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DISC CHARACTERIZATION OF
OPTICAL STORAGE SYSTEMS

Trainingship report DCT 2001.17

Jan van Helvoirt
DISC CHARACTERIZATION OF OPTICAL STORAGE SYSTEMS

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Eindhoven University of Technology
Faculty of Mechanical Engineering
Section Dynamics and Control Technology

April 2001
At the end of last year I was searching for a research subject I could work on during my second trainingship. My goal was to perform this trainingship outside the University so I could combine the research with working in an industrial environment. My professor, Maarten Steinbuch, offered me some interesting assignments at various foreign institutes and companies. One of them was an assignment at Philips Optical Storage in Singapore. The country of Singapore, the well-known company Philips and the outline of the assignment were the most important factors for me to choose for this particular assignment. At Philips Optical Storage Singapore they asked for a student who could do research to some aspects of the optical storage systems they are developing. In order to be fully prepared for this task it was decided that the subject of my first trainingship at the Eindhoven University of Technology would be in the same line as the assignment in Singapore.

While the first contacts with the people in Singapore were laid, I started working on the first assignment begin January of this year. After familiarizing myself with the optical disc drive in the laboratory I started to work on the actual research goal, obtaining knowledge and models for one of the important disturbances for the system, the so-called track signal. This report is a detailed description of the work I have done and the results that are obtained during the research.

Right here I want to thank Maarten Steinbuch for giving me this challenging opportunity and for all the guidance and suggestions he gave me during the work. Also I want to thank Pieter Nuij whose practical knowledge of signal analysis in general and performing measurements on an optical disc drive in particular were of great help to me. In addition I want to thank my colleagues Jaap Janssens and Maik van de Molengraft, both students who also worked on the optical disc drive in the laboratory. The discussions we had together about the problems we encountered during our work were not only very valuable but also pleasant and amusing. Further I like to thank Jeroen Raaymakers, George Leenknegt and Pepijn Wortelboer from Philips Eindhoven. The discussion we had at Philips was very valuable and the critical questions and suggestions certainly improved my knowledge of optical disc drives and gave some clear directions for the further research in Singapore. Finally I also like to thank Henrik Ladegaard, Bobby Singh and Paul Wong from Philips Singapore for giving me the chance to work with them. The good communications and the smooth preparations for my journey were an extra stimulant in finishing this work and getting fully prepared for the assignment in Singapore.
CONTENTS

PREFACE iii

1 INTRODUCTION 1

2 OPTICAL DISC DRIVES 2
   2.1 General principle 2
   2.2 Basic drive elements 2
   2.3 Servo mechanism 3

3 SYSTEM MODELLING 5
   3.1 Motion systems 5
   3.2 Equipment and procedure 7
   3.3 Experiments 8
   3.4 Actuator model 11

4 TRACK RECONSTRUCTION 12
   4.1 Track disturbances 12
   4.2 Reconstruction procedure 14
   4.3 Implementation 14

5 DISC CHARACTERIZATION 17
   5.1 Statistic signal properties 17
   5.2 Time domain analysis 18
   5.3 Frequency domain analysis 23
   5.4 Quantitative characterization 26

6 CONCLUSIONS AND RECOMMENDATIONS 27

REFERENCES 28

A ESTIMATING TRANSFER FUNCTIONS 29

B DETERMINATION OF C(s) 32

C MATLAB® ROUTINES FOR TRACK RECONSTRUCTION 34

D TRACK RECONSTRUCTION TEST DISCS 38
INTRODUCTION

The term optical storage system refers to different kind of devices, which all decode and reproduce digital data that is stored on a reflective plastic disc. Philips first announced the discovery of the technique to store data on an optical disc in 1972. Within ten years the Compact Disc Digital Audio system proposed by Philips and Sony was accepted as a standard. In the following two decades this system has become a mass consumer product and nowadays still other CD-based applications are developed. Examples are CD-ROM, Video CD and DVD (Digital Versatile Disc). The main advantage of these systems is the relatively high storage capacity of the optical discs and the fact that the stored information remains unchanged under playback, temperature variations and dust.

The new applications that are developed or are still under development are much more demanding and the fact that mass consumer products must be produced at minimal costs ask for new and intelligent solutions to guarantee the required performance. At present the design of optical disc drives is based on the disc specifications laid out in the various standards. It is found that these specifications in practice are very conservative and adjusting them could lead to serious improvements in the controller design and hence the performance of the whole optical storage system.

From the above it follows that an accurate characterization of the class of disturbances affecting the optical storage system can lead to a sensible reduction of the design specifications. One important ‘disturbance’ is the track signal. The presence of this signal is a result of the absence of a mechanical connection between the information carrier and the decoding device. Due to various tolerances and inaccuracies this track signal deviates from an ideal shape. In this report an attempt is made to get an accurate model for this track signal and finding some important characteristics of it. By increasing the knowledge of this important disturbance source hopefully better controllers can be designed leading to even more powerful applications of the optical storage principle.

In Chapter 2 first an introduction of the optical disc drive is given. The general principle of operation, the basic system elements and the control problem are discussed. This will form a basis for the experimental system modelling, which is the subject of Chapter 3. The model that will be derived is necessary for the analysis of the track signal later on. Besides the experimental set-up and accuracy considerations some other general information about the system is given that help to derive a usable model and interpret the experimental results. Since the signal of interest, the track disturbance is not measurable directly a method must be developed to obtain the wanted information from other measurements. How this is done will be discussed in Chapter 4. The suggested method is used to reconstruct the track signal for various test discs. The results of these experiments are covered in Chapter 5. Next to the identification of some general disc characteristics some other remarkable phenomena are discussed and explanations are given where possible. Finally some conclusions from this research are drawn and recommendations for further investigations and improvements are given.
OPTICAL DISC DRIVES

Nowadays a wide variety of optical disc drives exists. These drives differ in their construction and specifications depending on the type of application for which they are used. Despite this diversity all drives are based on the same principle. This principle will be discussed briefly in Section 2.2. Furthermore they all consist of several basic elements that can be found in any optical disc drive. These elements and their function within the whole system are the subject of Section 2.3.

2.1 General principle

In an optical data storage system the optical disc (CD, CD-ROM, DVD-ROM e.g.) serves as the information carrier. The information layer of the disc consists of a spiral of small pits that represent the data in a binary form. In order to convert this pattern of pits into an electrical signal the reflection of a laser beam is measured. This reflection will change when a pit on the disc passes the beam. The resulting signal has to be processed in a certain way to obtain the data on the disc in a usable form.

The optical disc rotates in order to let the sequence of pits pass the laser beam. Because this sequence forms a spiral on the disc, the so-called information track, a mechanism is needed to move the laser beam from the inner to the outer radius of the disc to follow this track.

2.2 Basic drive elements

In Fig. 2.1 a schematic view of a relatively old optical disc drive is shown. Nowadays drives use linear two-stage mechanisms with a long stroke sledge and a short stroke second actuator instead of the single stage radial arm mechanism shown in Fig. 2.1. The mechanism is composed of a turntable DC-motor for the rotation of the disc, and a balanced radial arm for the following of the track. An optical pick-up unit (OPU) is mounted to the end of this radial arm. In the OPU a diode generates a laser beam that passes through a series of optical lenses to give a spot on the information layer of the disc. An objective lens, suspended by a spring mechanism, can move in a vertical direction to give a focusing action. All these elements are part of the servo layer of the optical disc drive.

![Figure 2.1 Schematic view of a rotating arm CD mechanism.](image-url)
The signal of the OPU that contains the actual data from the disc is send to a decoder. This layer of the optical disc drive consists of electronics by which algorithms are implemented to process the signal from the OPU. The data is transformed to a usable form to play music or to work with in a computer.

The third layer consists of a microprocessor. This processor forms the interface between the drive and the user (control panel of an audio CD player or a computer). Also it implements several decision making algorithms in order to make sure that the drive functions properly or at least as best as possible. In this report the focus will be on the servo layer of the optical disc drive. The decoder and processor and their functions in the whole system will not be discussed further.

### 2.3 Servo mechanism

The early optical disc drives were designed to operate at a constant scanning velocity of the laser spot on the disc. Due to the changing radial position of the spot, the disc itself had to rotate at a variable speed. However new applications demand a significantly higher scanning velocity, which make it impossible to vary the rotational speed of the disc accurately enough. So in those cases the disc rotates at a constant speed, which eliminates the need for a motor speed control mechanism for the turntable DC-motor. The occurring variations in the rotational speed of the disc have to be considered as disturbances that mainly influence the quality of the data carrier signal.

The radial arm of the drive is used to move the OPU to the desired radial position on the disc. The allowable radial position error is about 0.1 \( \mu \text{m} \). In order to achieve this accuracy a controller mechanism is needed.

The OPU consists of several elements. The diode that generates the laser beam and the various optical lenses can be found in every OPU. The mechanism that makes the focusing action of the objective lens possible is needed in order to read the data from the disc under the influence of disturbances. There exist various actuator designs that can take care of the focusing of the laser spot. The OPU also contains several photo-diodes that receive the reflected laser beam. The resulting signal is not only used as a data carrier but because an array of photo-diodes is used, it is also possible to obtain radial and vertical track position data from it. This information can be used to actively control the radial position and the focus of the laser spot.

![Block diagram of the optical disc drive servomechanism.](image-url)
Servo control problem

From the above it becomes clear that a control system is necessary to maintain the desired radial and vertical position of the laser spot, relative to the track of the disc in the presence of various disturbances and uncertainties. In Fig 2.2 a block diagram of the servo control system is shown. The transfer function $C(s)$ represents the controller and generates the control current $u$, which is fed to the actuator of the system. The transfer function from control currents to (absolute) spot position is indicated by $H(s)$. Mechanical shocks and vibrations are present in the input channel. The actual track position is shown as output disturbance in Fig. 2.2. This track deviates from the perfect spiral shape due to production tolerances and drive imperfections and other external factors. Hence the track is considered to be a disturbance. The relative spot position is detected by the OPU and it generates the error signal $e$, which is polluted with measurement noise and fed into the controller. The reference signal $r$ is equal to zero in this scheme [12].

The goal of the controller can be formulated as achieving good tracking under the influences of disturbances and given uncertainties arising from modelling errors and variations from manufacturing. From the diagram in Fig. 2.2 it becomes clear that the real track position, which is shown as an output disturbance, influences the controller design and the resulting performance of the controlled system. In the following chapters the properties of the disturbance signal will be investigated, where we only focus on the radial servo loop.
3 SYSTEM MODELLING

The first step in the investigation of the track disturbances in the radial loop as defined in Chapter 2 is obtaining a model for this loop. When this model becomes available, it will be possible to investigate the properties of the system in general and of the disturbance signal and its influence on the system in particular. In Section 3.1 some general modelling considerations for optical disc drives are discussed. The experimental set-up that is used during the research is the subject of Section 3.2. After an introduction of the used equipment the followed procedure to obtain an accurate model of the system will be discussed. Also some remarks are made about this procedure in comparison with other possible methods to obtain the desired model. To obtain a valid and accurate model the measurements must be done with great care. Various settings of the measuring equipment and the post processing can influence the results. Hence they must be chosen carefully. The settings that are used during the experiments are outlined in Section 3.3. Furthermore the preliminary results and some practical issues that emerged during the experiments are discussed. Finally in Section 3.4 the resulting model of the drive’s radial servo loop is presented. The model is validated and several distinct model properties and their impact on the system behaviour are discussed.

3.1 Motion systems

The mechanism of the optical disc drive can be classified as a motion system. In general the task of a motion system is to move a mass along a prescribed trajectory in such a way that a certain process can take place. In the case of the optical disc drive the mass is formed by the radial arm and the OPU mounted on the end of it. The trajectory is set by the information track on the disc. This track must be followed in a way so that the OPU can read out the data that is stored on the disc. Other examples of motion systems are pick-and-place machines and welding robots.

In general most motion systems exhibit the same type of dynamic behaviour, which is mainly determined by the movement of the mass or masses. Mechanical connections with finite stiffness and damping between different masses lead to resonances and phenomena like friction also alter the dynamic behaviour. However a motion system can be approximately modelled as a single mass (i.e. a double integrator). This approximation can be of great help in the design of feed forward signals or when a dynamic model has to be deduced from experimental frequency response data.

As stated before a positioning control system is needed to position the OPU relative to the information on the disc with an exacting accuracy. Besides the external disturbances such as shocks, vibrations and track imperfections (see Fig. 2.2), the mechanics of the servo play an important role in the performance of the system. Before the actual model of the system is determined it is useful to investigate these mechanics to form some basic understanding of their effects on the servo system.
System modelling

Servo mechanics

In order to follow the information track with the laser beam despite of the disturbances mentioned earlier, a 'stiff' connection between the track and the OPU should exist. This connection is not a physical one but an electrical actuator generates it. Below a simple calculation of this so-called servo stiffness is given [3]. The maximum radial acceleration $a$, of the information track is calculated using an estimate for the amplitude of the radial error $A$ and the frequency of rotation $f$.

The needed mechanical stiffness of the connection is then given by division of the force, needed to generate the calculated acceleration with the required accuracy $x$.

$$c_m > \frac{F}{x} = \frac{m \cdot a}{x} \approx \frac{m \cdot A \cdot (2\pi f)^2}{x}$$

(3.1)

The driving force $F$ must be exerted on the OPU as a function of the position error $e$ through an actuator. The error signal is generated by the OPU as discussed before in Section 2.3. With the calculation of the required mechanical stiffness $c_m$ from (3.1) it is relatively simple to calculate the needed servo stiffness from the following formula:

$$c_s > \frac{F}{e}$$

(3.2)

By using the calculated stiffness an estimate for the required bandwidth of the servo system can be obtained from equation (3.3).

$$f_m > \frac{1}{2\pi} \sqrt{\frac{c_s}{m}}$$

(3.3)

With the estimated parameter values for the drive under investigation given in Table 3.1 the bandwidth of the system becomes:

$$c \approx \frac{0.01 \cdot 0.2 \cdot 10^{-3} \cdot (2 \cdot \pi \cdot 12)^2}{0.1 \cdot 10^{-6}} = 1.14 \cdot 10^5 \Rightarrow f_m \approx \frac{1}{2\pi} \sqrt{\frac{1.14 \cdot 10^5}{0.01}} = 540 \text{ Hz}$$

These calculations are based on a very simple mechanical system, but they can be used to quickly check experimental results. The actual mechanical system of an optical disc drive is more complex. Actuator flexibilities, resonances in the guiding system and drive foundation influence the dynamic behaviour and therefore the performance of the system. Also external shocks and vibrations play a role in the dynamic behaviour of the servo system and the drive itself.

Table 3.1  Estimated drive parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass OPU</td>
<td>$1.0 \cdot 10^{-2}$ [kg]</td>
</tr>
<tr>
<td>Disturbance amplitude</td>
<td>$2.0 \cdot 10^{-4}$ [m]</td>
</tr>
<tr>
<td>Rotational frequency</td>
<td>$1.2 \cdot 10^1$ [Hz]</td>
</tr>
</tbody>
</table>
3.2 Equipment and procedure

The platform that is used for this research is CDM9. It is a radial arm (single stage) mechanism, installed in a car loader. The electronic circuit board is specially designed to do measurements and implement computer designed controllers on the disc drive. Several connectors are present on the board to access the electronics. The drive has a constant frequency of rotation and the radial and focus control systems are analogue PID-controllers. A block diagram of the system is given in Fig. 3.1.

![Figure 3.1 Schematic view of the experimental set-up for the radial loop.](image1)

The measuring device is a four-channel SigLab™. This digital data-acquisition system is capable to perform a wide variety of time and frequency domain experiments. The SigLab™ user interface is integrated within the Matlab® environment, which simplifies the retrieving and post-processing of measurement data.

System identification

When the system under investigation is complex it is difficult to write down an accurate dynamic model for it. Even when this is possible still all the model parameters need to be identified, which can become very time-consuming and can lead to inaccurate models (see Appendix A). A better approach is to use frequency response data of the system and use a numerical routine to generate an estimated model for the system. The drawback of this method is that, especially when using high order models, the physical interpretation of the resulting model becomes difficult.

![Figure 3.2 Block diagram of the closed radial loop.](image2)
Since the actuator itself is not asymptotically stable the frequency response measurement must be done under closed loop conditions. Due to accuracy considerations that will be discussed later a sensitivity measurement is conducted instead of a direct measurement of the closed loop transfer function. The corresponding transfer function is given by (3.4), which is derived from Fig. 3.2.

\[ e_1 = \frac{1}{1 + C(s)H(s)} n_l + \frac{H(s)}{1 + C(s)H(s)} d_1 + \frac{1}{1 + C(s)H(s)} d_2 \quad (3.4) \]

The first part of the transfer function in (3.4) that links the input \( n_l \) to the output \( e_1 \) is called the sensitivity function \( S \) of the system [4]. When conducting measurements the input signal \( n_l \) has to be chosen larger than \( d_2 \) or the measurements must be averaged so that the influences of this disturbance on the measurements can be neglected. The open loop transfer function can be derived from the frequency response data \( (e_1/n_l) \) through (3.5).

\[ C(s)H(s) = S^{-1} - 1 \quad (3.5) \]

The transfer function of the controller \( C(s) \) can be measured very accurately when the loop is opened \((v_l/n_l \text{ in Fig. 3.1})\). The process \( H(s) \) can now be found by dividing (3.5) with \( C(s) \). The resulting frequency response data of the optical disc drive can now be fed into a numerical routine to obtain an estimated model for the system.

**Measurement accuracy**

From (3.4) it follows that the influence of \( d_2 \) on the output \( e_1 \) is the same as the influence of \( n_l \). This is the reason that \( n_l \) must be chosen larger than \( d_2 \). It is also clear that for low frequencies the influence of \( d_1 \) becomes relatively large. Therefore it is important that external shocks and vibrations are avoided during the measurements. Other disturbances contained in \( d_l \) such as for instance amplifier noise are assumed to be negligible.

Another method of determining the open loop frequency response is to measure the closed loop transfer from input \( n_l \) to output \( e_2 \). The open loop transfer function then can be found by rearrangement of the first term in (3.6).

\[ e_2 = \frac{C(s)H(s)}{1 + C(s)H(s)} n_l + \frac{H(s)}{1 + C(s)H(s)} d_1 + \frac{1}{1 + C(s)H(s)} d_2 \quad (3.6) \]

It follows from (3.6) that for high frequencies the output \( e_2 \) becomes small compared to the input \( n_l \). This also leads to a relatively large influence of \( d_2 \) compared to the influence of \( n_l \). So using this method makes it difficult to measure mechanical resonances that mainly occur at high frequencies above the bandwidth of the system.

For the method of measuring the open loop directly \((i.e. e_2/e_1)\) the same analysis can be done. It follows that for this case both for low and high frequencies inaccuracies occur due to the large influences of the disturbance signals \( d_1 \) and \( d_2 \) respectively.

**3.3 Experiments**

The measurements of the sensitivity function (3.4) are done with the SigLab™ Virtual Network Analyser. This broadband FFT based network analyser computes the transfer function over a band of frequencies simultaneously. In order to accomplish the broadband measurement, the excitation
to the system (signal $n_i$ in Fig. 3.2) must contain frequency components that cover the selected
frequency range [11].

The measurement bandwidth is set to 10 kHz because test measurements proved that the first
resonances of the system occur around 4 kHz. Phenomena above 10 kHz are attributed to noise and
the influences of the dynamics that do exist above this frequency are neglected. With the record
length set to the maximum of 8192 samples a spectral resolution of 3.125 Hz is obtained. The
number of averages is set to 256 and a Hanning window is used to prevent signal leakage [6].
For the first measurements band limited white noise with an output of 0.4 Volt rms is used as
estimation signal. With these settings the results at low frequencies are not satisfactory. To improve
the measurements so-called pink noise with an output of 0.4 Volt rms is used instead. Several
measurements are done with different discs to check if the results are reproducible. The results of
these measurements are shown in Fig. 3.3. In Appendix A some important aspects of the transfer
function measurements and some general experimental modelling consideration are given.

![Graph 1](image1.png)

**Figure 3.3** Sensitivity measurements with pink noise excitation.

Inspection of the amplitude of the measured sensitivity shows that the curve remains under the
0 dB line. From this result it can be concluded that the amplitude curve of the sensitivity amplitude
should lay higher than shown in Fig. 3.3 cause the sensitivity function always goes to one for high
frequencies [4]. This amplitude shift is caused by amplification of the excitation signal in the
electronic summation point where it enters the system. This gain is represented in Fig. 3.1 by the
block $K$. The sensitivity data can easily be corrected by multiplying the data with $1/K$. Measuring
the transfer from $n_i$ to $e_i$ with the radial loop opened shows that the value of $K$ is approximately
0.67.

The amplitude of the sensitivity transfer function should approach 0 dB for high frequencies.
At 10 kHz this is still not the case. This is caused by noise and high frequent dynamics above this
frequency as discussed earlier. Measurements with a larger bandwidth show that the sensitivity
eventually approaches 0 dB as expected.

Furthermore it can be seen that the measurements are very poor below 100 Hz. This is mainly
due to the strong influence of the harmonic components in the disturbance signal $d_2$, which are
caused by eccentricity of the disc. The bad quality of the measurements in the low frequency range
makes it impossible to investigate the influence of the flexible electronic connector between the
OPU and the drive foundation. Although this connector has a very low stiffness it is expected that
the amplitude of $S$ becomes constant when the frequency approaches zero.

From the set of measurements one measurement is selected to use in the model-estimating
algorithm. This selection is made, based on the cumulative coherence of the whole data set for each
measurement. The selected measurement is shown in Fig. 3.4. The correction for the summation point gain is carried out and the data below 100 Hz is discarded because of the bad quality in that frequency region.

![Figure 3.4](image)

**Figure 3.4** Sensitivity measurement with highest cumulative coherence.

**Controller identification**

As suggested in Section 3.2 the frequency response of the internal controller of the optical disc drive is also measured. Because of the good linear behaviour of the analogue electronics the measurement is very accurate and only the correction for the summation point gain is needed. From the electrical scheme of the drive also an analytical expression for the controller can be obtained. The mathematical derivation can be found in Appendix B. The resulting transfer function is given below. In Fig. 3.5 the frequency responses of both the measured and analytically determined controller are shown.

\[
C(s) = \frac{-0.34 \cdot 10^{-1} s^2 + 5.4 \cdot 10^2 s + 1.0 \cdot 10^5}{0.17 \cdot 10^{-1} s^2 + 5.2 \cdot 10^3 s + 1.0 \cdot 10^5}
\]

![Figure 3.5](image)

**Figure 3.5** Frequency response of internal controller.
3.4 Actuator model

Finally the data of the selected measurement is used to obtain an estimated model for the system. The frequency response data of the system $H(s)$ can easily be found by processing the data as discussed in Section 3.2. With the Matlab® routine `frfit` from the DIET-toolbox a model can be generated, based on a least-squares estimation. In Fig. 3.6 the resulting 20th order state-space model is shown. In this model two pure integrators are used to approximate the minus two slope of the amplitude for low frequencies. A check of the eigenvalues of the resulting system matrix $A$ shows that the model is marginally stable (due to the double integrator).

![Magnitude and Phase plots](image)

**Figure 3.6** Identified 20th order model of the radial actuator.

As discussed earlier the very low frequent behaviour is not correct. The stiffness of the electronic connector is neglected. The very high gain at frequencies below 100 Hz is of great help in suppressing the disturbances to obtain the desired position accuracy. From the phase plot the marginal stability of the system becomes clear [4]. Some phase lead should be added by a controller to obtain a system bandwidth of around 500 Hz as calculated before. The major resonance peak of the actuator and the corresponding phase shift lays at 4 kHz. Above 7 kHz the model becomes inadequate.
4

TRACK RECONSTRUCTION

Knowledge of the various disturbances that influence a dynamic system can be of great help during the design or the improvement of the system itself and the controller if one is needed. One of the disturbances that is present in optical disc drives is the actual shape of the information track on the optical disc as discussed in Chapter 2. The fact that the optical disc itself actually forms a part of the servo system makes it possible to obtain information about this disturbance source. How this information can be retrieved is the subject of this Chapter. In Section 4.1 the concept of considering the track on the optical disc as a disturbance is discussed and some nuances of the general idea are given. For this reason the various factors that influence the shape of the track that is seen by the laser spot are discussed. Also a physical interpretation of the various signals in the servo loop is given that forms the basis of the reconstruction procedure. The method for track reconstruction that is used during the research is outlined in Section 4.2. A simple mathematical derivation is given based on the results from preceding chapters. Also several assumptions and limitations for the method are discussed. During the implementation of the track reconstruction several problems emerged. The solutions for these problems and the settings of the various parameters are discussed in Section 4.3. Finally some experimental results are presented and the method is validated.

4.1 Track disturbances

In Fig. 4.1 a schematic view of an optical disc is shown. As stated in Chapter 2 the information track forms a spiral on the disc that is followed by the laser spot to read out the data. The pits that represent the data in a digital form and the laser spot are shown in the zoomed box in Fig. 4.1.

![Figure 4.1 Information track on an optical disc.](image)

In reality the shape of the track that moves past the laser spot is not a perfect spiral. Production tolerances lead to small variations in the pitch, which is normally 1.6 μm. Another cause of this deviation is the eccentricity of the disc. When the centre hole of the disc, which is placed on the disc clamp, is not perfectly centred, the track moves inwards and outwards under the laser spot. The same happens when the centre of the track spiral does not coincide with the disc centre or
when the motor shaft deflects under mechanical loading or bearing imperfections. The total effect of these disturbances is represented by the track disturbance signal $d$ in Fig. 2.2. Although these effects are caused by the system itself they lead to deviations from the ideal case and further they are not measurable [9, 12]. Vibrations of the disc due to unbalances, shocks and other external vibrations can also cause the track to move relatively to the laser spot but they are treated separately as can be seen in Fig. 2.2. Note that all these movements of the track have to be followed by the radial actuator. In fact they can be viewed as a reference signal. However since none of them is measurable they are denoted as output and track disturbances.

**Servo signals**

The block diagram in Fig. 2.2 shows the various signals that are present in the servo loop. In order to read out the data the centre of the laser spot must be positioned on the centre of the track with an accuracy of 0.1 μm. How this is done is already discussed in Section 2.3. The physical meaning of the various signals involved in this servo control problem becomes clear from Fig. 4.2.

![Figure 4.2 Interpretation of the servo signals.](image)

The signal $y$ represents the position of the laser spot centre relative to a fixed reference position. This position is controlled by the current $u$ that is sent to the voice coil motor (VCM) actuator of the radial arm. The distance of the actual track centre to the same reference position is represented by the signal $d$. The difference of the signal $y$ and $d$, which is a measure for the relative position error, is called $e$. This error signal is generated in the OPU by measuring the relative portions of the reflected laser beam received by the various photo-diodes.

Due to the summation point in the block diagram (see Fig. 2.2) the signal that enters the controller is actually $-(e+n)$, hence the controller must also contain a minus sign to counteract this sign change (see Appendix B). In Fig. 4.3 is shown how the error signal $e$ can be interpreted. Due to the symmetric placement of the photo-diodes in the OPU the error signal is zero not only when the spot centre is perfectly above the centre of the track but also when it is located precisely between two tracks. This again stresses the need for a sufficiently high servo stiffness to prevent the laser spot from skipping tracks.
4.2 Reconstruction procedure

From the block diagram in Fig. 3.2 a relation between the error signal and the disturbance signal \(e_2\) and \(d_2\) respectively can be derived [9, 10]. This relation is given in equation (4.1).

\[
d_2 = [1 + C(s)H(s)]e_2 = S^{-1} \cdot e_2
\]  

In Chapter 3 models for \(C(s)\) and \(H(s)\) are derived so an estimate for the first term on the right-hand side of (4.1) is available. From Fig. 3.1 it follows that the signal \(e_2\) can be measured. With the relation given in (4.1) the disturbance signal can be reconstructed by filtering the measured error signal with the inverse sensitivity approximation.

The procedure described above is based on the assumption that the servo control loop behaves as a linear closed loop system or at least its behaviour is approximately linear. Tests must show if this assumption is valid for the system under investigation. Results of these linearity tests are given in Section 4.3.

By using this method to reconstruct the track disturbances all the information stored in the error signal is interpreted as a track disturbance [10]. The measurements must be conducted very carefully to avoid shocks, vibrations and phenomena like unbalance because they would be mistakenly interpreted as track disturbances. This fact also stresses that it will be difficult to distinguish the relative influence of the different sources of the track disturbance as mentioned in Section 4.1.

4.3 Implementation

With the results from Chapter 3 it is fairly straightforward to construct the inverse sensitivity filter given in equation (4.1). The approximation of the plant transfer function is not correct for low frequencies as already discussed in Section 3.4. For the \(S^{-1}\)-filter this will result in an infinite gain for frequencies approaching zero. In order to prevent numerical problems a high-pass Butterworth filter is added. A fourth order filter with a cut-off frequency of 5 Hz is used. This frequency is based on some low frequent test measurements but the exact position is not important. This is because no relevant information in the disturbance signal is expected below the rotational frequency of 12 Hz. In order to prevent phase lag the filtering of the measured error signal with the
high-pass Butterworth filter must be done in an anti-causal way. Implementation of the constructed filter with the Matlab® routines \texttt{filtfilt} and \texttt{filter} still lead to numerical problems due to the ill conditioning of $S^I$. Therefore the $S^I$-filter finally is implemented using Simulink®, without taking care of the phase lag due to the high-pass filter. The effect of this phase lag entered into the disturbance signal is not investigated further. A Bode diagram of the filter is given in Fig. 4.4.

![Bode diagram of the filter](image.png)

**Figure 4.4** Inverse sensitivity filter in series with a fourth order high-pass Butterworth filter.

The constructed filter given in Fig. 4.4 can now be used to filter the measurements of the error signal (\textit{error_rad CH2} in Fig. 3.1). In order to generate enough data to be able to investigate the various properties of the track disturbance SigLab™ ‘long record capture’ (VCAP) measurements are conducted. To be able to compare the different frames (sets of 8192 samples with a measuring time of 3.2 seconds) in the whole data set, a trigger signal is used. With this signal it is possible to start each measurement frame at the same angular position so no phase differences will occur between the measured frames.

The measurement bandwidth for the error measurements is set to 1 kHz. It is expected that for higher frequencies the error signal will mainly consists of noise and hence can be discarded. The number of samples is 8192, which leads to a spectral distance of 0.3125 Hz. During each measurement 25 frames are measured, which results in a total measuring time of 80 seconds for the whole data set. The settings for the trigger signal are tuned manually for each optical disc to obtain the best results. The used Matlab® routines that are used to process the data, finding the trigger instants and finally filtering it with the $S^I$-filter are included in Appendix C.

![Resulting disturbance signals](image.png)

**Figure 4.5** Resulting disturbance signals from a test measurement at 12 Hz (left) and 24 Hz (right).
Validation

In Fig. 4.5 some test results of the reconstruction procedure are shown. The first part of the data is not usable due to the filter transient and must be discarded. The amount of samples that is cut off is set by hand, depending on the frequency of rotation of the disc during the measurement. The oscillatory behaviour of the disturbance signal that is clearly visible in Fig. 4.5 is caused by the strong dependence of this signal on the rotational frequency. The amplitude of the steady state signal is approximately the same for the two figures, indicating that the linear approximation assumed in this method is valid. Further it must be noted that all error measurements are done with the optical pick-up following the track from the outer towards the inner radius of the disc. This unusual rotating direction will not influence the results when it is taken into consideration during the interpretation of the results. In Chapter 5 the obtained disturbance signals will be discussed in detail.
5 DISC CHARACTERIZATION

Now that a method is available to reconstruct the track disturbance signal from error measurements, the various properties of this signal can be investigated. Explanations for the phenomena that occur in the track disturbance can be sought and an assessment of the quality of different optical discs can be made. The track disturbance is caused by various imperfections of the disc and the optical disc drive. These imperfections can differ significantly from one disc to the other and even at different positions on the same disc differences can occur. In order to analyse and compare the track data for different discs and different locations on these discs, statistical methods are used. In Section 5.1, various statistic signal properties are discussed. The measured error signals and the resulting disturbances are functions of time. In Section 5.2, these track disturbances are analysed in the time domain. In order to get more information from the reconstructed tracks, a transformation of the signals to the frequency domain is conducted. In Section 5.3, this transformation is discussed shortly. Then the results of this transformation are discussed. In Section 5.4, an overview of the most important properties of the track disturbance signal is given and the several test discs are compared.

5.1 Statistic signal properties

The time domain data of the reconstructed track disturbance signals is cut into pieces. Each part represents the track disturbance for one revolution of the disc. Although it is reasonable to assume that the shape of the track will not change in time, the pieces of the track corresponding to one revolution on the disc can be regarded as realizations of a stochastic process. This becomes even clearer when tracks of different discs are compared with each other [8].

A stochastic process (random process) is a process where for each moment in time the value of a stochastic variable can be laid down. Formally, a random process is formed by the set \( \{ x(t), t \in T \} \) where \( t \) is interpreted as time and hence the index set \( T \) is formed by the real variables. A random process thus can be considered as a function \( x(t, \omega) \) of two variables. For fixed \( \omega = \omega_0 \), the function \( x(x, \omega_0) \) is an ordinary time function called a realization. For fixed \( t = t_0 \), the function \( x(t_0, \cdot) \) is a random variable [1]. The set of all possible realizations is called the ensemble (Fig 5.1).

![Figure 5.1 An ensemble of a random process.](image-url)
Disc characterization

For a random process several statistic properties exist. The ensemble average at the specific time point $t_0$ is the average value of the random variable $x(t_0)$. The time average of a specific realization $\omega_0$ of the random process is the average value of the time function $x(\cdot, \omega_0)$.

For a single realization of the random process $X(t)$ the probability distribution function is defined as follows:

$$F_X(x; t) = P(X(t) \leq x)$$

Equation (5.1) defines the chance that the value of the signal $x(t)$ is larger than a specific value $x$. The derivative of (5.1) with respect to $x$ leads to the probability density function $f_X(x)$ that denotes the change that the signal $x(t)$ takes a value in the arbitrarily small interval $[x, x+\delta x]$. With the probability density function the expected value or average and the stochastic autocorrelation function can be defined:

$$\mu_x(t) = E[X(t)] = \int_{-\infty}^{\infty} x f_X(x; t) dx$$

$$R_{xx}(t_1, t_2) = E[X(t_1)X(t_2)]$$

A stochastic process is called Gaussian or normal if both moments given in (5.2) have a normal probability density $[6, 7, 8]$. The process is called (weakly) stationary when the expected value function is constant and the autocorrelation function $R_{xx}$ only depends on the difference $\tau$ between $t_1$ and $t_2$.

Another useful relation is the power spectral density function or auto power spectrum. It denotes in which way the total power of a signal is distributed over the whole frequency domain. The auto power spectrum for a weakly stationary process can be derived from the autocorrelation function by using the Wiener-Khintchine relation $[6]$, yielding:

$$S_{xx}(f) = \int_{-\infty}^{\infty} R_{xx} (\tau) e^{-2\pi j f \tau} d\tau$$

### 5.2 Time domain analysis

For the analysis nine different optical discs are used. In a statistical sense this number is relatively low but the emphasis will be on finding characteristic properties of the information track. Hence the number of test discs is kept low to reduce the amount of test data that will be generated. The set of test discs contains audio-CDs and CD-ROMs as well. Although specifications for the various types of discs are different most players must be able to handle several types of discs. By using different disc types general characteristics, valid for all discs can be investigated.

A trigger signal is used to make it possible to compare the different frames in the measurements with each other (see Section 4.3). The optical sensor that is used to generate this signal reacts on the reflective marker every time it passes. Hence the resulting signal can also be used to cut the track data in pieces corresponding with a single revolution of the disc. Now it is possible to investigate local changes in the track shape and the influence of the spiral radius. The results must be handled carefully because no accurate radial position information is available. In Appendix C the Matlab® routines are given that are used for this data manipulation.

In Fig. 5.2 the result for one specific test disc is given. Each picture corresponds to one measurement frame and therefore shows the track for approximately thirty revolutions.
Figure 5.2  Track reconstruction for 9 frames of each 33 disc revolutions; CD 1.

Figure 5.3  Ensemble average of track disturbance per revolution; CD 1.
Disc characterization

From Fig. 5.2 the large influence of the frequency of rotation on the track disturbance becomes clear. The periodic nature of the track with the fundamental frequency equal to the rotational frequency is mainly caused by the disc and/or track eccentricity. The signal however is not a perfect sinusoid, due to other minor imperfections of the track. Figure 5.2 also shows that the amplitude of the track disturbance decreases when the laser spot moves from the outside to the inside of the disc (first frame to last frame). From the complete overview of the results in Appendix D it follows that all reliable measurements show this amplitude reduction. No good explanation for this phenomenon is found yet. In the upper three frames (frame 1, 2 and 3) the separate parts of the track for different revolutions differ more than in the other frames. This is partly due to the fact that the trigger signal has a variation of a few samples so not every track piece starts at the same angular position. Because all frames should suffer from this inaccurate trigger, the large variation in the first three frames indicates some local track disturbances.

In Fig. 5.3 the average track for a single revolution is given. This is called the ensemble average because all parts of the reconstructed track corresponding to one revolution of the disc, are considered to be realizations of a random process [8]. From Fig. 5.3 it follows directly that the expected value \( \mu(t) \) depends on the time \( t \) and hence the process is not stationary. Further it must be noted that this average value is not representative for the whole disc since only 800 of the 20,000 track revolutions are used. Due to the found amplitude reduction for smaller track radii the ensemble average for the whole disc is probably lower than the one shown in Fig. 5.3.

From the data presented in Fig. 5.2 another average value can be determined, namely the average value for the track disturbance over one revolution of the disc. Looking at Fig. 5.2 and 5.3 it can be expected that this average value will be close to zero, such as that of a perfect sine. In Fig. 5.4 these averages are shown for all revolutions that the disc made during the measurement.

![Figure 5.4](image.png)

**Figure 5.4** Time averages of track disturbance for all measured disc revolutions; CD 2.

The average values of the track disturbance for the different revolutions are around zero as expected. The large negative spikes at the left are due to the inaccurate removal of the \( S^1 \)-filter transient. In Fig. 5.5 a histogram of these average values is given.
Disc characterization

Figure 5.5  Histogram of time averaged track disturbance for all measured disc revolutions; CD 2.

From the histogram in Fig. 5.5 it can be concluded that there are other sources causing the track disturbance. The deviations from the expected value for the time average of zero can be caused by local track imperfections due to the limited production tolerances of the optical disc. The relatively high variance of the time averaged values make it very unlikely that those deviations are purely due to measurement noise. The shape of the histogram approaches that of a normal distribution, which is consistent with the central limit theorem [7, 8]. Since the normal distribution is completely specified by its mean value and variance this leads to a convenient way to characterize the track disturbance of optical discs. For the little offset of the mean from zero no good explanation is found yet.

The results found so far are applicable to all measured test discs (see Appendix D) and in Section 5.4 a summary of these results will be given. Now some typical phenomena found in several individual measurements are discussed and explanations for them are given.

In Fig. 5.6, 5.7 and 5.8 the ensemble averages are shown for the measurements of CD 7 at 9, 12 and 15 Hz respectively. At 12 and 15 Hz an extra periodic component can be seen in the track disturbance for one revolution. Its presence at 15 Hz is more distinguishable and at 9 Hz it is completely vanished. This leads to the conclusion that it is caused by external vibrations of the whole drive module. Probably these vibrations are caused by some unbalances of the disc [10]. Verification of the measurements ruled out any other external vibration source. Another remarkable issue is the large variation of the disturbance amplitude for the three measurements. Since the disc is removed and re-entered between the measurements this is probably caused by the way in which the disc is clamped on the turntable.
**Figure 5.6** Ensemble average of track disturbance; CD 7 at 9 Hz.

**Figure 5.7** Ensemble average of track disturbance; CD 7 at 12 Hz.

**Figure 5.8** Ensemble average of track disturbance; CD 7 at 15 Hz.
5.3 Frequency domain analysis

The results from Section 5.2 already showed the predominantly periodic nature of the track disturbance signal. Although the influence of the fundamental frequency, which is equal to the rotational frequency of the disc, is very high some other components are expected to be present. In order to investigate this, the obtained track disturbance signal is transformed into the frequency domain. Therefore the auto power spectra for the various measurements are determined. Since the process is not stationary equation (5.3) does not apply here but with a numerical routine based on the Fast Fourier Transformation algorithm, the desired spectra still can be determined.

In Fig. 5.9 the spectra corresponding with the time domain measurements in Fig. 5.2 are shown. For the sake of clarity only for five measurement frames the spectra are given. From all spectra an average auto power spectrum can be determined. The result again must be interpreted carefully cause the radius-dependent amplitude as discussed in Section 5.2 is also present in the frequency domain. The resulting auto power spectrum is shown in Fig. 5.10.

![Figure 5.9](image1.png)

**Figure 5.9** Auto power spectra of the track reconstruction per disc revolution; CD 1.

![Figure 5.10](image2.png)

**Figure 5.10** Averaged auto power spectrum of the reconstructed track; CD 1.
The average auto power spectrum in Fig. 5.10 is only shown for frequencies below 100 Hz. At higher frequencies the signal becomes noisy and hence not much useful information can be obtained from it.

To compare the relative influence of the harmonics up to 100 Hz the peak values are determined and are normalized with respect to the amplitude of the fundamental harmonic [9, 10]. The results for the first eight harmonics are shown in Fig. 5.11.

\[ \text{Relative amplitude \%} \]
\[ \text{Harmonic order} \]

\[ 10^0 \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10 \]

**Figure 5.11** Harmonic components of the track disturbance signal; CD 1.

From Fig. 5.11 one more the very high contribution of the fundamental harmonic to the track disturbance signal becomes clear. The higher order harmonics are at least one order smaller in magnitude and above 60 Hz their relative influence has become less than one percent. Above 100 Hz the line remains more or less constant due to the present noise, which has constant energy content over a wide frequency range. The peak at the fourth harmonic, corresponding to 48 Hz, is probably caused by the so-called 'four-leaf clover' eccentricity. This phenomenon is a result of the four different mould entries in the injection-moulding machine used to produce the optical discs.

\[ 10^0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \quad 7 \quad 8 \quad 9 \quad 10 \]

**Fig. 5.12** Cumulative auto power spectrum of the track disturbance signal; CD 1.
Another way to assess the relative influence of the different frequency components present in the track disturbance signal is plotting the cumulative auto power spectrum [12]. For the spectrum presented above this is done in Fig. 5.12. The circles indicate the position of the first eight harmonics. In this picture a steep line segment indicates a large influence and flat segments indicate the relative low influence in that frequency range.

To illustrate the usefulness of the frequency domain analysis in analysing the track disturbances the auto power spectra corresponding to Fig. 5.6, 5.7 and 5.8 are investigated. In Fig. 5.13 a), b) and c) respectively the amplitudes of those spectra for the different harmonic orders are shown.

![Figure 5.13](image)

**Figure 5.13** Normalized harmonic components at a) 9 Hz, b) 12 Hz and c) 15 Hz; CD 7.

From Fig. 5.13 a) it can be seen that the influence of the higher order harmonics at 9 Hz is almost an order in magnitude lower than in the measurements at 12 and 15 Hz. This effect was already seen in the time domain analysis and was probably caused by the bad clamping of the disc after insertion. The extra track disturbance component in Fig. 5.7 and 5.8, caused by vibrations can also be identified from the peak at the seventh harmonic in Fig. 5.13. From Fig. 5.13 a) it becomes clear that the vibration is also present at 9 Hz but due to the low relative influence it cannot be seen in the time domain measurements. Fig. 5.13 b) and c) show that another component at 60 Hz gains influence at higher rotational speeds, justifying the conclusion that this phenomena is caused by vibrations of the disc drive module.

The complete results of the frequency domain analysis for all test discs can also be found in Appendix D. In the next section some of the characteristics of the track disturbance signal that are found during the analysis are summarized in a quantitative way.
5.4 Quantitative characterization

In this section some parameters are introduced that can be used to assess the quality of different optical discs. These parameters are based on the performed analysis discussed above. From the time domain results two important properties of the track disturbance signal emerged. The first is the amplitude of the averaged track disturbance for a single revolution, the so-called ensemble average of the track disturbance (see Fig. 5.3). The second one is the variance of the time averaged track disturbance for a single revolution. This parameter is chosen since it is found that the time average value behaves approximately normal. The normal distribution can be completely described by the mean value and the variance. It is expected that the unexplained offset of the mean value does not influence its variance (see Fig. 5.5). The results for the various test discs are given in Table 5.1.

Table 5.1  Time domain characteristics for all test discs.

<table>
<thead>
<tr>
<th>Test disc</th>
<th>Mean disturbance amplitude [V]</th>
<th>Variance of time average [V²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD 1</td>
<td>5.71·10¹</td>
<td>7.59·10⁻²</td>
</tr>
<tr>
<td>CD 2</td>
<td>1.82·10²</td>
<td>1.89·10⁻¹</td>
</tr>
<tr>
<td>CD 3</td>
<td>2.28·10¹</td>
<td>8.58·10⁻²</td>
</tr>
<tr>
<td>CD 4</td>
<td>4.35·10¹</td>
<td>7.96·10⁻²</td>
</tr>
<tr>
<td>CD 5</td>
<td>1.05·10²</td>
<td>1.80·10⁻¹</td>
</tr>
<tr>
<td>CD 7</td>
<td>2.98·10¹</td>
<td>3.33·10⁻²</td>
</tr>
<tr>
<td>CD 8</td>
<td>7.65·10¹</td>
<td>5.74·10⁻¹</td>
</tr>
<tr>
<td>CD 9</td>
<td>7.94·10¹</td>
<td>1.04·10⁰</td>
</tr>
</tbody>
</table>

From the frequency domain data another general parameters can be deduced, namely the cumulative auto power spectrum value. Since this value is an indication for the total energy content in the track disturbance signal it can be compared with the mean disturbance amplitude. Since both values are mainly influenced by the fundamental harmonic they both give some information about the magnitude of the track disturbance signal. The calculated values for all test discs are given in Table 5.2.

Table 5.2  Frequency domain characteristics for all test discs.

<table>
<thead>
<tr>
<th>Test disc</th>
<th>Cumulative power spectrum [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD 1</td>
<td>8.90·10⁶</td>
</tr>
<tr>
<td>CD 2</td>
<td>8.45·10⁶</td>
</tr>
<tr>
<td>CD 3</td>
<td>1.09·10⁵</td>
</tr>
<tr>
<td>CD 4</td>
<td>5.76·10⁵</td>
</tr>
<tr>
<td>CD 5</td>
<td>2.79·10⁶</td>
</tr>
<tr>
<td>CD 7</td>
<td>2.27·10⁵</td>
</tr>
<tr>
<td>CD 8</td>
<td>2.05·10⁵</td>
</tr>
<tr>
<td>CD 9</td>
<td>1.63·10⁶</td>
</tr>
</tbody>
</table>

The values presented in Table 5.1 and 5.2 are all based on three measurements per disc. The measurements are conducted right after each other. By adding the three measurements the total reconstructed track approximately describes 10 percent of the total disc. Since some parameters are found to change according to the radial position of the measurement point, the values presented in Table 5.1 and 5.2 are not representative for the whole disc and hence careful interpretation is necessary. The results for disc number 6 are left out because those measurements cannot be trusted, probably due to the bad quality of the trigger signal.
6

CONCLUSIONS AND RECOMMENDATIONS

In this report a method for characterizing one important class of disturbances for the optical storage system is given. From the general discussion of optical disc drives and the servo control problem involved, it becomes clear that an optical disc drive is a complex mechatronic system. Electrical, mechanical and electronic components are fully integrated in this mass consumer product. In order to fulfill the increasing performance demands more knowledge of the system and the influencing disturbances is necessary. One of these disturbances is one that is inherently present in each optical storage system, namely the actual track shape that contains the information on the disc. Characterizing this signal and obtain a statistically validated model for it could be of great help in the design of new and better controllers.

In order to be able to investigate this track disturbance a model of the system is needed. The suggested identification method leads to a usable model. However the results for very low frequencies are inaccurate so further research and perhaps combining several identification methods is needed to improve the dynamic models that are used during the analysis of optical disc drives.

With the available model an inverse sensitivity filter is calculated to reconstruct the immeasurable track disturbance from other signals in the system that are measurable. This method is based on linear systems theory. Measurements at different rotational speeds give similar results, leading to the conclusion that the linearity assumption is valid. Some more investigations of this issue however are recommended. Another problem that occurs while using the proposed track reconstruction procedure is the ill conditioning of the used filter. A numerical analysis and some mathematical improvements of the method will certainly add to the accuracy of the resulting track signals.

Characteristic parameters of the resulting track signals are the signal amplitude and the variance of the time averaged track disturbance. With these parameters it is possible to assess the quality of different optical discs. Next to the eccentricity of the actual track shape and disc also vibrations and local track imperfections can be identified from the results. In order to accurately identify the various disturbance sources more research is needed.

From the results it occurred that the rotational frequency of the disc has a major influence on the track disturbance signal. Attempts are made to use the averaged track disturbance to reduce this effect but it is found that the phase information of the reconstructed signals was not accurate enough. By improving this phase information it is believed that the reduction of the eccentricity influence can lead to more insight in the various other disturbances present in the track signal.

During this work only track disturbances are taken into account. In order to counteract these disturbances high servo bandwidths are required. However, surface defects of the disc such as scratches and fingerprints for instance, place a limit on the obtainable servo bandwidth. Further research about this so-called 'playability' is necessary to make a good trade-off in the controller design between tracking and playability. Only then the results obtained here can be fully used during the improvement of new optical disc drive controllers. How to do this is still an open question.
REFERENCES


A

ESTIMATING TRANSFER FUNCTIONS

A.1 Parametric modelling

Based on physical principles it is possible to derive a simple model for the radial actuator [2]. In Fig. A.1 a representation of the radial arm is given.

A Voice Coil Motor (VCM) drives the radial arm. The current $i_{rad}$ flowing through the coil of the motor generates a proportional torque $T$ on the radial arm according to:

$$T = K_{motor} i_{rad} \quad (A.1)$$

With Newton’s applied to the radial arm this torque leads to:

$$T = J_{arm} \dot{\alpha} \quad (A.2)$$

Double integration and Laplace transformation of equation (A.2) yields the following relation between the angular position of the arm and the motor current:

$$\hat{\alpha}(s) = \frac{K_{motor}}{J_{arm}} \frac{1}{s^2} \hat{i}_{rad}(s) \quad (A.3)$$

Finally it is assumed that the radial position of the laser spot (at the end of the radial arm) is proportional to the angular displacement of the arm, which leads to the following second order model of the radial actuator:

$$\hat{y}(s) = K_{arm} \hat{\alpha}(s) = K_{arm} \frac{K_{motor}}{J_{arm}} \frac{1}{s^2} \hat{i}_{rad}(s) \quad (A.4)$$
The model presented in equation (A.4) describes the radial actuator at low frequencies. Above 800 Hz the rigid body assumption is no longer valid due to flexible bending and torsion of the arm and the disc. Further the assumed proportional relation between the angular arm displacement and radial spot position is not exactly correct and non-linear in reality.

A.2 Experimental transfer function estimation

In order to obtain an accurate model of the desired transfer function an experimental approach can be used. By conducting measurements of the system, noise is entered into the data that will influence the results. Because the method described here is based on linear system theory care must be taken to conduct the measurements in the linear range of the system, which in reality of course is non-linear. Unfortunately a trade-off between linearity and noise must be made cause both phenomena require opposite counter measures. In Fig. A.2 a schematic view of a transfer function measurement with SigLab™ is given [11].

![Figure A.2 Optimal SigLab™ measurement set-up.](image)

In Fig. A.2 the term \( n_x(t) \) takes account for the entire measurement uncertainty. No assumptions are made about the character of this noise other than when the excitation is zero, the response of the system \( y(t) \) is zero and \( y_{off}(t) = n_x(t) \) is the only term left. The key point in this kind of measurements is that it is relatively easy to obtain an unbiased estimate of the transfer function.

The transfer function estimation is computed from cross and auto power spectra estimates as shown in equation (A.5):

\[
\hat{H}(\omega) = \frac{\hat{P}_{xy}(\omega)}{\hat{P}_{xx}(\omega)}
\]  

(A.5)

The upper term is the cross power spectrum between the excitation \( x_m(t) \) and response \( y_m(t) \) and the lower term is the auto power spectrum of the excitation signal. Next to the transfer function estimate also the coherence of the measurement is calculated from equation (A.6). The coherence
Disc characterization

31

gives an indication of the portion of the systems output power due to the input excitation and hence of the quality of the measurement.

\[
\hat{C}(\omega) = \frac{\hat{P}_{xy}(\omega)}{\hat{P}_{xx}(\omega)\hat{P}_{yy}(\omega)}
\]  

(A.6)

The value of the coherence has a range from zero to one, where one indicates that all of the measured output power is due to the input excitation. This is the ideal situation and will only be true at frequencies where the spectral energy of the noise $n_0(t)$ is negligible.

The cross and auto power spectra estimates are computed in SigLab™ using the FFT algorithm, windowing and frequency domain averaging. Cause the transfer function estimate is unbiased the estimate will eventually converge to the actual transfer function when the amount of averaging is increased. This is true even when the coherence is very low due to extensive noise.

A.3 Experimental considerations

In SigLab™ there are two possible methods to compute the transfer function estimate. The first one is the broadband FFT technique. Here the transfer function is estimated over a band of frequencies simultaneously. Hence the excitation signal must contain components that cover the selected frequency range. Besides the standard chirp and random excitation some other signals can be used, for instance so-called pink noise. This is a random signal but it is scaled with the frequency so that the amplitude of the higher frequencies is lower and their influence on the estimate is reduced. The second method is the swept-sine technique. Here a sine signal with a single frequency is used as excitation of the system. The accuracy of the frequency can be influenced by digital tracking band-pass filters to provide greater noise immunity. The transfer function estimate is calculated for this frequency in the same way as discussed before. When the transfer function estimate has been computed, the output source frequency is advanced to the next frequency desired for the transfer function estimate. The benefit of this method is its good accuracy; even for noisy and non-linear systems but the measurement time for accurate measurements is very long.

To counteract the influence of measurement noise, yielding low coherence, the excitation power can be increased. By this increase the noise will be simply overpowered and hence its influence can be neglected. The drawback is that by using higher excitation power levels the system starts to behave increasingly non-linear. Hence a trade-off between the signal-to-noise ratio and the non-linearity of the system must be made. Another way to deal with the bad signal-to-noise ratio is by using a larger number of averages. By this averaging the influence of noise can be minimalized.

Open loop measurements of control system transfer functions are difficult. This is due to the fact that the open loop system is often marginally or even and measurements often must be done under operating conditions. It is however possible to conduct closed loop measurements and use a mapping from closed loop to open loop to derive the desired transfer function. In order to enter an excitation signal into the loop a summation point must be used. The resulting closed loop transfer function estimate depends heavily on the gains of this summation point, especially at low frequencies. Hence those gains must be measured very accurately and taken into account when the open loop transfer function is calculated. Of course the same accuracy considerations discussed earlier apply and a good trade-off between noise and non-linearity must be made for closed loop measurements as well.
B

DETERMINATION OF C(s)

The internal controller of the optical disc drive is implemented on the electronic circuit board [5]. It consists of an operational amplifier, several resistors and two capacitors. The symbolic representation of the controller is given in Fig. B.1.

![Electrical scheme of the internal controller.](image)

For the components the following values are given:

- $C_1 = 6.8 \text{ nF}$
- $C_2 = 470 \text{ nF}$
- $R_1 = 4.7 \text{ k}\Omega$
- $R_2 = 100 \text{ k}\Omega$
- $R_3 = 10 \text{ k}\Omega$
- $R_4 = 100 \text{ k}\Omega$

The impedances $Z_1$ and $Z_2$ can be used to simplify the scheme and hence the calculation of the controller transfer function $C(s)$. The arrows in Fig. B.2 indicate the direction in which the current flows.

![Equivalent electrical scheme.](image)
The simplified scheme of Fig. B.2 forms the starting point in finding the controller transfer function. Applying Ohm’s law to this circuit yields:

\[ I_1 = \frac{V_{\text{out}} - V_{\text{in}}}{Z_2} \quad (B.1) \]

The voltage \( V_+ \) at the negative side of the amplifier is equal to that on the positive side, \( V_+ \). Since \( V_+ \) is grounded both voltages are equal to zero. Using Ohm’s law again leads to a second equation for the current \( I_1 \).

\[ I_1 = \frac{V_+ - V_{\text{in}}}{Z_1} \quad (B.2) \]

Eliminating \( I_1 \) from (B.1) and (B.2) and setting \( V_+ \) to zero yields:

\[ \frac{V_{\text{out}}}{Z_2} = -\frac{V_{\text{in}}}{Z_1} \quad \Rightarrow \quad \frac{V_{\text{out}}}{V_{\text{in}}} = -\frac{Z_2}{Z_1} \quad (B.3) \]

Equation (B.3) is the complex transfer function \( C(s) \), relating the input to the output voltage. The next step is to calculate the two impedances \( Z_1 \) and \( Z_2 \) to obtain the desired expression for \( C(s) \).

For two parallel resistors the following holds:

\[ \frac{1}{R_{\text{tot}}} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{R_1 + R_2}{R_1 \cdot R_2} \quad (B.4) \]

Using this result gives the following expression for the impedance \( Z_1 \):

\[ Z_1 = \left( \frac{1}{j \omega C_1} + \frac{1}{R_1} \right) \cdot \frac{R_2}{1 + j \omega C_1 \cdot (R_1 + R_2)} \quad (B.5) \]

The same can be done for impedance \( Z_2 \) yielding:

\[ Z_2 = \frac{R_4 + R_3 R_4 j \omega C_2}{1 + j \omega C_2 \cdot (R_3 + R_4)} \quad (B.6) \]

Combining (B.3), (B.5) and (B.6), replacing \( j \omega \) with \( s \) and filling in the given values for the various components yields the desired expression for the transfer function \( C(s) \). The minus sign counteracts the fact that the input of the controller is \( -e \) (see Section 4.1).

\[ H(s) = \frac{-0.335 s^2 + 540 s + 1 \cdot 10^5}{0.165 s^2 + 5.17 \cdot 10^7 s + 1 \cdot 10^5} \quad (B.7) \]
MATLAB® Routines for Track Reconstruction

%FILTERDAT  Filtering of measured error to obtain system disturbance.
% This program loads the error measurement and filters the data frame by
% frame with an inverse sensitivity filter to obtain the system disturbances.
% The obtained data is saved for each revolution frame by frame in the
% structure 'Dist_frame' which is saved as 'distframe.mat'. The total filtered
% data matrix 'Dist_all' containing the disturbance for each frame is saved
% as 'distall.mat'.
% FUNCTIONS CALLED: framecut.m
% tri9find.m
% cfiltmod.mdl

% INTERNAL TRAINEESHIP, 4W409
% Eindhoven University of Technology
% Faculty of Mechanical Engineering
% Section Control Systems Technology
% Jan van Helvoirt, February 2001

clear
close all

% Initialization
curdir = pwd;  % Loading data
cd c:\\Traine-1\\Internal\\data\\errors
[fname, fpath] = uigetfile('*.mat', 'Select data file');
addpath(fpath);
load(fname);
wcd = fpath(length(fpath) -4:length(fpath)-1);
rmpath(fpath)
cd(curdir)

ch1 = 1.3e-3;  % SigLab voltage offset Channel 1 [V]
err = VCAP_DATA(:,1);
err = err - ch1;  % Correction for voltage offset
opb = VCAP_DATA(:,2);
clear VCAP_DATA VCAP_SAMPLERATE

load errfilt  % Loading constructed inverse sensitivity filter
[Acf, Bcf, Ccf, Dcf] = ssdata(Herrc);

prompt = {'Sample frequency [Hz]', 'Number of samples', 'Number of frames', ...
'Trigger Channel range [V]', 'Trigger threshold'};
title = ['Measurement settings for ', wcd];
lines = [1 40; 1 40; 1 40; 1 40; 1 40];
def = {'2560', '8192', '25', '2.5', '-0.09'};
answer = inputdlg(prompt, title, lines, def);
var = str2num(char(answer));

fs = var(1);  % Sample frequency [Hz]
N = var(2);  % Number of samples
df = fs/N;  % Spectral distance [Hz]
T = t/df;  % Total measuring time for each frame [s]
dt = 1/fs;  % Discretisation timestep [s]
totframe = var(3); % Number of frames taken in each measurement
Volt = var(4); % Voltage range of trigger channel in Siglab VNA&VCAP [V]
Treshold = var(5); % Threshold of trigger [%]

%Making structure
Data.ydat = [];
Disturbance.Frame(1:totframe)=Data;

%Filtering error measurement frame by frame
[ferr, fopb] = framecut(err, opb, N, totframe);
t = (d*(0:N-1))';
fdis = [];
for k = 1:totframe
    u = ferr(:,k);
    sim('cfiltmodt') % Filtering error signal with inverse sensitivity
    fdis = [fdis, cdistl];
end

%Sorting filtered data for each revolution per frame
revdis = [];
flag = 0;
for frame = 1:totframe
    [tin, mins] = trigfind(fopb(:,frame), Volt, Treshold, N);
    if flag == 1 % Check for new smaller mins
        if mins >= minsold
            mins = minsold;
        else
            for l = 1:frame-1 % Rebuilding matrices with new (smaller) rowsize
                Dist_frame.Frame(l).ydat = Dist_frame.Frame(l).ydat(1:mins,:);
            end
        end
    else
        flag = 1;
    end
    revnr = length(tin);
    for k = 1:revnr-1 % Sorting data for each revolution
        revdis = [revdis, fdis(tin(k):tin(k)+(mins-1),frame)];
    end
    Dist_frame.Frame(frame).ydat = revdis(:,6:size(revdis,2)); % Cutting off filter transient
    revdis=[];
    minsold = mins;
end

t = dt*(0:mins-1)';
Dist_frame.tvec = t;

%Saving useful data
Dist_all = fdis;

cd c:\Traine-1\Internal\data\filtdat
newname = ['dist', fname(4:length(fname))];
[nfile, npath] = uiputfile(newname, ['Save disturbance data of ', wcd, ' to file']);

cd(npath);
save(nfile, 'Dist_frame', 'Dist_all', 'fs', 'N', 'Volt', 'Treshold', 'totframe')

cd(curdir);
function [ye, yo] = framecut(merr, mopb, N, totframe)
%FRAMECUT Cuts the total dataset into its separate frames.
% ye = frameavg(frame,N,totframe) cuts the specified data set into its
% separate frames. The vectors 'merr' and 'mopb' contain the measurement
% data and the corresponding trigger signal. 'N' is the number of samples
% taken for each frame and 'totframe' is the total number of frames taken.
% The output 'ye' and 'yo' of the function are matrices with columns containing
% the measured data and the trigger signal respectively for each separate frame.

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% Eindhoven University of Technology
% Faculty of Mechanical Engineering
% Section Control Systems Technology
% Jan van Helvoirt
% February 2001

% Generating indices
i1 = zeros(1, totframe);
i2 = zeros(1, totframe);
for k = 1:totframe
    i1(k) = (k-1)*N+1;
    i2(k) = k*N;
end

% Constructing matrix with data of measurement frames
errframe = zeros(N, totframe);
opbframe = zeros(N, totframe);
for k = 1:totframe
    errframe(:,k) = merr(i1(k):i2(k));
    opbframe(:,k) = mopb(i1(k):i2(k));
end

% Generating output
ye = errframe;
yo = opbframe;
function [y, mins] = trigfind(mopb, Vo, Tr, N, frame, allframes)
%TRIGFIND Determines the sample instants where a trigger event took place.
%
% [y, mins] = trigfind(mopb, Vo, Tr, N) determines the sample instants
% where the trigger took place in a specified measurement frame. The variable
% 'mopb' contains the corresponding trigger signal of the measurement of
% interest. The variables 'Vo' and 'Tr' contain information about the Siglab
% VNA&VCAP trigger settings. 'N' is the number of samples of the measurement.
%
% [y, mins] = trigfind(mopb, Vo, Tr, N, frame, allframes) determines all the
% sample instants of a specified measurement frame where a trigger event took
% place. The string 'allframes' can be set to 'loop' to evaluate the trigger
% events frame by frame for a multiple frame measurement. The variable 'frame'
% must contain the number of the frame of interest. 'mopb' in this case must
% contain the whole trigger signal of the total measurement. When 'allframes' is
% set to 'all' the function returns all the trigger event indices at once.
%
% The output of the function is a vector 'y' containing all the sample indices
% and 'mins' contains the minimum number of samples that are taken between two
% successive trigger events.
%
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%
%Checking inputs
if nargin < 6
    allframes = 'all';
end
if nargin < 5
    frame = 1;
end
if nargin < 4
    disp('Invalid function call, not enough input arguments used')
end
if strcmp(allframes,'loop')
    framevec = ((frame-1)*N+1:frame*N);
elseif strcmp(allframes,'all')
    framevec = 1:frame*N;
else
    disp('Invalid value for variable ALLFRAMES')
    return
end

Trigger = Tr*Vo; Treshold = (Tr-0.09)*Vo;
flag = 0; tin = [];

%Searching algorithm
for k = framevec
    if flag == 1
        if mopb(k) > Trigger
            tin = [tin, k]; flag = 0;
        end
    else
        if mopb(k) < Treshold
            flag = 1;
        end
    end
end
%Generating function output
y = tin; mins = min(diff(y));
In this appendix the most important experimental results of all test discs are presented. The used test discs are given in Table D.1. For all discs three consecutive measurements are done, which account for approximately ten percent of the total disc. All results shown here are based on the averages from those measurements and hence must be interpreted carefully. Further some other interesting results are given here to give more insight in the phenomena that occurred during the research.

<table>
<thead>
<tr>
<th>Disc number</th>
<th>Disc type</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD 1</td>
<td>CD-ROM</td>
<td></td>
</tr>
<tr>
<td>CD 2</td>
<td>CD-R</td>
<td></td>
</tr>
<tr>
<td>CD 3</td>
<td>CD-ROM</td>
<td></td>
</tr>
<tr>
<td>CD 4</td>
<td>CD-ROM</td>
<td></td>
</tr>
<tr>
<td>CD 5</td>
<td>CD-DA</td>
<td></td>
</tr>
<tr>
<td>CD 6</td>
<td>CD-DA</td>
<td></td>
</tr>
<tr>
<td>CD 7</td>
<td>CD-DA</td>
<td>Usher 'My way'</td>
</tr>
<tr>
<td>CD 8</td>
<td>CD-DA</td>
<td></td>
</tr>
<tr>
<td>CD 9</td>
<td>CD-R</td>
<td></td>
</tr>
</tbody>
</table>

The results obtained with CD 6 are shown below. They do not make any sense, probably due to the bad quality of the trigger signal for this disc. Hence the results of this disc are not used during the research.

Figure D.1 Inaccurate test results due to bad triggering; CD 6.
Figure D.2 Time domain results; a) and b) ensemble average track disturbance for CD 1 and CD 2, c) and d) histogram time averaged track disturbance for all revolutions for CD 1 and CD 2.

Figure D.3 Track disturbance amplitude for all revolutions; a) CD 1 and b) CD 2.
Figure D.4  Time domain results; a) and b) ensemble average track disturbance for CD 3 and CD 4, c) and d) histogram time averaged track disturbance for all revolutions for CD 3 and CD 4.

Figure D.5  Track disturbance amplitude for all revolutions; a) CD 3 and b) CD 4.
Figure D.6  Time domain results; a) and b) ensemble average track disturbance for CD 5 and CD 7, c) and d) histogram time averaged track disturbance for all revolutions for CD 5 and CD 7.

Figure D.7  Track disturbance amplitude for all revolutions; a) CD 5 and b) CD 7.
Track reconstruction test discs

Figure D.8  Time domain results; a) and b) ensemble average track disturbance for CD 8 and CD 9, c) and d) histogram time averaged track disturbance for all revolutions for CD 8 and CD 9.

Figure D.9  Track disturbance amplitude for all revolutions; a) CD 8 and b) CD 9.
Figure D.10  Contributions of harmonic orders to track disturbance spectrum; a) CD 1, b) CD 2, c) CD 3 and d) CD 4.
Figure D.11 Contributions of harmonic orders to track disturbance spectrum; a) CD 5, b) CD 7, c) CD 8 and d) CD 9.