A simulation model of focus and radial servos in Compact Disc players with Disc surface defects

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Abstract

Compact Disc players have been on the market in more than two decades. As a consequence most of the control servo problems have been solved. A large remaining problem to solve is the handling of Compact Discs with severe surface defects like scratches and fingerprints. This paper introduces a method for making the design of controllers handling surface defects easier. A simulation model of Compact Disc players playing discs with surface defect is presented. The main novel element in the model is a model of the surface defects. That model is based on data from discs with surface defects. This model is used to compare a high bandwidth and a low bandwidth controller's performance of handling surface defects.

1 Introduction

Compact Disc players (CD players) have been on the market in more than two decades. As a consequence most of the control servo problems have been solved. Two servos are focusing and radially tracking the Optical Pick-up Unit (OPU) at the information track on the CD without any problems on all discs fulfilling the specifications and most discs not doing so. However, many users have experienced problems with discs with surface defects such as scratches, finger prints etc.

The problem in handling surface defects is that the defects change the indirect focus and radial distance measurements. This means that the servos controllers react on false distance signals. It is the object of the servo controllers to keep these signals at zero, I.e. a false measurement will cause the controllers to force the OPU out of focus and radial tracking. These false measurements are in part due to the fact that defects decrease the reflection rate of the disc, the defect also introduces virtual focus and radial distances. It can cause severe problems if the servo controllers try to suppress these virtual errors. This means that handling the defects in principle requires a low bandwidth of the servo controllers. Handling disturbances such as mechanical shocks, on the other hand require a high controller bandwidth. These highly conflicting control problem is often tried to be solved by turning of the controller during defects. A new approach is presented (Vidal *et al.*, 2001*b*), where a Fault Tolerant Control approach is used.

Previously the design of the fault tolerant part of the controller has been based on trial and error on real test systems since no simulation models of the defects are available. The CD player servos consist roughly of two parts: an electro-magnetic part - the actuator, and the electro-optical part - the sensor. A large amount of work has been performed in modelling and identification of the mechanical and electro-magnetic parts of CD players. (Bouwhuis *et al.*, 1985) focus on the modelling of these parts of the system and (Vidal *et al.*, 2001*a*) describes a simple method to perform open loop system identification. Both (Yeh and Pan, 2000) and (Dettori, 2001) perform some work on the cross-couplings in the mechanical and electro-magnetic parts between focus and radial loop. Regarding the optical part of the system the present control strategies are based on simple linear models not concerning the optical-cross coupling (Bouwhuis *et al.*, 1985) and (Stan, 1998). A more detailed optical model is made in (Odgaard *et al.*, 2003*d*).

The work done in modelling of defects is limited to some studies of experimental data of the sensor signals, see (Vidal *et al.*, 2001*c*) and (Pavua *et al.*, 1999). The work in (Vidal *et al.*, 2001*c*) indicates that a good simple way to model surface defects is to model the defects as a scaling of the sensor signals as they would have been if no defects occurred. This model is also intuitive, the defect decreases the disc reflection rate. In (Odgaard *et al.*, 2003*b*) and (Odgaard *et al.*, 2003*c*) this model is described in more details. But still it does not give any informations about these scalings except they are almost equal to one in the normal situation without any defects.

In (Odgaard and Wickerhauser, 2003) some work is done on finding a good approximating basis of surface defects. It is done by finding the Karhunen-Loève basis on a set of experimental data with defects. The defects are by inspection also classified into two groups: small and large defects.

By using a Karhunen-Loève basis, based on experimental data, the defects can be approximated with a few coefficients. This can be used to simulate defects, by computing the required coefficients by random numbers with the same mean and variance as the training data did have.

In this paper the known electro-magnetic and electro-optical models are described and summarised. The simulation model is developed based on a Karhunen-Loève approximation and the mean and variance of the experimental data. In addition noises are added at the relevant places in the system. Simulations are performed in closed loop with two different controllers with and without a surface defect. The first simulated controller has high bandwidth which makes it good for handling disturbances. The second simulated controller has a lower bandwidth which makes it better for handling surface defects.

2 Model

The idea of the discrete time model is to simulate focus and radial servo loops in CD players with relevant disturbances as well as surface defects represented with models based on experimental data. The control servos job is to keep the OPU focused and radially tracked on the disc information track. The actuator used to move the OPU in focus and radial directions is a 2-axis linear electro magnetic actuator. This Electro Mechanical System (EMS) is used to set the OPUs absolute position, $\mathbf{x}[n] = \begin{bmatrix} x_{\mathrm{f}}[n] \\ x_{\mathrm{r}}[n] \end{bmatrix}$. The track position is given by the position reference $\mathbf{x}_{\mathrm{ref}}[n] = \begin{bmatrix} x_{\mathrm{ref,f}}[n] \\ x_{\mathrm{ref,r}}[n] \end{bmatrix}$, these references are due to eccentricity and skewness of the disc. These focus and radial errors are illustrated in Fig. 1. A sledge takes care of the larger radial movements, but can be disregarded. The Optical System, OS, is used to retrieve data from the disc and to generate four detector signals, $\mathbf{s}[n] = \begin{bmatrix} D_1[n], & D_2[n], & S_1[n], & S_2[n] \end{bmatrix}^T$, which are used to approximate the focus and radial errors. This approximation is done in the Signal Converter, SC. The SC computes normalised approximations of the error signals, $\mathbf{e}_{\mathrm{n}}[n]$. In (Odgaard *et al.*, 2003*b*) and (Odgaard *et al.*, 2003*a*) defects are modelled by

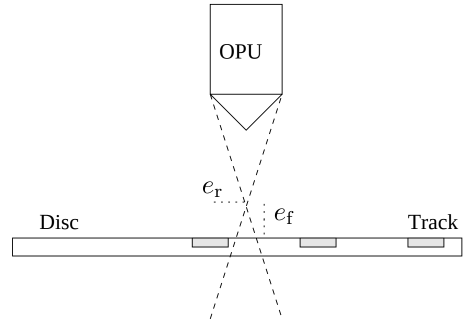

Figure 1: The focus error e_{f} is the distance from the focus point of the laser beam to the reflection layer of the disc, the radial error is the distance from the centre of the laser beam to the centre of the track. The OPU emits the laser beam towards the disc surface and computes indirect measurements of e_{f} and e_{r} based on the received reflected light. In addition the OPU generates two residuals which can be used to detect surface defects as scratches.

$$\mathbf{s}_{\mathrm{m}}[n] = \mathcal{B} \cdot \mathbf{s}[n], \tag{1}$$

where

$$\mathcal{B}[n] = \mathrm{diag}(\beta_{\mathrm{f}}[n], \beta_{\mathrm{f}}[n], \beta_{\mathrm{r}}[n], \beta_{\mathrm{r}}[n]), \tag{2}$$

and $\beta_{\mathrm{f}}[n], \beta_{\mathrm{r}}[n]$ are two defect model parameters. This defect model is the best known, but unfortunately a defect affects the detector signal in another more problematic way. Defects also introduce virtual focus and radial errors, $\mathbf{e}_{\mathrm{d}}[n]$, which are added to $\mathbf{e}[n]$. The task of the controller is to keep the OPU focus and radially tracked. It is done by feeding the EMS with control signals $\mathbf{u}[n]$ calculated from past and present values of $\mathbf{e}_{\mathrm{n}}[n]$. In order to simulate external disturbance like shocks, a disturbances, $\mathbf{d}[n]$ is added to $\mathbf{u}[n]$ before they are fed to the EMS. The overall structure of the simulation model is illustrated in Fig. 2. Each of these submodels are described in following.

2.1 Model of the Electro Mechanical system

The electro mechanical system is the actuator part of the OPU. The OPU is a 2-axis device, enabling a movement of the OPU vertically for focus correction and horizontally for radial correction of focus and radial errors. Linear electro-magnetic actuators are used for both focus and the radial corrections. The magnetic field in the actuators is controlled by focus and radial control voltages $u_{\mathrm{f}}(t)$ and $u_{\mathrm{r}}(t)$. The OPU itself can be modelled as a mass-spring-damper system, with one or two masses dependent on the required details. This results in a second or fourth order model for both focus and radial actuator dynamics, see (Stan, 1998), (Vidal *et al.*, 2001*a*) and (Bouwhuis *et al.*, 1985). In (Vidal

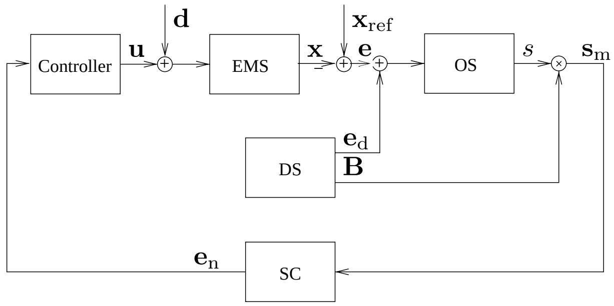

Figure 2: Illustration of the structure of the CD player simulations model. The submodels in the models are: EMS denote the Electro Mechanical system. OS is the Optical System of the OPU. DS denotes Defect Synthesiser, and simulates surface defects. SC denotes Signal Converter which computes normalised focus and radial differences which are approximations of focus and radial distances. In addition focus and radial disturbance; $\mathbf{d}[n]$, and an unknown references, $\mathbf{e}_{\mathrm{ref}}[n]$, are added to the system.

et al., 2001*a*) a system identification on the same CD player setup, as used for experimental work in this paper, is performed. The second order model found in (Vidal *et al.*, 2001*a*) will be used in this paper. Focus and radial models are of the following structure:

$$\dot{\eta}(t) = \begin{bmatrix} -a_0 & -a_1 \\ 1 & 0 \end{bmatrix} \cdot \eta(t) + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \cdot u(t), \tag{3}$$

$$e(t) = \begin{bmatrix} 0 & b \end{bmatrix} \cdot \eta(t), \tag{4}$$

where a_0, a_1, b are model parameters. The values of a_0, a_1, b are found in (Vidal *et al.*, 2001*b*).

Now it is possible to merge focus and radial models.

$$\dot{\eta}(t) = \mathbf{A}_{\mathrm{CD}} \cdot \eta(t) + \mathbf{B}_{\mathrm{CD}} \cdot \mathbf{u}(t) + \mathbf{E} \cdot d(t), \tag{5}$$

$$\begin{bmatrix} e_{\mathrm{f}}(t) \\ e_{\mathrm{r}}(t) \end{bmatrix} = \mathbf{C}_{\mathrm{CD}} \cdot \eta(t), \tag{6}$$

where

$$\mathbf{A}_{\mathrm{CD}} = \begin{bmatrix} \mathbf{A}_{\mathrm{f}} & \mathbf{0} \\ \mathbf{0} & \mathbf{A}_{\mathrm{r}} \end{bmatrix}, \tag{7}$$

$$\mathbf{B}_{\mathrm{CD}} = \begin{bmatrix} \mathbf{B}_{\mathrm{f}} & \mathbf{0} \\ \mathbf{0} & \mathbf{B}_{\mathrm{r}} \end{bmatrix}, \tag{8}$$

$$\mathbf{C}_{\mathrm{CD}} = \begin{bmatrix} \mathbf{C}_{\mathrm{f}} & \mathbf{0}, \\ \mathbf{0} & \mathbf{C}_{\mathrm{r}} \end{bmatrix}, \tag{9}$$

$$\mathbf{E} = \begin{bmatrix} \mathbf{E}_{\mathrm{r,f}} & \mathbf{0} \\ \mathbf{0} & \mathbf{E}_{\mathrm{r,r}} \end{bmatrix}, \tag{10}$$

where $\mathbf{A}_{\mathrm{f}}, \mathbf{B}_{\mathrm{f}}, \mathbf{C}_{\mathrm{f}}$ are the model matrices in the focus model, and $\mathbf{A}_{\mathrm{r}}, \mathbf{B}_{\mathrm{r}}, \mathbf{C}_{\mathrm{r}}$ are the model matrices in the radial model. Since this submodel is in continuous time it has to be discretised before any further use. This is done by the use of a zero-order-hold method.

2.2 Optical model

One of the most important things, in making a CD player work, is to focus the laser beam at the information track. The CD player used in this work has its detector system implemented as a hologram, but works as a three beam single Foucault detector system. The main beam is used both to retrieve the information saved on the disc, and to focus the beam at the disc reflection layer. Two additional beams are used to keep the main beam radially tracked. The information in the track is stored by using two different levels, called pit and land, (the land has the same level as the area outside the track). The level difference is a quarter of the wave-length of the laser beam in the material. I.e. when the light is reflected, the light reflected from a pit interferes destructively with the light reflected from a land, see (Bouwhuis *et al.*, 1985) and (Pohlmann, 1992). These pits and lands are also important in the task of modelling the optics of the system.

2.2.1 The focus and radial optical models:

This optical model is expressed by the mappings, described in (11-14).

$$f_1 : \; (e_{\mathrm{f}}[n], e_{\mathrm{r}}[n]) \to D_1[n], \tag{11}$$

$$f_2 : \; (e_{\mathrm{f}}[n], e_{\mathrm{r}}[n]) \to D_2[n], \tag{12}$$

$$f_3 : \; (e_{\mathrm{f}}[n], e_{\mathrm{r}}[n]) \to S_1[n], \tag{13}$$

$$f_4 : \; (e_{\mathrm{f}}[n], e_{\mathrm{r}}[n]) \to S_2[n]. \tag{14}$$

In (Odgaard *et al.*, 2003*d*) these mappings are approximated by the following separated from:

$$f_i(e_{\mathrm{f}}, e_{\mathrm{r}}) \approx h_i(e_{\mathrm{f}}) \cdot g_i(e_{\mathrm{r}}), \tag{15}$$

where

$$i \in \{1, 2, 3, 4\}. \tag{16}$$

The eight functions involved in (15) are given in (Odgaard *et al.*, 2003*d*) where a cubic spline approximation is also given for computational reasons. This spline approximation is used in this work.

2.3 Defect model

In (Odgaard *et al.*, 2003*a*), (Odgaard *et al.*, 2003*b*) and (Odgaard *et al.*, 2003*c*) the measured detector signals are modelled by the use of the optical model and a fault model. This fault model is based on experimental work and the observation that a surface defect decreases the reflection rate of the disc. This leads to the following defect model:

$$\mathbf{s}_{\mathrm{m}}[n] = \mathcal{B}[n] \cdot \mathbf{s}[n] = \mathcal{B}[n] \cdot \mathbf{f}\left(\mathbf{e}[n]\right), \tag{17}$$

$\mathbf{s}[n]$ is the output of the optical model and takes the values which the detectors would have had if no defect had occurred. $\mathcal{B}[n]$ is a 4×4 matrix with two scaling parameters in the diagonal, one parameter for scaling the focus detector signals and one parameter for scaling the radial detector signals. $\mathbf{f}(\mathbf{e}[n])$ is the optical model represented by a mapping. In (Odgaard *et al.*, 2003*a*) the inverse problem of the defect model is solved, meaning that $\mathbf{s}_{\mathrm{m}}[n]$ can be parameterised with two defect parameters and two distance parameters. Unfortunately a defect also influences $e_{\mathrm{f}}[n]$ and $e_{\mathrm{r}}[n]$ during the occurrence of the defect. A simple explanation for this fact is the following. In commercial CD players focus and radial distances are approximated by: $e_{\mathrm{f}} = D_1[n] - D_2[n]$, $e_{\mathrm{r}} = S_1[n] - S_2[n]$. For focus and radial distances in the normal control range this approximation is good. These differences are dependent the reflection rate of the disc, in way that the reflection rate is scaling the four detector signals. This means that a change in reflection rate will also effects approximated focus and radial errors. In order to compensate for this the difference is normalised. The normalisation also removes the detector scaling effect due to the defect. Given $D_1[n]$, $D_2[n]$ it is easy to see that normalised difference removes $\mathcal{B}[n]$ from the measurement:

$$\frac{\beta_{\mathrm{f}}[n] \cdot D_1[n] - \beta_{\mathrm{f}}[n] \cdot D_2[n]}{\beta_{\mathrm{f}}[n] \cdot D_1[n] + \beta_{\mathrm{f}}[n] \cdot D_2[n]} = \frac{D_1[n] - D_2[n]}{D_1[n] + D_2[n]} \qquad (18)$$

This means that a surface defect changes the detector signals in another way. This can partly be explained in the way that the defect introduces virtual focus and radial distances, meaning that during a defect, focus and radial distances consist of two parts: the real distances and the virtual distances due to the defect. A more detailed defect model can now be constructed by the use of (17)

$$\mathbf{s}_{\mathrm{m}}[n] = \mathcal{B}[n]\mathbf{f}\left(\mathbf{e}[n] + \mathbf{e}_{\mathrm{d}}[n]\right). \qquad (19)$$

2.4 Defect synthesiser

The defects are now parameterised. The next step is to synthesise the values of these parameters during a defect. One approach would be to take measured data, from a real CD player playing a CD with a surface defect, and use these measured data in the simulation representing a surface defect. This approach has a severe drawback, since it limits the number of possible defects in simulation to those measured. In this paper another approach is presented, which is based on Karhunen Loève approximations of the defects.

Blocks of 256 samples are extracted from experimental data, where each block contains at least one defect. The experimental data represent fingerprints, short and long scratches etc. In (Odgaard *et al.*, 2003*a*) the experimental setup used to measure the data is described. By inspection the experimental data is separated into three groups in (Odgaard and Wickerhauser, 2003): short and long scratches and disturbance like defects. The next step in this approach is to compute the best

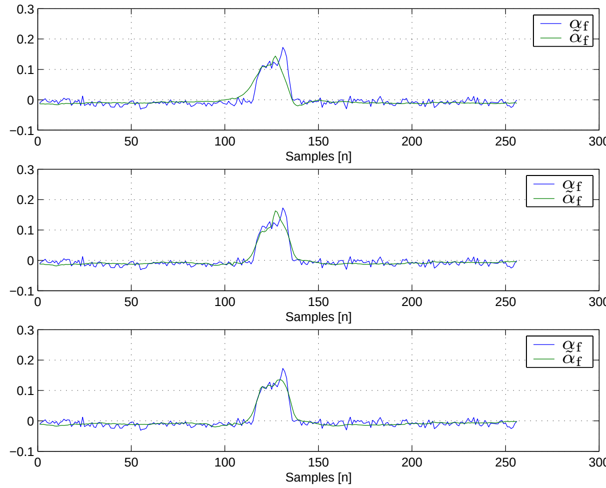

Figure 3: Illustration of the Karhunen-Loève approximation of α_{f} which contain a typical scratch. The approximation is denoted with $\tilde{\alpha}_{\mathrm{f}}$. The first approximation is based on the most approximating coefficient, the second approximation is based on the five most approximating coefficients, and the third approximation on the seven most approximating coefficient.

approximating basis of this set of data - the Karhunen Loève basis, see (Mallat, 1999). The approximating potentials is illustrated in Fig. 3. This illustrates a scratch approximated with the most approximating coefficient, the five most approximating and the seven most approximating coefficients. Note approximation with only one coefficients is a good approximation of the scratch.

Denote a matrix, where the column vectors are blocks of zero mean data, $\spadesuit$. The Karhunen Loève basis, $\clubsuit$, of $\spadesuit$ is the set of eigenvectors of the autocorrelation of $\spadesuit$:

$$\clubsuit = \{\text{eigenvectors}\left(\spadesuit\spadesuit^T\right)\}. \qquad (20)$$

The Karhunen Loève (KL) basis of all the measured β_{f} is denoted $\clubsuit_{\beta_{\mathrm{f}}}$, $\clubsuit_{\beta_{\mathrm{r}}}$ denotes the KL basis of measured β_{r}. $\clubsuit_{e_{\mathrm{d,f}}}$, $\clubsuit_{e_{\mathrm{d,r}}}$ denote the KL basis of measured $e_{\mathrm{d,f}}$ and $e_{\mathrm{d,r}}$.

Assume that the measured defects consist of a signal part and a noise part. Using the KL basis the signal part can be approximated with a few coordinates in that basis, (the first k coefficients). The remaining noise part could be approximated with the remaining $n-k$ coefficients. Next compute the mean m_i and variance σ_i of each coordinate. Assuming that each KL coordinate can be simulated as independently distributed normal random variables with σ_i and m_i, where these statistics are found based on the KL coordinates. The signal part can then be synthesised as:

$$\diamondsuit = \sum_{i=1}^{k} \heartsuit_i \mathbf{c}_{k,i}, \tag{21}$$

and the noise as

$$\diamondsuit_{\mathrm{n}} = \sum_{i=k+1}^{n} \heartsuit_i \mathbf{c}_{k,i}, \tag{22}$$

where

$$\heartsuit \in \{\clubsuit_{\beta_{\mathrm{f}}}, \clubsuit_{\beta_{\mathrm{r}}}, \clubsuit_{e_{\mathrm{d,f}}}, \clubsuit_{e_{\mathrm{d,r}}}\}, \tag{23}$$
$$\mathbf{c}_{k,i} \in \mathcal{N}_i(m_i, \sigma_i), \tag{24}$$

and $\diamondsuit$ denote the synthesised $\beta_{\mathrm{f}}, \beta_{\mathrm{r}}, e_{\mathrm{d,f}}, e_{\mathrm{d,r}}$, and $\diamondsuit_{\mathrm{n}}$ the noise part of these. Since $k << n$ the signal synthesis is cheap in computations, but the noise part is expensive. Instead the noise signal can be computed as

$$\diamondsuit_{\mathrm{n}} = \begin{bmatrix} y_1 \\ \vdots \\ y_i \\ \vdots \\ y_n), \end{bmatrix} \tag{25}$$

where $y_i \in \mathcal{N}(0, \frac{\sigma}{\sqrt{n}})$, σ is equal $\sqrt{\sigma_{k+1}^2 \cdots \sigma_n^2}$. The coordinates in the noise vector are independent, identically distributed normal random variables, since

1 Lemma
If T:$\mathcal{R}^n \rightarrow \mathcal{R}^n$ is orthonormal and y is defined in (25), then the coordinates of Ty are independent, identically distributed normal random variables signal with same mean and variance.

It is now possible to synthesise a defect. The statistics used for the defect construction is based on all defects in a defect group. But a defect does not vary much from one encounter to the next encounter. This is illustrated in Fig. 4, where $\beta_{\mathrm{f}}[n]$ of a small scratch from a number of revolutions is illustrated.

The fact that a defect do not vary much from an encounter to the next encounter has to be taking into account when the next defect encounter is simulated. σ_i are computed as the mean of variance of coefficients of encounter of defects. The mean used in the construction is the simulated coefficient value from the last defect encounter.

This defect synthesiser constructs the defects in blocks meaning that it is required to compute a long block of defect parameters before the simulation of the CD player, and then during the simulation use these computed values.

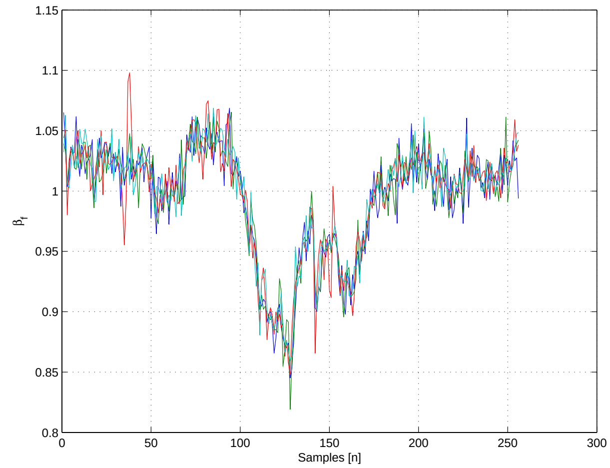

Figure 4: $\beta_{\mathrm{f}}[n]$ of a small scratch from a number encounters of the same defect. Notice the small variation from encounter to encounter.

2.5 Disturbances and references

The CD player's unknown reference is mainly due to eccentricity and skewness. It is computed as a sine with the period being the rotation period of the given rotation. These periods increase with one sample each third rotation, due to the linearly increased rotation length measured in number of samples. The amplitude of the reference can be freely chosen, (with the player requirements stated in (Stan, 1998)), and in this simulation both are chosen to be 30 μm. The disturbances are white noise added to the control signals, where the variance 0.01 is chosen based on experience.

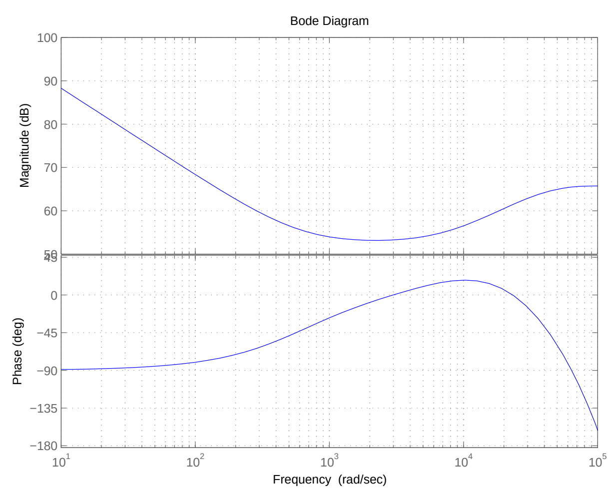

Figure 5: Bode plot of a typical focus controller.

2.6 Signal converter

The Signal Converter is described in Section 2.3, where it is described that focus and radial distances are approximated by the use of the normalised difference between D_1 and D_2 for focus and S_1 and S_2 for radial, see (18).

2.7 Controller

The intended use of this model is to simulate performance of designed controllers before implementing them on a real system. It is as a consequence possible to try any controller on the simulation model as long as they have $\mathbf{u}[n]$ as output. In the simulation in this paper two simple PID- controller are used. The first one is the typical PID controller described in (Stan, 1998) with a gain adapted to the given CD players optical gains, see Fig. 5. The second one has a lower bandwidth in order to handle surface defects better. A bode plot of the focus controller is shown in Fig. 6. This

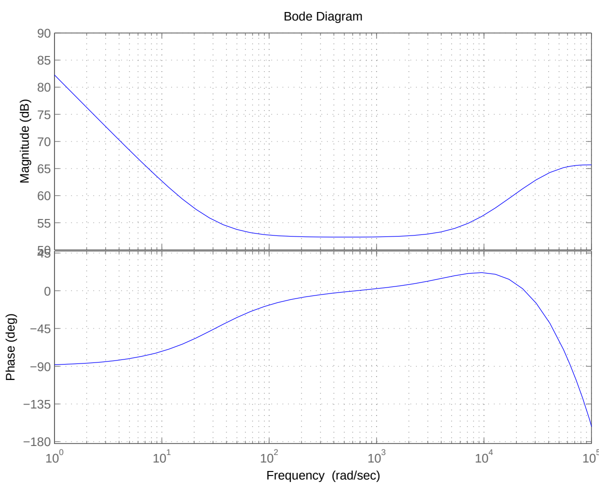

Figure 6: Bode plot of a focus controller with lower bandwidth.

simulation model gives a method to validate controller performance regarding handling of defects.

2 DEFINITION *Define* $\mathbf{e}[n]$ *in the defect free case as* $\mathbf{e}_1$ *and in the case of a defect as* $\mathbf{e}_2$. *Then the defect handling performance,* $\mathcal{DP}$, *can be defined as:*

$$\mathcal{DP} = \left\|\mathbf{e}_1 - \mathbf{e}_2\right\|_2 \tag{26}$$

3 Simulations

The simulations are performed in closed loop, where the two simulated controllers control the CD player model, with the objective to suppress the disturbances and the unknown reference. The first simulation of the two controllers are simulations without any surface defects. The normal PID controller simulation can be seen in Fig. 7. The low band width controller simulation can be seen in Fig. 7. It can be seen that the used controllers do not suppress the unknown reference totally, the original reference signal has a amplitude on 30 μm. However, the normal controller with the highest bandwidth handles the disturbance best, which one would also assume.

The upper subfigures in Fig. 7, the defect free simulation, is important in order to validate the given controllers capability to handle a defect, since any differences from the upper subfigures in Fig. 7 are due to the defect, and not the controllers ability to suppress disturbances. These signals are as consequence used in Def. 2 where these errors are denoted $\mathbf{e}_1$.

The controllers react to a sum of the real distances and the virtual ones. To illustrate how the controller forces the system out of focus and radial tracking during a defect, the simulated real distances are illustrated and not the distances used for controlling the system, since they contain the virtual part too. The simulation output of the normal PID controller can be seen in lower part of Fig. 7. From this figure it is clear that the defect handling by the controller causes problems. A zoom on the first defect in $e_{\mathrm{f}}[n]$ in Fig. 7 is shown in Fig. 8. The second subfigure in Fig. 8, is a zoom on the defect, $e_{\mathrm{d,f}}[n]$. This means that the controller reacts on the focus error component due to the defect, $e_{\mathrm{d,f}}[n]$, which is undesired. The controller with a lower bandwidth is illustrated in Fig. 7. This figures shows that the low bandwidth controller handles the defect better than the normal one.

The two controllers can be compared by using Def. 2, the computed indexes can be seen in Table 3, in addition the nominal performances, $\mathcal{NP}$, are also computed defined as:

$$\mathcal{NP} = \left\|\mathbf{e}_1\right\|_2 \tag{27}$$

The two-norm of the error signal can be use to compare the nominal performance of the two controllers since the same reference, disturbances and defects are applied to them in the simulations. The performance index consists of two elements the first is the focus index and the second element is the radial index. Based on these results it can be seen that the nominal controller is better for handling disturbances, but on the other hand the low bandwidth PID controller is better for handling the surface defects. This supports the known controller specification conflict between handling defects and disturbances. One should notice that the simulated defect in this situation is a small defect, which controllers normally survives, but in a non-optimal way. Handling larger defects cause larger problems for the controller, meaning that a fault tolerant approach is relevant in order not to react to surface defects, where surface defects are viewed as being sensor faults. The use of this simulation model has a potential to make the design of controllers handling surface defect faster, since the use of simulations can eliminate

	Normal PID Controller	Low bandwidth Controller
$\mathcal{DP}$	$\begin{bmatrix} 3.9863 \cdot 10^{-6} \\ 5.3710 \cdot 10^{-8} \end{bmatrix}$	$\begin{bmatrix} 2.9456 \cdot 10^{-6} \\ 3.6612 \cdot 10^{-8} \end{bmatrix}$
$\mathcal{NP}$	$\begin{bmatrix} 2.3808 \\ 1.7404 \end{bmatrix}$	$\begin{bmatrix} 5.6806 \\ 7.8883 \end{bmatrix}$

Table 1: Table of the defect handling performance $\mathcal{DP}$ and the nominal performance $\mathcal{NP}$, for both the normal PID controller and the low bandwidth PID controller. The performance indexes are vectors with the first element being the focus index and the second the radial index.

some of the practical experiments in the controller design process. The simulations are implemented in Matlab. The used Matlab and data files can be seen at (Odgaard *et al.*, 2003*e*).

4 Conclusions

In this paper a closed loop simulation model of a CD player playing a CD with surface defects is presented. The use of this simulation model has a potential to make the design of controllers handling surface defects faster, since the use of simulations can eliminate some of the practical experiments. The simulations show that a typical CD player focus and radial servo react on the defect in a non-desired way. In addition a controller with a lower bandwidth is simulated. A performance index of the controllers handling defect is also defined and used to compare the two simulated controllers. This comprising validates a known fact that handling disturbances in CD players requires a high bandwidth and handling surface defects on CDs requires a low bandwidth.

5 Acknowledgement

The authors acknowledge the Danish Technical Research Council, for support to the research programme WAVES (Wavelets in Audio Visual Electronic Systems), grant no. 56-00-0143. The authors give their thanks to Department of Mathematics, Washington University for hosting the first author during some of the research for this paper.

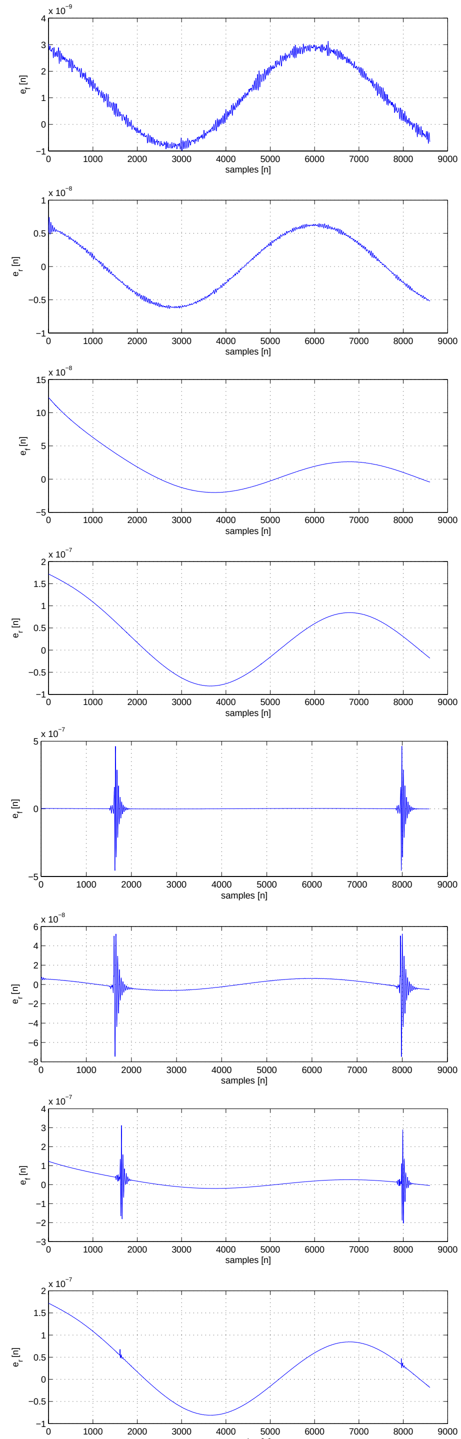

Figure 7: The upper two plots is system simulation of the normal PID controller without a surface defect. The first plot is of $e_{\mathrm{f}}[n]$ and the second one is of $e_{\mathrm{r}}[n]$. The lower two plots is system simulation of the low bandwidth controller without a surface defect. The third plot is of $e_{\mathrm{f}}[n]$ and the fourth one is of $e_{\mathrm{r}}[n]$. The fifth and sixth plots is system simulation of the normal PID controller with a group 1 surface defect. The 5th plot is of $e_{\mathrm{f}}[n]$ and the 6th one is of $e_{\mathrm{r}}[n]$. The 7th and 8th plots is system simulation of the low bandwidth controller with a group 1 surface defect. The 7th plot is of $e_{\mathrm{f}}[n]$ and the 8th one is of $e_{\mathrm{r}}[n]$

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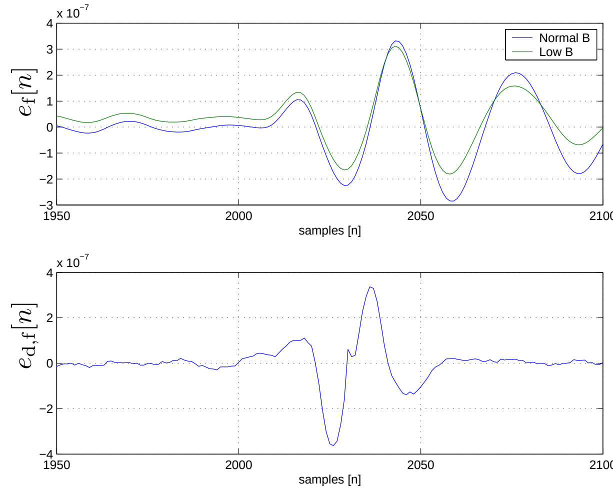

Figure 8: The upper plot is a zoom on the first defect in $e_{\mathrm{f}}[n]$ in Fig. 7, for both controllers. Notice the low bandwidth controller reacts less on the defect. The lower plot is of $e_{\mathrm{d,f}}[n]$, for the same defect. $e_{\mathrm{f}}[n]$ is strongly correlated to $e_{\mathrm{d,f}}[n]$ this means that the controller react on the virtual error signal. I.e. the controller handle this defect in an undesirable way.