbf{u}(k)) + \mathbf{e}^T(N) \mathbf{Q}_{Ne} \mathbf{e}(N) + \mathbf{x}_i^T(N) \mathbf{Q}_{Ni} \mathbf{x}_i(N) \quad (6)$$

The weight matrices are chosen by trial and error. There are though two restrictions:  $\mathbf{Q}_2 \neq 0$ , otherwise the solution will include large components in the control gains, and the  $\mathbf{Q}'$ s must also be nonnegative definite, which is most easily accomplished by picking the  $\mathbf{Q}'$ s to be diagonal with all diagonal elements positive or zero.

Once the weights are determined, software with control packages can be used, e.g. Matlab where the optimal gain matrix  $\mathbf{L}$  can be calculated such that the state feedback law minimizes the cost function.

## VII. RESULTS

The designed focus and radial controllers together with the observer and fault detection algorithm were implemented on a 300 MHz Pentium II with an I/O card which has 12-bit A/D and D/A converters. Direct Access Memory (DMA) was used to avoid CPU overload. The sampling frequency was 35 [kHz]. Due to high computational constraints, the controllers were implemented separately, letting the on-board PID controller of the CD-player control the other control loop.

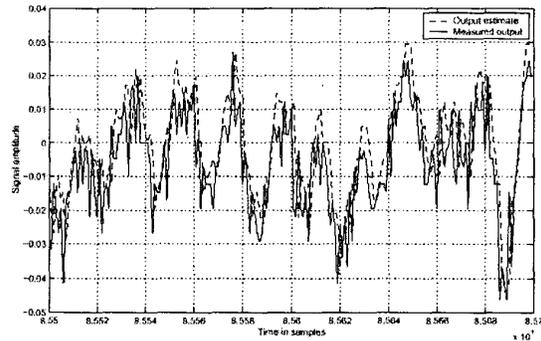


Fig. 5. Estimated (dashed line) and measured (solid line) radial error.

Figure 5 shows the estimated (dashed line) and measured (solid line) radial error. It can be seen that the observer performs

satisfactorily as there is no appreciable difference between the two signals. Equivalent results were obtained for the focus loop. The bandwidth of the designed observers were,

$$\begin{aligned} Obs_{focus} &= 2707 [Hz] \\ Obs_{radial} &= 5052 [Hz] \end{aligned}$$

which are considerably higher than the bandwidth of the controllers:

$$\begin{aligned} LQR_{focus} &= 456 [Hz] \\ LQR_{radial} &= 336 [Hz] \end{aligned}$$

By increasing the bandwidth of the controllers further, better performance against external disturbances may be achieved.

In order to demonstrate that the fault detection algorithm only reacts against surface defects an experiment was performed where a disk with a scratch was placed in the compact disk player. The lower graph in figure 6 shows the value of the weight factor  $w$  when the compact disk player is playing in normal conditions. The scratch is detected periodically and no false alarms are registered. The upper graph shows the value of  $w$  when the compact disk player is subjected to mechanical vibrations. The fault detection algorithm is able to detect the scratches and reacts minimally against the mechanical vibrations. Therefore it can be concluded that the fault detection algorithm behaves as intended.

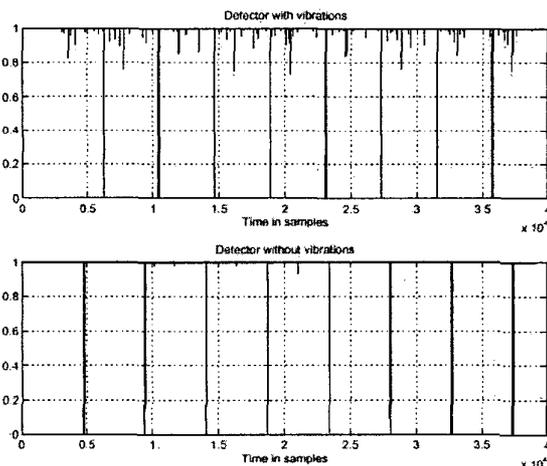


Fig. 6. Detection of defects of the disk surface with mechanical vibrations (upper graph) and without vibrations (lower graph).

Several experiments were performed in order to evaluate the reliability of the fault detection algorithm combined with the observer and the LQR. In the first experiment, two slight scratches of approx.  $0.25[\text{mm}]$  width and one deep scratch of approx.  $0.5[\text{mm}]$  width were made on the disk surface. The upper graph in figure 7 shows the control signal of the radial controller and the lower graph shows the normalized radial error.

It can be observed that the LQR is able to cope with the slight scratches but over reacts when the optical pick-up passes the

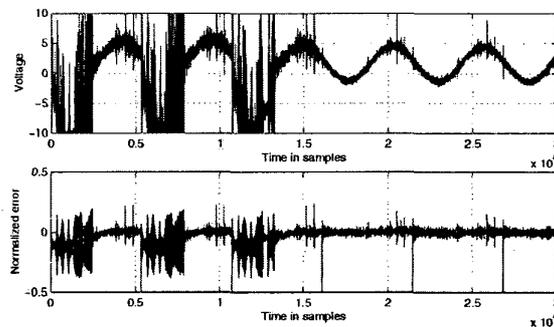


Fig. 7. Radial loop disturbed by three scratches. Control voltage (upper graph) and normalized radial error (lower graph).

deep scratch which results in jumps backwards and forwards over the tracks. At sample  $1.5 \cdot 10^4$  the fault detection algorithm is activated and the LQR can now cope with such a surface defects without jumping over the tracks. There are some spikes in the control signal after activating the fault detection algorithm as surface defects cannot be detected immediately.

The suggested control strategy has also been tested in the radial and focus loop with other surface defects. The performance results are summarized in table 1.

	scratch	pen marker	finger mark
radial loop	↑↑	↑↑	↑
focus loop	↔	↑↑	↑

TABLE 1

↑↑=IMPROVED, ↑=SLIGHTLY IMPROVED, ↔=UNCHANGED.

Due to the fact that the fault detection algorithm cannot be implemented in both control loops at the same time (computational constraints), the focus loop performance did not show an improved performance in the test as the radial loop was also disturbed by the same scratch. It is believed that better results may be achieved by implementing the suggested control strategy in both controllers at the same time.

## VIII. CONCLUSION

The trade off in the design of the positioning controllers of the pick-up in CD players between acceptable suppression of external disturbances and acceptable immunity against defects on the disk is minimized with the suggested fault detection algorithm. The detection algorithm combined with an observer and a Linear Quadratic Regulator have shown to enhance the playability of the compact disk player. Similar results may be achieved in other ODDs like DVDs and DVD-ROMs.

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