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The modeling and control of the sledge system in the BEOSOUND 3000

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Abstract

In this report, a model has been developed for a part of a CDM-12 Industrial module used in the B&O BeoSound system, namely the sledge and radial system. The influence of movements of the sledge on the radial error signal has been investigated and a simulation has been done with the nowadays used control strategy. This strategy is based on pulsing the DC-motor that is driving the sledge until it starts to move. This leads to a very non-smooth movement of the sledge and also there is a possibility that the radial actuator will saturate which leads to big errors.

To generate a more smooth movement of the sledge, a controller has been designed, consisting of a PD controller and a feed forward part, that makes the position of the sledge follow a reference. Unfortunately, the position of the sledge is not measured and therefore this signal cannot be used as feedback. The sledge system is used in the first place to keep the radial control signal from saturating so a natural choice for a feedback signal is this radial control signal. Another PD controller with feed forward is designed which tracks a 'reference radial control signal' when this is needed. Since there is backlash and stiction present in this system, there are some restrictions on the bandwidth of this controller. Because of the stiction, the biggest disturbance on the radial system is generated when the sledge starts to move. To decrease this error, another radial controller can be used which has a higher bandwidth. This gain scheduling approach has also been added to the total system and simulations are done.
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1. Introduction

1.1 Background
In the design of optical storage, playability and low manufacturing costs play an important role. Unfortunately, these two are each other's opposites. In order to guarantee good playability, good controllers and precise mechanisms should be implemented. In the Beosound 3000 system designed by Bang & Olufson, a sledge system is present which makes sure that the radial controller operates in its linear range. This sledge should move as the radial actuator almost saturates. Nowadays, the sledge is steered by giving electric pulses, however, the disturbance caused by this movement on the radial loop is not known. Because of the fact that in the sledge system friction, stiction and backlash are present and measurements of the position of this sledge are not available due to production costs, a continuous controller has not successfully been designed.

1.2 Goal
The goal of this report is to make a model of the sledge system and the radial controller and to determine the influence of the movement of the sledge on the radial loop. This should first be done for the nowadays used control strategy based on pulses and after that an effort should be made to design a controller which moves the sledge more continuous and as few times as possible. This can be done by letting the sledge follow a smooth reference which brings the radial controller from one end of its range to the other.

1.3 The system
The system used is a CD-player manufactured by Bang & Olufsen, the BeoSound system and specific the CDM 12 Industrial module. In chapter two the general CD-player system is described.

1.4 Problem description
In order to generate a model of the total system, the various subsystems have to be identified and modeled. A model has to be made for the DC-motor, gear mechanism, sledge mass with friction and the radial actuator (lens connected with a coil). A S-function has to be written which simulates the pulse steered control signal and a smooth continuous controller has to be designed. Position measurements of the sledge are not available so another signal has to be used for feedback.

1.5 Outline of the report
At first, something will be said of the CD-player mechanism itself. Chapter three covers the modeling of the radial actuator and sledge system including the DC-motor and the gear mechanism. In the next chapter a radial controller is designed and the nowadays used pulse steered sledge controller is implemented. After this, in chapter five, a continuous controller is designed together with a gain scheduled radial controller. Finally, conclusions and recommendations are presented in the sixth chapter.
2. System description

This section contains a description of the CD and the optical system together with a description of the actuators and sensors which constitute the CD-player system.

2.1 Structure of the compact disc

A CD is a medium on which data is stored in digital form. Analogue music is sampled and recorded and encoded on the CD using Pulse Code Modulation (PCM). For successful storage some additional data is added such as error correction, synchronization and modulation. The storage area of the disc extends from the inner to the outer perimeter and the dimensions can be seen in figure 2.1.

![Figure 2.1: Structure of the CD](image)

The inner and outer part of the disc are used for storage of the lead-in and lead-out data. The stored data is represented on a spiral formed track, which consists of pits and flats. The laser sees these pits as bumps on the disc surface while a flat levels with the rest of the surface. The pits have different lengths (0.833 – 3.054 μm) and they represent the PCM data which can be read by a laser. The dimensions of the data track layout can be seen in figure 2.2.

![Figure 2.2: Dimensions of pits and track](image)
When the data is read from the disc the laser passes through a transparent layer that is approximately 1.2 mm thick. The effect of this layer is that the laser beam is narrowed down from the disc surface to the signal surface from 0.8 mm to 1.7 μm (see figure 2.3).

![Figure 2.3: Laser beam focusing](image)

The advantage of this effect is that a scratch or other disc irregularities on the surface of the disc are only a fraction of their original size at the signal layer.

The laser used to read the data from the disc has a wavelength of 780 nm in air and 500 nm in the CD causing the angle of refraction between the air and the disc. The height of a pit is one fourth of the wavelength, so the light hitting a pit travels one half of a wavelength shorter than the light that hits a flat (see figure 2.4). This creates a phase difference between the light reflected from the pit and the flat which results in destructive interference. A pit reflects about 25% of the original intensity and a flat about 90%. This change in light intensity makes the CD-player able to distinguish between pits and flats and in this way to read the data.

![Figure 2.4: Reflection of the laser on a pit and a flat](image)

2.2 The optical system

The optical pickup system in the Philips CDM-121 drive mechanism uses the 3-beam system. It consists of a main beam, which is used for focussing and reading the data and two satellite beams which are used for tracking of the radial position. Figure 2.5 gives a schematic overview of this optical pickup system:
At first the laser beam is generated by the laser diode. Then the following happens:

- The beam passes through a light diffraction that generates the two satellite beams.
- The beams hit a polarization prism where only the vertical light passes.
- The beams are converted to parallel beams by the collision lens.
- The beams are turned 45° by a one fourth wavelength.
- The beams are reflected by the disc and send back through the wave sheet, which results in another turning of 45° so that the beams are converted to horizontal outgoing beams.
- The beams hit the polarized prism again and are reflected to the photodiodes on the pickup.
- The main beam is reflected to diode $D_{D1}$, $D_{D2}$ and $D_{D3}$. The two satellite beams are reflected on diodes $D_{S1}$ and $D_{S2}$ (see figure 2.6)

Figure 2.6 shows the arrangement of the photodiodes used in the optical pickup system.

With this setup the diodes can be used to generate the focus and radial errors as explained in the next section.
2.3  Focus and radial sensors

In the 3-beam optical pickup system the mainbeam detector diode is used for the generation of the focus error signal and the satellite diodes (side beam detectors) are used to generate the radial error signal.

As the distance between the objective lens and the disc reflective surface varies, the focal point of the optical system also changes and the image projected by the cylindrical lens changes its sharpness. This image projected on the mainbeam diode generates three currents were the diodes $D_{D1}$ and $D_{D2}$ are compared to determine whether or not the optical pickup is in focus while $D_{D3}$ is used to read the data on the spiral track. Three cases can be distinguished which are showed in figure 2.7.

In the first figure the focusing is optimal and the currents generated by $D_{D1}$ and $D_{D2}$ are equal and the focus error signal $e_f = D_{D1} - D_{D2}$ is zero. If the focus point is too close to the disc, more light falls on $D_{D1}$ than on $D_{D2}$ so the focus error signal is positive and when the focus point is too far away, this error signal is negative. This information can be used as input to a controller that keeps the optical pickup always in focus.

To detect if whether or not the optical pick is on track, the two satellite diodes $D_{S1}$ and $D_{S2}$ are used. For this system also three cases can be distinguished which are showed in figure 2.8.

In the first figure the focusing is optimal and the currents generated by $D_{D1}$ and $D_{D2}$ are equal and the focus error signal $e_f = D_{D1} - D_{D2}$ is zero. If the focus point is too close to the disc, more light falls on $D_{D1}$ than on $D_{D2}$ so the focus error signal is positive and when the focus point is too far away, this error signal is negative. This information can be used as input to a controller that keeps the optical pickup always in focus.
In case (a) the main beam is located too far to the left while in case (b) the main beam is located too far to the right. As the three spots drift to either side of the pit track, the amount of light reflected by the three beams that encounter more pit area is reduced while the light intensity reflected by the beams that encounter less pit area, is increased. The relative output from the two satellite diodes provides a tracking error signal, 
\[ e_r = D_{s1} - D_{s2} \]. When the situation is as depicted in figure (c), the two satellite diodes receive the same amount of light and the radial error signal is zero. Since the tracking beam is aligned to different areas of the disc, the signal of the leading beam is delayed 30 μs in order to compare the light intensity on basis of the same pit. The same situation can occur when the main beam is between two tracks. In order to distinguish between this case and the case where the main beam is on track, the error signal is divided by the sum of the two satellite diode signals, 
\[ e_r = \frac{D_{s1} - D_{s2}}{D_{s1} + D_{s2}} \]. When the main beam is between two tracks, the sum signal of \( D_{s1} \) and \( D_{s2} \) is larger than when the main beam is on track so by the use of this factor the two situations can be separated.

2.4 The servo mechanism in the CD-player

To make sure that the laser is always focused on the right track several servomechanisms are necessary. The CD-player uses four actuators to maintain the accurate data readout:

- **Disc motor servo:**
  The data from the disc must be read at a constant rate to feed the digital signal processing circuit with data. Without control of the disc motor speed, the speed with which the data bits would arrive would depend on the position of the laser pickup. The disc motor is constantly adjusted so the pickup reads the data with constant velocity to keep the data buffer always half full. This means that the motor speed must vary between 1.2 and 1.4 m/s.

- **Tracking servo mechanism:**
  In order to ensure accurate tracking of the laser beam along the 0.5 μm track, a tracking servo is necessary. The servo must be able to cope with disc eccentricity, fingerprints on the CD, scratches, vibrations of the player, etc. The track may have a maximum side-to-side swing of ±0.6 mm which is equivalent to 750 tracks. For this reason the radial actuator must be able to compensate and move at high speeds with an accuracy of ±0.1 mm. This is done by the use of an electro motor that consists of a combination of coils and permanent magnets (figure 2.9).

- **Focus Servo mechanism:**
  Since no disc is perfectly flat, the specifications allow for a vertical deflection ± 600 μm. The laser beam must stay focussed within a ±2 μm tolerance, otherwise the phase interference between the direct and the reflected light is lost along with the audio data and the tracking information. It is evident that a servo system is necessary to give correct focus of the optical pickup. This is also done by the use of an electro motor (figure 2.9).

- **Sledge servo mechanism:**
  Since the radial actuator has to move along the complete disc, just an electro motor does not have enough range. To make sure that the complete disc can be read, an extra actuator is necessary: the sledge servo mechanism. This is a system which
consists of a DC motor, a worm gear and a reduction gear assembly. In the sledge the radial and focussing actuator are mounted. Because such a system exhibits backlash and friction, it is difficult to obtain a smooth and high-speed movement. Therefore this actuator is only used for slow and large corrections in the horizontal direction.

\[\text{figure 2.9: Actuator for radial positioning and focussing}\]

In order to compare control strategies for the sledge controller a model must be made from the influence of the sledge movement on the radial actuator from the optical pickup unit. In the next chapter this model will be derived.
3. Modelling of radial and sledge system

The radial actuator is connected to the sledge by means of plastic arms so the influence of the movement of the sledge is regarded as a disturbance on the radial actuator. Therefore, models of both the radial actuator and the sledge system have to be derived. In the next section a model of the radial actuator will be presented.

3.1 Model of radial actuator:
In order to describe the influence of the sledge system on the radial loop, a model of this radial loop should be derived. The radial actuator consists of a coil and a permanent magnet; it can be regarded as an energy converter, which converts electrical current to mechanical motion. The actuator consists in this way of an electrical and a mechanical part.

3.1.1 Electrical part of radial actuator
The electrical part consists of a current-carrying coil which interacts with a permanent magnet to create a force field which results in movement of the optical pickup. The electrical diagram of the actuator is shown in figure 3.1.

\[ \text{Figure 3.1: Electrical diagram of radial actuator} \]

In this diagram, \( L \) is the inductance of the coil, \( R \) is the resistance of the coil and \( r_m \) is a shunt for current measurement. The AC-sensitivity is represented by \( Bl \) according to Faraday's law:

\[ \text{emf} = -\frac{d\Phi_B}{dt} = -Bl\frac{dx}{dt} \]  \hspace{1cm} (3.1)

and \( x \) is the displacement of the lens. Now Kirchhoff's law can be applied:

\[ u(t) = (R + r_m)i(t) + Bl\frac{dx}{dt}x + L\frac{di}{dt}i(t) \]  \hspace{1cm} (3.2)

To determine whether or not the inductance is important in the actuator, the break frequency of the low-pass filter, formed by the two resistances and the inductance, can be computed:

\[ \frac{I(s)}{U(s)} = \frac{1}{R + r_m + Ls} = \frac{1}{\frac{R}{L} + \frac{r_m}{L} + s} \]  \hspace{1cm} (3.3)

In the data sheet from B&O the values can be found (appendix A.1). The break frequency is computed to be:
\[ f_{\text{break}} = \frac{R + r_m}{2\pi L} \frac{18 + 1}{2\pi 165 \cdot 10^{-6}} = 18.3 \text{ kHz} \]  

(3.4)

Since the frequency range of the total system is only 0-2 kHz, the inductance can be neglected. When a voltage \( u \) is applied to the coil a current \( i \) will flow through it and due to the magnetic field from the magnet a force \( f_{el} \) proportional to the current will be generated according to Laplace’s law:

\[ dF = Idl \times B \]  

(3.5)

Using this equation with equation 3.2, the next expression for the electrical force can be derived:

\[ f_{el}(t) = Bl \cdot i(t) = \frac{Bl \cdot u - (Bl)^2 \cdot \frac{dx}{dt}}{R + r_m} \]  

(3.6)

### 3.1.2 Mechanical part of radial actuator

Now the mechanical part of the actuator has to be modeled. The optical pickup unit is placed in the sledge by four lever arms which hold the pickup in the middle of the operating range. This system can be divided into two parts, a mass from the lens and a mass from the levers, see figure 3.2.

This approach leads to a fourth order model of the actuator but since it is obvious from the bode diagram supplied by B&O that the dominating dynamics can be described by a second order transfer function, the actuator will be regarded as one mass which is attached to the sledge. Since the mass of the sledge is approximately 14 gram and the mass of the optical pickup is only 0.56 gram the influence from the pickup on the sledge is neglected. In this case the sledge can be regarded as a wall with a certain movement and the following schematic representation of the system can be made:
The following equations of motion can now be derived:

\[ m\ddot{x} = f_{ci} - k(x - v) - c(\dot{x} - \dot{v}) \]  

If equations 3.6 and 3.7 are combined the next equation is formed:

\[ m\ddot{x} = \frac{Bl \cdot u}{R + r_m} - \frac{(Bl)^2}{R + r_m} \dot{x} - kx - cx + kv + cv \]  

(3.8)

The states are chosen to be \( x = [x \hspace{1em} \dot{x}]^T \), the disturbance is chosen to be \( v = [v \hspace{1em} \dot{v}]^T \) and the input to this system is \( u \). With these variables a state space representation of the second order system can be formed:

\[
\dot{x} = \begin{bmatrix}
0 & \frac{1}{m(R + r_m)} \\
\frac{k}{m} & c + \frac{(Bl)^2}{m(R + r_m)}
\end{bmatrix} x + \begin{bmatrix}
0 \\
\frac{Bl}{m(R + r_m)}
\end{bmatrix} u + \begin{bmatrix}
0 & 0 \\
\frac{k}{m} & c
\end{bmatrix} v
\]

(3.9)

\[ y = [1 \hspace{1em} 0] x \]

Most of the variables can be found in the datasheet of B&O, the spring and damper constant are the only unknown variables. They can be found by fitting the parameters to a measured bode plot of the system. In [1] this has been done. All values can be found in appendix A.1.

The bode diagram of this system is depicted in figure 3.4:

\textit{figure 3.4: Bode diagram of radial actuator}
3.2 Model of sledge system
The sledge system consists basically of three parts:
- DC-motor
- Gear mechanism
- Moving mass in which the optical pickup is mounted: the sledge itself
In the next sections all these parts will be modeled.

3.2.1 DC-motor
The DC-motor consists of an electrical part and a mechanical part, see figure 3.5. In the next subsections these parts are described.

3.2.1.1 Electrical part:
The electrical part of the motor consists of the voltage source \( V \), a resistor \( R \), an inductance \( I \) and a back (induced) electromotive force (emf) generated by the turning of the motor. The torque delivered by the motor is proportional (with the armature constant \( k_m \)) to the current that flows through the circuit.

\[
emf = k_{emf} \theta ; \text{ so } \frac{di}{dt} = -\frac{R}{L} i(t) - \frac{k_{emf}}{L} \theta + \frac{1}{L} V
\]

and:
\[
T = k_m i
\]

For this system the next equations hold:

\[
V - emf = L \frac{di}{dt} + Ri,
\]

The used values lead to a time constant of \( 1.6 \times 10^{-3} \) second. This is equal to 637 Hz and this is beyond the bandwidth of the sledge system. However, the absence of the induction leads to an algebraic loop when the model has to be solved so it will be used in the model.
3.2.1.2 Mechanical part
In the mechanical part friction is present so three cases have to be distinguished, namely the case when there is movement, the case when there is no movement and the driving torque is less than the static friction and finally the case where there is no movement but the driving torque is bigger than the static friction. Now the mechanical part can be described by the following equation:

\[
\vartheta = \begin{cases} 
\frac{1}{J_m} (T - T_r - b \vartheta - T_{cm} \text{sign}(\vartheta)) & \text{if } v \neq 0 \\
0 & \text{if } v = 0 \text{ and } (T - T_r) < T_{cm} \\
\frac{1}{J_m} (T - T_r - T_{cm} \text{sign}(\vartheta)) & \text{if } v = 0 \text{ and } (T - T_r) > T_{cm}
\end{cases}
\] (3.13)

Here \(J_m\) is the moment of inertia of the motor, \(k_m\) the armature constant of the motor (equal to \(k_{em}\)), \(b\) the motor damping coefficient, \(T\) the torque reduced from the load and \(T_{cm}\) the motor starting torque.

Equations (3.10) and (3.12) together describe the behavior of the motor.

3.3 Gear transmission
A known feature in the sledge system is backlash. In order to describe this phenomenon the gear mechanism should be treated as a separate part of the model. This part should make the connection between the DC-motor and the sledge itself. The gear mechanism consists of a worm wheel (1), two cogwheels (2 & 3) and a toothed bar (4), see figure 3.6.

![Gear mechanism of sledge](image)

Figure 3.6: Gear mechanism of sledge

The backlash is most visible between the two cogwheels (2 & 3) so the gear mechanism can be split in two parts, one part that consists of the worm wheel and one cogwheel and one part that consist of the second cogwheel and the toothed bar. Between these parts a dead zone can be implemented to simulate backlash. To determine the gear ratio, the teeth on the wheels and the toothed bar can be counted and for the computation of the ratio of the worm wheel the datasheet can be used. This is done in appendix A.2.

With the backlash, the torque delivered to the load \((T_l)\) can be written as:

\[
T_l = \begin{cases} 
0 & \text{if } |\theta_{mr} - \theta_l| \leq \theta_b \\
k_s (|\theta_{mr} - \theta_l| - \theta_b) \text{sign}(\theta_{mr} - \theta_l), & \text{otherwise}
\end{cases}
\] (3.14)
where \( k \), is the gear stiffness, \( \theta_m \) and \( \theta_l \) the motor position reduced to load and the load position respectively and \( \theta_b \) the amount of backlash. The torque on the motor reduced from the load can be written as:

\[
T_m = NT_s
\]  

(3.15)

### 3.4 The sledge

The torque delivered by the first part of the gear mechanism is directly fed to the second part on which the sledge is mounted. In this system, friction plays an important role. There are four kinds of friction that are incorporated in this system:

- **Coulomb friction:**
  This friction depends only on the sign of the velocity. It can be described by equation (3.16).
  \[
  F = F_c \text{sign}(v)
  \]  

(3.16)

- **Viscous friction:**
  This part of the friction depends on the value of the velocity and is described by equation (3.17).
  \[
  F = f_s v
  \]  

(3.17)

- **Stiction:**
  Experiments have shown that stiction plays an important role in the sledge mechanism. This stiction is position dependent and it is modeled by the next equation:
  \[
  F_s = F_s + F_{ss} \sin(5v)
  \]  

(3.18)

- **Stribeck friction:**
  In general, the friction force due to stiction does not drop suddenly when velocity increases. Stribeck observed that the friction has an exponential shape with a minimum at the Stribeck velocity.

The total friction force can now be described with a combination of all friction parts. This done in equation (3.19).

\[
F = \begin{cases} 
  F_s(v) & \text{if } v \neq 0 \\
  T_s & \text{if } v = 0 \text{ and } |T_s| < F_s \\
  F_c \text{sign}(F_c) & \text{if } v = 0 \text{ and } |T_s| > F_s 
\end{cases}
\]  

(3.19)

Where:

\[
F_s = F_c \text{sign}(\dot{\theta}_l) + f_s \dot{\theta}_l + (F_s - F_c) e^{-b|\dot{\theta}_l|}
\]

This leads to friction force depending on the velocity as seen in figure 3.7.
In the real system the sledge does not always move when a pulse is given. To model this phenomenon the stiction can obtain different values.

If the states are chosen as $x = [i_m \quad \theta_m \quad \theta_l \quad \theta_r]^T$ and the input as $u = [V]$ a state space description of the sledge system can be formed:

$$
\begin{align*}
\dot{x} &= \begin{bmatrix}
\frac{1}{L} (-Rx(1) - k_w x(3)) + u \\
\frac{1}{J_m} (k_m x(1) - \frac{1}{n_1} k_s \left( \frac{1}{n_1} x(2) - x(4) - \theta_b \right) \text{sgn} \left( \frac{1}{n_1} x(2) - x(4) \right) - \frac{1}{n_1} x(5)) - \frac{1}{n_1} x(3) - b x(3) \\
\frac{1}{J_s n_2} (k_s \left( \frac{1}{n_1} x(2) - x(4) - \theta_b \right) \text{sgn} \left( \frac{1}{n_1} x(2) - x(4) \right) - F_s \text{sgn}(\dot{\theta}_s) - f_s \dot{\theta}_s - (F_s - F_w) e^{-\beta x(5)}
\end{bmatrix} \\
\gamma &= [x(5)]
\end{align*}
$$

Since this is a highly non linear model the best solution to do simulations is to make a model in Simulink. Most of the modeling in Simulink is straightforward. However, there are some possible problems which should be avoided such as numerical problems, unwanted zero-crossings, algebraic loops, etc. In figure 3.8, the global model of the sledge system is depicted. The various parts of this model can be found in appendix B.
This system can now be coupled to the radial actuator which is also presented in appendix B.
The coupled Simulink model of the sledge system and the radial actuator with controller is given in figure 3.9.

In the next chapter controllers for the radial loop and the sledge system will be made and the influence of the sledge movement on the radial loop will be investigated.
4. Design of radial controller and pulse steered sledge controller

In this chapter, a controller for the radial loop will be computed and the existing control solution to the sledge will be simulated.

4.1 Controller for the radial loop

As stated in chapter 2, the radial controller should be able to follow the track on the CD. To suppress disturbances like shocks this system should have a high bandwidth to compensate quickly for these. However, to suppress faults like scratches on the CD the controller should have a low bandwidth, otherwise the radial actuator will see the scratch as a track and will start to follow it. A trade-off has to be made between these two situations. In addition, when the radial controller has a higher bandwidth, acoustic noise is more audible when playing compact discs. A commonly used controller is a PID controller with a bandwidth of 1000 Hz. Based on the model of the radial actuator derived in the previous chapter such a controller is designed straightforward. The controller is depicted in figure 4.1.

![Figure 4.1: Bode diagram of the controller of the radial loop](image)

The radial control signal cannot grow boundless while compensating so a saturation on this signal has to be implemented in the model. When the signal saturates, the controller still ‘thinks’ the computed signal is fed to the system and accordingly the integral action will start to wind up and thus the control signal will grow more. This leads to unnecessary big errors in the radial loop. To avoid this phenomenon, an anti-windup system is added. This is done by subtracting the difference between the computed and saturated control signal from the radial error that goes to the integrator. See for this implementation appendix C, figure C.1. In figure C.2 in the same appendix the Nyquist diagram of the open loop radial system is depicted.
4.2 Pulse steered controller for the sledge system

As stated before, the sledge is only used for slow and large movements in the horizontal direction. There are several possible solutions to control the sledge. At the moment, the sledge is controlled by sending pulses to the DC-motor when the sledge has to be moved. At first, it is assumed that the both the position of the sledge and the radial control signal can be measured. This method is chosen since it is difficult to make a continuous controller due to friction, stiction and backlash in the system.

A problem with this method is that it is not certain that the sledge will move when a pulse is given. If for example the stiction is too high or the backlash is too big it is possible that the sledge does not move when a pulse is given. This is the reason why the pulses have an increasing amplitude. The disadvantage of this way is that there is no way to determine how big the amplitude of the pulse has to be. It is possible that the first pulse is just a bit too low and that the second is much too big. In this way a bigger disturbance than needed will be imposed on the radial loop. It is even possible that the pulse brings the radial actuator to the other side of its non-linear area. This can lead to mutes or loss of the track. Another problem which occurs is that, since the sledge does not move at the desired moment, the radial loop can saturate which leads to bigger error signals. This control method can be implemented in Simulink through the use of a S-function that generates the pulses.

The sledge is supposed to move when the radial loop gets into its non-linear area. The pulses are therefore triggered by a threshold on the control signal of the radial loop. Since it is not known when the sledge is going to move, this threshold should be lower than the saturation voltage of the radial loop. The saturation voltage is set to ± 3 V. The threshold is then set to 2.75 V. In the simulations the balance between the ramp part of the radial control signal and the sinusoid part (caused by eccentricity of the disc) is exaggerated. This is done to make sure the sledge moves in the simulated time. The model of the controlled system is given in figure 4.2.

![figure 4.2: Pulse controlled system](image)

As stated earlier, the purpose of the sledge control mechanism is to avoid the radial loop from getting into saturation. The control signals to the sledge and the radial actuator look now as follows:
The radial error signal with and without saturation of the radial loop look than as depicted in figures 4.5 and 4.6.

The disturbances imposed by the sledge are not that big but if the radial actuator saturates, the influence is obvious. To avoid this, a continuous controller can be used. This is showed in the next chapter.
5. The design of a continuous controller

A controller based on pulses gives a large disturbance on the radial loop. Therefore, it is better to make a more smooth control for the sledge in order to minimize disturbances on the radial loop and to avoid saturation. This system exhibits a lot of friction and backlash and this imposes restrictions on the sledge controller. If there is overshoot in the system for example, the controller will try to compensate for this by giving a control signal of opposite sign. However, the backlash will generate a torque to the sledge which is too big and there will be overshoot in the opposite direction. Therefore, saturation has to be implemented such that the control signal can be only positive or negative during a movement. Another problem is the stiction, the sledge has to move all the time otherwise it will stick and still a non-smooth movement will be the consequence.

5.1 Control strategy for sledge

To control the sledge, a PD controller is designed since perfect tracking is not necessary. For now, it is assumed that the position of the sledge can be measured in this set-up. Because it is not recommended to have more movement in the total system then is necessary, the sledge is moved semi-continuously. This means that the sledge is only moved at times when the radial control signal is about to saturate but when it is moved, the sledge will follow a continuous reference. To limit the times the sledge has to be moved, this reference will bring the radial actuator from one bound of its range to the other. It is assumed that the position of the sledge can be measured and that it therefore can be used as feedback.

5.2 System and controller

In the end of chapter three the state-space description of the sledge system has been derived. In order to design a PD controller, this system has to be linearized. This leads to the following system:

\[
\dot{x} = \begin{bmatrix}
-\frac{R}{L} & 0 & -\frac{k_{cm}}{L} & 0 & 0 \\
0 & 0 & 1 & 0 & 0 \\
\frac{k_m}{J_s} & -\frac{k_m}{J_s} & 0 & 0 & 0 \\
0 & 0 & 0 & -\frac{k_s}{J_s} & \frac{1}{J_s} \\
0 & \frac{k_s}{J_s} & 0 & -\frac{k_s}{J_s} & -\frac{f_s}{J_s}
\end{bmatrix} x + \begin{bmatrix} 1 \\ L \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} u
\]

(5.1)

\[
y = \begin{bmatrix} 0 & 0 & 0 & \frac{1}{n_2} & 0 \end{bmatrix} x
\]

The bode diagram of this linearized system and the designed controller can be seen in figures 5.1 and 5.2.
As can be seen there is a resonance around 746 Hz. This is caused by the stiffness in the model of the gear transmission. Every time the radial control signal reaches a certain level, a S-function generates a 3rd order smooth reference signal which brings the sledge to the desired position. As mentioned earlier, the system exhibits stiction and backlash. These two phenomena give rise to a trade-off in bandwidth of the controller. Because of the backlash, the control signal is not supposed to change sign since this will lead to a limit cycle. Overshoot in the system should be avoided because then the sledge will stop and stiction will prevent it from moving until the control signal has enough energy to move it again and overshoot occurs again, this leads to non-smooth movement. The bandwidth of the controller should not be too high in order not to have overshoot because of the backlash (see appendix C, figure C.5) but it should not be too low as well since a low bandwidth implies that it takes a long time before the control signal has enough energy to overcome the stiction and a step like movement occurs which leads to big disturbances on the radial loop (see appendix C, figure C.6). To overcome a part of the backlash a feed forward signal is implemented as well. This signal consists of three pulses which are too low in amplitude to move the sledge but high enough to move the DC-motor and gear mechanism. This feed forward is fed to the system just before the reference signal. The Simulink model of the controlled system with feed forward can be found in appendix C, figure C.3. In figure C.4 the Nyquist diagram of the controlled system is depicted. Since the sledge is moved in a smooth way (see figure 5.3), the radial error is overall smaller than in the case the pulses were used as can be seen in figure 5.4. If figure 5.4 and 4.5 are compared, note that the simulation time in figure 5.4 is twice the time from figure 4.5. This way of controlling the sledge gives better results than the pulse control approach. The sledge is not moved as often as is the case when pulses are used, the error is smaller and saturation of the radial loop can be avoided.
There is only one problem: in the real system the position of the sledge is not known since it is not measured. To overcome this problem another signal has to be used as feedback to the sledge controller. This is done in the next section.

5.3 Using the radial control signal
Since the actual position of the sledge is not known, another signal has to be used to control this position. When the sledge is moved, the radial control signal will drop. This signal can therefore be used to control the sledge. Another advantage of choosing this signal is the fact that the sledge is moved in the first place to avoid that the radial controller saturates. This saturation depends on the radial control signal so it would be best to control this signal. This signal is easily measured in the real system.

5.3.1 Reference signal
The radial control signal consists of generally two parts. The first part is a ramp caused by the fact that the data on the disc is stored in spiral tracks and the second part is a sinusoid caused by the eccentricity of the disc. Only the ramp is important considering the sledge movement and thus the radial control signal has to be filtered. A low-pass filter however gives too much delay so another way has to be found. In this report a notch filter is used that filters out the sinusoid at the rotational frequency. This frequency is not the same throughout all positions on the disc but varies from inner to outer diameter from 9 till 4 Hz. This filter can therefore not be used in the real system, however, there are ways to split the radial control signal in its various frequency content and thus this control strategy can be implemented.

The sledge should move in a smooth way to keep the disturbances on the radial loop as small as possible so also a smooth reference signal should be used. In figure 5.5 a possible reference signal is depicted.
Every time the radial control signal reaches a threshold, the desired trajectory for this signal is fed to the controller. This done by implementing a S-function in Simulink which generates this reference on the desired moments.

5.3.2 System and controller
To be able to design a controller a model should be made for the system with as input a voltage to the sledge and as output the control signal to the radial actuator. This transfer could be determined as follows. The position and the velocity are added as a disturbance on the radial system. This is depicted in figure 5.6.

\[ T_{new} = P_r \cdot K \cdot \left( -\frac{C_r H_r}{1 + C_r H_r} \right) \]  

The bode diagram of this system and the designed controller at a bandwidth of 45 HZ are depicted in figure 5.7 and 5.8.
It is obvious that the bode diagram of this model looks very much like that from the one where the position is used as feedback. This is due to the fact that the closed loop \( \frac{-C_r H_r}{1+C_r H_r} \) has gain 1 (0 dB) till approximately the bandwidth, see figure 5.9.

As can be seen in figure 5.7, there is +180° extra phase in the system. This can be explained by the fact that when the sledge moves forward, the radial control signal moves downwards. A minus sign has therefore been introduced. The controlled sledge system has a bandwidth of 45 Hz. The Nyquist diagram can be found in appendix C, figure C.7. The total control scheme is depicted in appendix C, figure C.8.
5.3.3 Results
If the correct bandwidth is used together with the feed forward a smooth movement results, see figure 5.10. In the next figure the reference and actual filtered control signal are depicted.

\[\text{figure 5.10: Sledge movement following}\]

\[\text{figure 5.11: Reference}\]

The radial control signal and the radial error signal are given in figures 5.12 and 5.13 (compare to figure 4.5 and 5.4). The sledge control signal can be found in appendix C, figure C.9.

\[\text{figure 5.12: Radial control signal}\]

\[\text{figure 5.13: Radial error}\]

As can be seen from figure 5.13 the radial error caused by the sledge movement is not so obvious than when pulses are used. When the sledge is moved continuously, movement
can be predicted better and the sledge does not have to move as many times as was the case with pulse steering. An error can be seen when the sledge starts to move, this error can be made smaller by using a radial controller with a higher bandwidth at the moment the sledge starts to move. This is done in the next section.

5.4 Gain scheduling

Since the radial error is most obvious when the sledge starts to move, it is possible to use a controller with a higher bandwidth for the radial loop during a short time when the sledge moves. This approach is also possible with pulse steering, however, if a controller with higher bandwidth is used, it is possible that the actuator will follow a scratch on the CD. In the case of pulse steering the bandwidth should be increased every time a pulse is given since there is no telling when the sledge will move, this means that the bandwidth has to be increased too many times. With the semi-continuous moving this approach is possible because the sledge just moves a few times. As can be seen in figure 5.13, the radial error is most obvious when the sledge starts to move so the bandwidth only has to be increased in the beginning of the reference following. Since the sledge does not move as many times as is the case with pulse steering, the gain scheduling method can be applied.

In order to have a smooth transfer from one controller to the other some precautions have to be taken. If the two controllers are just switched, a step in the radial control signal will occur. To prevent this, the states of both controllers have to be the same when the switching is done. This can be done by using the same integrators in the Simulink model and just switch the other controller parts. In order to do so, the controllers should be divided in parts that make it possible to set the integrators free. The radial controller used is a PID controller, depicted in figure 4.1. The transfer function of the total controller is:

\[
\frac{Y}{U} = \left( \frac{1}{\tau_x s + 1} \right) \frac{\tau_p}{\tau_z} + \frac{\tau_p s}{\tau_p s + 1} \cdot \text{gain}
\]  

(5.3)

This transfer function can be split in the three parts, converted to state-space descriptions and to block diagrams:

Proportional:

\[
\frac{Y}{U} = \text{gain} \cdot \frac{\tau_p}{\tau_z} \Rightarrow u \xrightarrow{\tau_p/\tau_z} \text{gain} \xrightarrow{y}
\]

integral:

\[
\frac{Y}{U} = \frac{\text{gain} \tau_p}{\tau_x s} \Rightarrow \begin{bmatrix} \dot{x} = \text{gain} \frac{\tau_p}{\tau_x} u \\ y = x \end{bmatrix} \Rightarrow u \xrightarrow{\tau_x/\tau_z} \text{gain} \xrightarrow{\frac{1}{s}} y
\]
Derivative:

\[
\frac{Y}{U} = \frac{\text{gain} \cdot \tau_d s}{\tau_d s + 1} \Rightarrow \begin{cases} 
\dot{x} &= -\frac{1}{\tau_d} x - \frac{\text{gain}}{\tau_d} u \\
y &= x + \text{gain} \cdot u 
\end{cases} \Rightarrow u - \frac{\text{gain}}{\tau_d} + \frac{1}{s} y
\]

The total block scheme of the controller with the gain scheduling and anti-windup mechanism implemented can be found in figure C.10, appendix C. The controllers have bandwidths of 1000 and 2000 Hz, respectively. This means that for these PID controllers low frequent (at the disc rotation frequencies) the gain is raised with a factor 2\(^3\). Of course an important issue with gain scheduling is stability. In this report the stability is not addressed, however with use of e.g. [7] this can be done. From simulations it is obvious that the gain scheduled system is stable. The radial error with the gain scheduling implemented is depicted in figure 5.14, a close up on the schedule time is given in figure 5.15.

If figure 5.14 is compared to 5.13, it is clear that the biggest errors are reduced as was the idea with the gain scheduling. This control strategy provides a good way to move the sledge without use of extra measurements and to keep the radial error small without using a high bandwidth for a long time.

Figure 5.14: Error with gain scheduling

Figure 5.15: Close-up on radial error
6. Conclusions and Recommendations

A model has been developed for the sledge system consisting of a DC-motor, a gear mechanism and a mass to which the optical pickup system is attached. Simulations have been done on the nowadays used control method based on pulses. These simulations show that the pulses give many disturbances on the radial tracking system. Since it is not certain when the sledge moves due to backlash, stiction and friction pulses of increasing amplitude have to be used.

A better approach is a continuous movement of the sledge which brings the radial actuator from one end of its range to the other. A PD controller with position feedback gives good results in simulation but unfortunately this signal is not measured and can therefore not be used. If instead the filtered radial control signal is used for feedback simulations show also good results. The sledge does not have to move as often as was the case with pulse steering and the radial actuator capable of compensating the continuous movement of the sledge. The stiction gives rise to the problem that the reference is not followed immediately but just after a short period. This leads to the fact that there is a step wise start of the sledge movement and the radial error is most obvious at this moment. To decrease this error, a gain scheduled radial controller has been implemented that doubles the bandwidth at the moment the sledge starts to move. This total system gives promising simulation results. Due to the fact that the testing system was not finished at the end of this training period, real time experiments could not be done. The parameters for the sledge system such as friction parameters, stiction, backlash and motor constants are not determined experimentally so research to this data should still be done. It is also recommended to investigate the possibilities of filtering the radial control signal in such a way that only the ramp will be visible without too much delay. Another reference signal could be designed which incorporates the fact that there is backlash and stiction present in the system. The feed forward signal can be expanded to compensate for stiction and friction as well, possibly with iterative learning each time the sledge is moved since always the same reference is used.
References


Appendices

A.1: Values radial actuator and sledge system

Radial actuator:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min.</th>
<th>Typ.</th>
<th>Max.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moving mass (m)</td>
<td>-</td>
<td>0.56 × 10^{-3}</td>
<td>-</td>
<td>Kg</td>
</tr>
<tr>
<td>Q-factor coils</td>
<td>8</td>
<td>12</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Voltage on coils</td>
<td>42</td>
<td>3</td>
<td>Vdc</td>
<td></td>
</tr>
<tr>
<td>Resonance frequency</td>
<td>49</td>
<td>46</td>
<td>Hz</td>
<td></td>
</tr>
<tr>
<td>AC sensitivity (Bl)</td>
<td>0.2</td>
<td>0.25</td>
<td>0.3</td>
<td>N/A</td>
</tr>
<tr>
<td>DC sensitivity</td>
<td>-</td>
<td>0.24 × 10^{-3}</td>
<td>-</td>
<td>m/V</td>
</tr>
<tr>
<td>Resistance (R)</td>
<td>15.3</td>
<td>18</td>
<td>20.7</td>
<td>Ω</td>
</tr>
<tr>
<td>Shunt (r_m)</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>Ω</td>
</tr>
<tr>
<td>Inductance (L)</td>
<td>-</td>
<td>1.65 × 10^{-3}</td>
<td>-</td>
<td>H</td>
</tr>
<tr>
<td>c</td>
<td>-</td>
<td>0.014</td>
<td>-</td>
<td>Ns/m</td>
</tr>
<tr>
<td>k</td>
<td>-</td>
<td>53.1</td>
<td>-</td>
<td>N/m</td>
</tr>
</tbody>
</table>

For the computation of the spring and damper constant, the state space description can be converted to a transfer function with the next formula:

\[ T(s) = C(sI - A)^{-1}B + D \]

\[ A = \begin{bmatrix} 0 & k/m & c/m & \frac{1}{m(R + r_m)} \\ -k/m & -c/m & -\frac{(Bl)^2}{m(R + r_m)} & \frac{1}{m(R + r_m)} \end{bmatrix}; B = \begin{bmatrix} 0 \\ -\frac{Bl}{m(R + r_m)} \end{bmatrix}; C = \begin{bmatrix} 1 & 0 \end{bmatrix}; D = 0 \]

So the transfer function is:

\[ T(s) = \frac{Bl}{s^2 + \left(\frac{(Bl)^2}{m(R + r_m)} + \frac{c}{m}\right)s + \frac{k}{m}} \]

from these \( k \) and \( c \) can be derived as:

\[ k = \omega_n^2 m \]

\[ c = \frac{2\zeta\omega_n}{m} - \frac{Bl^2}{m^2(R + r_m)} \]

Now starting values of these parameters are available and in [1] these values have been fitted to the bode diagram of the radial system to determine the correct values as are stated in the above table.
Parameters sledge system:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor inertia ((J_m))</td>
<td>(1.2 \times 10^{-4})</td>
<td>Kg m²/rad²</td>
</tr>
<tr>
<td>Inductance of motor ((L))</td>
<td>(4.0 \times 10^{-5})</td>
<td>H</td>
</tr>
<tr>
<td>Resistance of motor ((R))</td>
<td>0.16</td>
<td>Ω</td>
</tr>
<tr>
<td>Armature gain ((k_m))</td>
<td>(4.88 \times 10^{-2})</td>
<td>Nm/A</td>
</tr>
<tr>
<td>Emf gain ((k_{em}))</td>
<td>(4.88 \times 10^{-2})</td>
<td>V/rad s⁻¹</td>
</tr>
<tr>
<td>Motor damping ((b))</td>
<td>7.6 \times 10^{-3})</td>
<td>Nm/s/rad²</td>
</tr>
<tr>
<td>Motor starting torque ((T_{cm}))</td>
<td>0.01</td>
<td>Nm/rad</td>
</tr>
</tbody>
</table>

A.2 Computation of the gear ratio

The gear mechanism consists of a worm wheel (1), two cogwheels (2 & 3) and a toothed bar (4), see figure A.2.1.

Data

- Toothed bar (4): Length: 40 mm, Teeth: 40
- Cogwheel (3): Teeth big wheel: 68, Teeth small wheel: 15
- Cogwheel (2): Teeth: 17

In the datasheet from B&O the total gear ratio from DC-motor to translation of the sledge can be found: 10 krad/m. The ratio from the motor to wheel (2) can be derived by dividing the total ratio by the ratio from cogwheel (2) to the translation of the sledge, which can be determined from the above data:

\[
\frac{\text{translation sledge}}{\text{rad.motor}} = 1 \times 10^{-4} = \frac{1}{\text{worm ratio}} \times \frac{1}{68} \times \frac{1}{2\pi} \times 15 \times 1 \times 10^{-3},
\]

\[
\text{ratio worm wheel} = 5.9683
\]
Appendix B: Simulink model of the sledge system

In this appendix the various parts from the sledge model as seen in figure 3.8 are presented.

**Electrical part DC-motor:**

**Mechanical part DC-motor:**

**Friction block:**
Zero crossing detector:

This part is to make sure the velocity does not change sign in one integration step because of numerical issues. The velocity at the present integration step is compared to the velocity at the previous one by means of a memory block and an additional very small delay to make sure the change of sign is detected. If there is no change, the new velocity equals the incoming velocity. If there is a change and the absolute value of the torque delivered to the motor is smaller than the coulomb friction to the motor, the new velocity is set to zero. Otherwise, the sign of the velocity will change and the coulomb friction will change sign so the torque is again in opposite direction of the velocity. This leads again to a change of sign of the velocity and of the coulomb friction and in this way to a velocity signal that is changing sign every integration step while in the real system this is not possible. If the torque delivered to the motor is greater than the coulomb friction the change of sign is a real change and the incoming velocity is passed through.

Gear:
Mechanical part of sledge:

Friction:

Restriction on velocity:
Stiction generator:

Simulink model of radial actuator:
Appendix C: Controllers

Radial loop:

figure C.1: Radial controller

figure C.2: Nyquist diagram controlled radial system

Sledge system:

figure C.3: PD controlled sledge system with position feedback
figure C.4: Nyquist diagram PD controlled sledge system with position feedback

figure C.5: Too high bandwidth

figure C.6: Too low bandwidth

Figure C.7: Nyquist diagram of controlled sledge system with radial control signal as feedback
figure C.8: Control scheme

figure C.9: Control signal to sledge
(pulses are visible before continuous control starts)
figure C.10: Gain scheduled controller with anti-windup