External control of a linear tape open drive

External control of a Linear Tape Open drive

T. ten Dam

DCT 2007.044

Traineeship report

Coach(es): R.A. de Callafon

Supervisor: M. Steinbuch

Technische Universiteit Eindhoven
Department Mechanical Engineering
Dynamics and Control Technology Group

Eindhoven, April, 2007

Summary

In order to test whether it is possible to increase the performance of a given linear tape-open (LTO) drive, a test setup is developed. This setup consists of an external LTO-drive and a data acquisition board in combination with the Matlab Simulink real time windows target. This software environment is used to implement the external controllers that will operate parallel to the internal controller that already is implemented in the external drive. The control gain of this internal controller can be set to zero in order to let the external controllers take over the control loop. To be able to design the new controllers, the dynamics of the LTO-tape are modeled. The frequency response of the plant is obtained by dividing the process sensitivity by the sensitivity. The offset gain of these dynamics is determined by looking at the sensitivity at high frequencies as the amplitude of the sensitivity will go to this offset gain at infinity. This data is used to fit a ninth order model on it. This model however does not represent the proposed setup completely, since another setup is used for identifying. To compensate for this, some extra phase loss should be added to the model. This phase loss is caused by the time delay of the zero order hold analogue-digital converter in the data acquisition board and since dividing the process sensitivity by the sensitivity causes some information loss. Measurements of the control sensitivity of the closed external control loop show that the proposed model is accurate and thus useful for control design. First a manual loop shaping technique is tried to improve the performance of the system. It turned out that this is not sufficient. This can be explained if one considers that our external control loop has some more time delay and the internal controller is probably designed using the same loop shaping techniques. Next a loop shaping with H?-synthesis control design is tested. The main idea of this approach is to shape the plant with input and/or output weighting functions. After which a controller is synthesized that minimizes four closed loop transfer functions using the H? norm. This controller could theoretically improve the performances of the tape drive, but has not yet been tested on the setup. Finally the position error signal (PES) has been used to identify the lateral tape motion (LTM). This is done by converting a time sequence of the PES into frequency domain by a Fourier transformation. The PES frequency data is multiplied by the inverse of the sensitivity to obtain the LTM frequency data. Analyses of the LTM frequency data show three different kinds of disturbances. The first one is a random noise up to 50 Hz and low in amplitude. The second one is a pulsating disturbance at 65 Hz and can be explained as a beating phenomenon in the tape drive, due to slight differences in the bearings and geometry of the spools. The last kind consists of 2 sets of moving disturbances: one series of harmonic disturbances changing to higher frequencies and one series of harmonic disturbances changing to lower frequencies. This can be due to (un)winding of the reels. This information can be used in the future to design a controller that suppresses the disturbances at exactly these frequencies and perhaps increase the performance.

Contents

List of Figures

Notation

Symbol	**Quantity**	**Unit**
$\alpha, \beta, \gamma, \delta, \kappa$	gain	[-]
PES_V	error signal	[V]
$PES_{\mu m}$	error signal	[m]
U_E, U_I, U_C	control signal	[V]
I_S, I_C, I_{SENSE}	control current	[A]
TF_{IN}, r	input signal	[V]
F, F_{coil}, F_{screw}	actuation force	[N]
LTM	disturbance signal	[V]
a, b	distance	[m]
ω	frequency	[rads^{-1}]
$\varepsilon, \epsilon_{max}$	stability margin	[-]
v, v_1, v_2	disturbance signal	[V]
r_0	radius	[m]
V	tape speed	[ms^{-1}]
t	time	[s]
τ	tape thickness	[m]
τ	time delay	[s]
$\dot{\theta}_e, \dot{\theta}_f$	angular velocity	[rads^{-1}]
Ψ	frequency	[rads^{-1}]

Chapter 1

Introduction

The amount of data one can store on hard disk drives or similar devices has increased extremely over the past years, storing data on tape remains the most cost effective way. In order to stay in that position, tape storage technology has to keep up, by increasing capacity and data transfer rates. One of the possibilities to do this is to improve error correction. One of the many magnetic tape data storage technologies available today is the Linear Tape-Open (LTO) which was developed by Seagate, Hewlett-Packard, and IBM and is now manufactured by several other companies.

The goal for this research is to investigate the improvement of the servo control algorithm by designing a model based servo controller to maximize control bandwith. The model based controller will be designed on the basis of a model obtained from closed-loop experimental data from an actual LTO drive. The LTO drive will be identified and modeled using Matlab for the computations and Siglab for measurements. The implementation of the controller will be realized using the Matlab Simulink Real-Time Windows Target and a data acquisition board. First a simple PID controller will be implemented to verify the concept after which more sophisticated controllers will be tested. For this project two different tape drives are available: one of the LTO-1 and one of the LTO-3 generations.

This report will start with a description of the two different systems and the used technology. Subsequently the identification will be dealt with. Then the different kinds of controller designs are presented. Finally the implementation of a simple PID controller will be discussed and some of the results are presented.

Chapter 2

System Description

This section will present the two different tape drives that are available for measurements. Give an insight in the used technology and explain some differences between the two drives. Moreover will be described which signals are available for measurements and what kind of control one has over the two different drives.

2.1 Linear Tape Open

Both drives available are using the same technology, namely Linear Tape Open (LTO). This is a data storage technology initially developed by Seagate, Hewlett-Packard, and IBM and is now manufactured by several other companies. The cartridges that are used contain a single reel and 1/2" wide tape. After inserting the cartridge in the drive, the tape is pulled out of the cartridge by means of a leader tape and will wind up on the take up reel inside the drive. LTO tape is laid out with four data bands sandwiched between five servo bands. The head unit straddles the two servo bands that border the data band that is being written or read. Data tracks are written in forward and reverse passes, also called wraps. It takes several wraps to completely fill a data band. All of the write elements in the head write simultaneously as the head passes over the data band from the physical start of the tape to the physical end. This makes one forward wrap. At the end, the head shifts to line up the write elements with a new set of tracks within the same data band, to make a reverse wrap. The servo bands are used to keep the head precisely aligned within the data band. When data is written to the tape it is verified by reading it back using the read heads that are positioned just behind the write heads. This allows the drive to write a second copy of any data that fails, without the help of the host system. The difference between the two available drives is that one is a LTO-1 and the other is a LTO-3 drive. This means that they are of a different generation, with three being the latest. Moreover they are both from a different manufacturer. Some of the differences concerning data storage can be found in table 2.1.

2.2 LTO-1 Drive

The picture in figure 2.1 shows the LTO-1 drive and a schematic of the internal signals is given in figure 2.2. This figure is divided into three parts: the plant, the internal controller and the external controller. This partitioning is chosen as such because of the measurable signals, which will become more clear in chapter 3.

Table 2.1: Differences on tape storage between LTO-1 and LTO-3

	LTO-1	LTO-3
Write elements	8	16
Wraps per band	12	11
Tape tracks	384 (4 x 12 x 8)	704 (4 x 11 x 16)
Linear density [bits/mm]	4880	9638

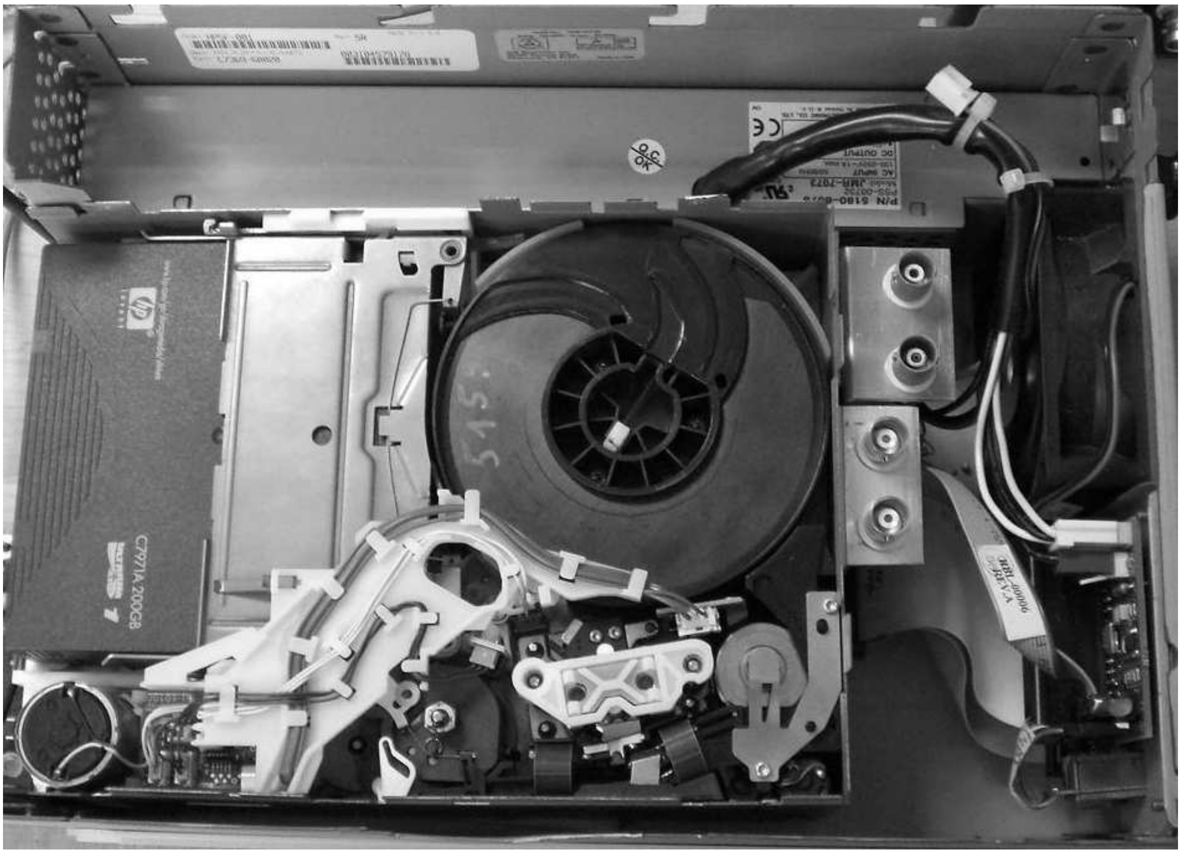


Figure 2.1: Picture of the LTO-1 drive available in the SICL

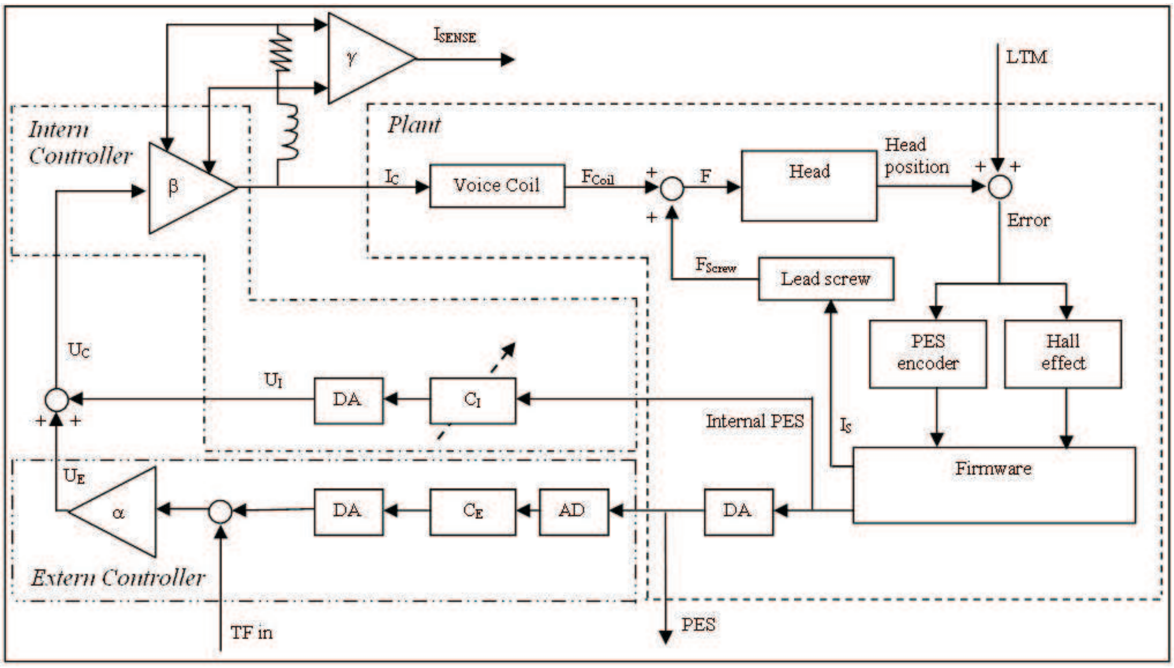


Figure 2.2: Schematic of the signal flow in the LTO-1 drive

The plant positioning system consists of two actuators: the voice coil and the lead screw. The lead screw is used for coarse positioning and the voice coil is used for the high precision positioning. Our focus is the design of an advanced servo controller for the high precision actuator, which is described in more detail in figure 2.2. The position error is measured by two different sensors, namely the position error signal (PES) encoder and the Hall effect sensor. Both sensor signals are combined and translated into an error signal by the firmware. The firmware uses this error signal to compute two different control signals: U_I and U_S for the control loop of the voice coil and the lead screw respectively. In figure 2.2 the computation of U_I by the internal controller is taken out of the firmware and thus out of the plant, because it is more relevant to the internal controller part. Moreover in this way it is easier to compare the internal controller to the external controller. The internal controller consists of a digital controller (C_I), an analogue-digital (AD) converter and a current amplifier (β). The controller is actually programmed in the firmware as mentioned before. The external controller consists of an AD and a DA converter, combined in a data acquisition board. The controller itself is implemented in software, using the Matlab Simulink Real-Time Windows Target. Furthermore there is an unknown gain difference (α) between the computed control signal and the actual control signal (UE). Extra gains can be added in front or after the data acquisition board to use the entire range of its AD and DA converters to assure maximum resolution. If one chooses to inject a signal without closing the external controller loop, the external signal can be injected as TF_{IN}. As you can see, there are two signals available for measurements, namely the PES and the I_{SENSE}. These signals divide the plant from the controllers. Besides there is one point where you can inject a signal, the TF_{IN}, and there is a disturbance signal caused by the lateral tape motion (LTM) which will be described more thoroughly in section 4.3. The PES is a signal based on the tracking of the servo bands. These bands contain a zigzag pattern as shown in figure 2.3 and the ratio of the open space in

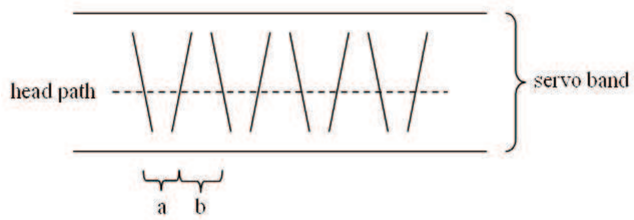


Figure 2.3: Zigzag pattern on the servo band

this pattern is a measure for the alignment of the head. The firmware computes this ratio using the PES encoder and converts it to a voltage, to be able to send it as an analogue signal. The calibration factor is 13.75 μm position error per volt of output. The I_{SENSE} is a signal to give an impression of the current going into the voice coils. This current (I_C) can not be measured directly, so instead a voltage difference over a resistor is measured. Because of that, there is a gain difference (γ) between I_C and I_{SENSE}. The LTO-1 drive is connected to a pc by one serial port. In this way one is able to send commands to the tape drive. Some of the commands, and their function, that can be send to the drive are:

- load/eject the cartridge
- servo the head or hold it still regardless of track position
- change the controller gain, this can be done on the run
- shuttle the tape between two specified points at a specified speed
- set tape tension

Notice that the controller gain can be set to zero. This will be used to turn-off the internal controller and let the external controller take over.

2.3 LTO-3 Drive

The LTO-3 drive (figure 2.4) is not much different from the LTO-1 drive. It uses the same kind of actuators and the available signals are alike. The PES is a measurement from the tape servo track and the I_{SENSE} is a measure of a voltage drop over a resistor. So figure 2.2 applies to the LTO-3 drive as well. There are some differences though, which will be described in the following. The experimental setup of the LTO-3 drive allows measurements of the PES via a separate DA converter. In addition, the DA converter can be programmed to adjust the full-scale resolution. This allows you to choose the minimal and maximal measurable ratio in order to get an optimal resolution for the error signal. The PES signal is in the range of 0 V to 2.5 V and has an offset of 1.25 V. To compare measurements with different DA settings, the PES can be converted from voltage to micro meters using equation (2.1).

$$PES_{\mu m} = (PES_V - 1.25) \cdot \frac{max\_ratio - min\_ratio}{2.5} \cdot 475.718 \tag{2.1}$$

The default nominal ratio is 0.5058, with a maximum range of 0.3 till 0.7. This compares to an error of $\pm$ 95 μm. The firmware samples the PES at 20 kHz. Since the LTO-3 drive is made by

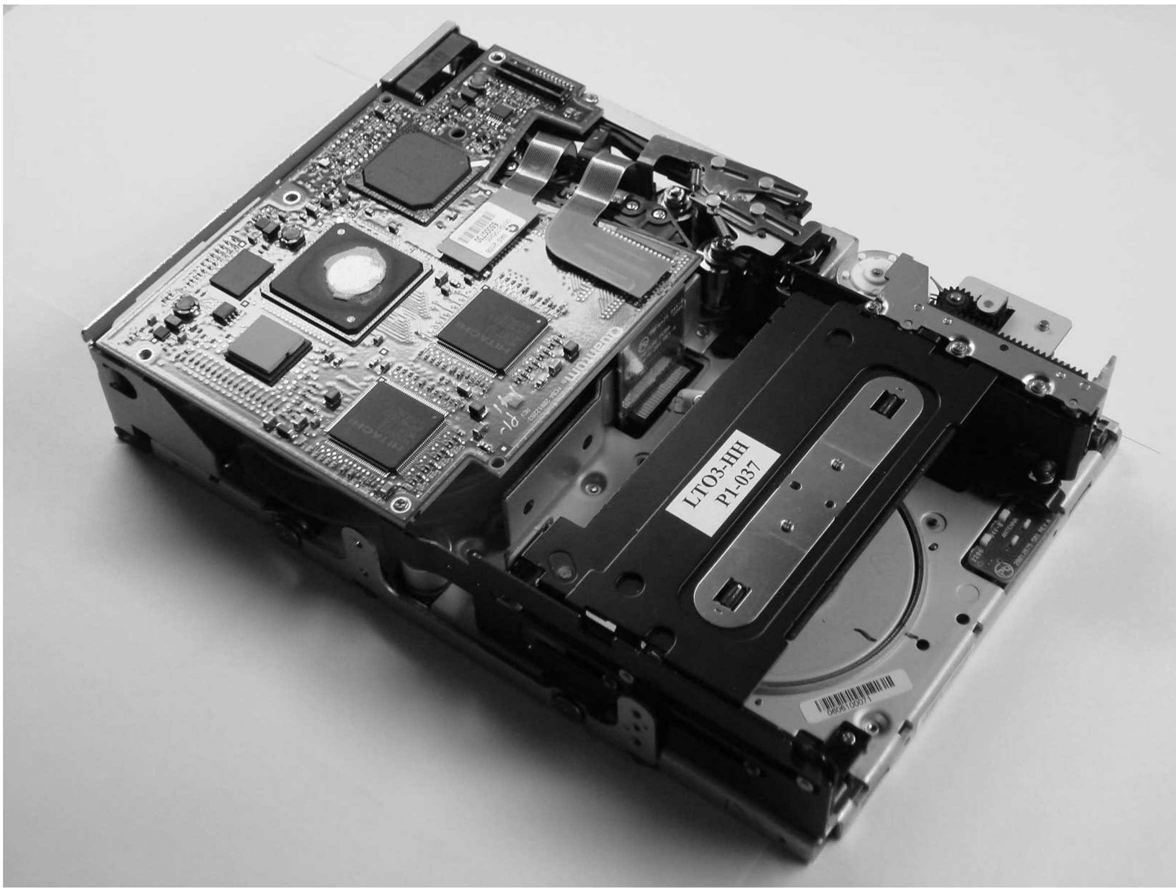


Figure 2.4: Picture of the LTO-3 drive

another manufacturer, the control over the tape drive is different. The LTO-3 drive is connected to a pc by two serial ports: one to send tape operation commands and one to send servo commands. Some of the tape operation commands are:

- load/eject the cartridge
- shuttle the tape and one can choose tape speed, nominal ratio, direction (wind or unwind the tape) and open or closed loop tracking

Some of the servo commands are:

- Change the controller gain, this can not be done on the run
- Activate the possibility to send in an external signal
- Program the DA converter

Notice that for the LTO-3 drive it is not possible to change the controller gain to zero on the run. So our external controller should be able to servo the tape from the start.

Chapter 3

System Identification

In this chapter the two systems presented in chapter 2 will be identified and modeled. In order to do that properly, a simplified model of the systems will be presented. After that, the measured frequency response functions (FRFs) will be discussed and how these FRFs can be used for modeling the plant. The measurements will be done using Siglab and the models will be computed using Matlab.

3.1 Model

The simplified model of the system, without the external control loop, is shown in figure 3.1. This model structure is the same for both the LTO-1 drive and the LTO-3 drive. In the LTO-1 case however the PES is taken care of in volts, while in the LTO-3 case the PES is converted to micrometers to be sure that all measurements are comparable no matter what the settings of the separate DA converter were. The difference between the left and the right figure is that on the right side the current amplifier (β) is seen as part of the internal controller (C_i). Together it is named C_i^*. The gains (α and γ) represent the gain differences as described in section 2.2 but may also include some extra gains introduced to condition the signals for better use of the AD and DA converters. C_i^* and P are the internal controller and the plant respectively as shown in figure 2.2 in the previous chapter. This separation between plant and controller is chosen in such a way, that the measurable signals are right between them: I_{sense} where the controller ends and the plant starts and for the PES it is the other way around. This separation makes it easier to interpret the measurements as discussed in the next section.

3.2 System Identification

Using the reference input signal (r) and the two output signals (I_{sense} and PES) one is able to measure two different FRFs via spectral analysis, namely the Sensitivity (S) and the Process Sensitivity (PS) as in equation (3.1) and equation (3.2) respectively. As can be seen, these are not exactly the Sensitivity and the Process Sensitivity, but there is a gain difference: $\alpha\beta\gamma$ and $\alpha\beta$.

$$r \rightarrow I_{sense} \quad : \quad \frac{\alpha\beta\gamma}{1+C_i^*} = \alpha\beta\gamma S \tag{3.1}$$

$$r \rightarrow PES \quad : \quad \frac{\alpha\beta P}{1+C_i^*} = \alpha\beta PS \tag{3.2}$$

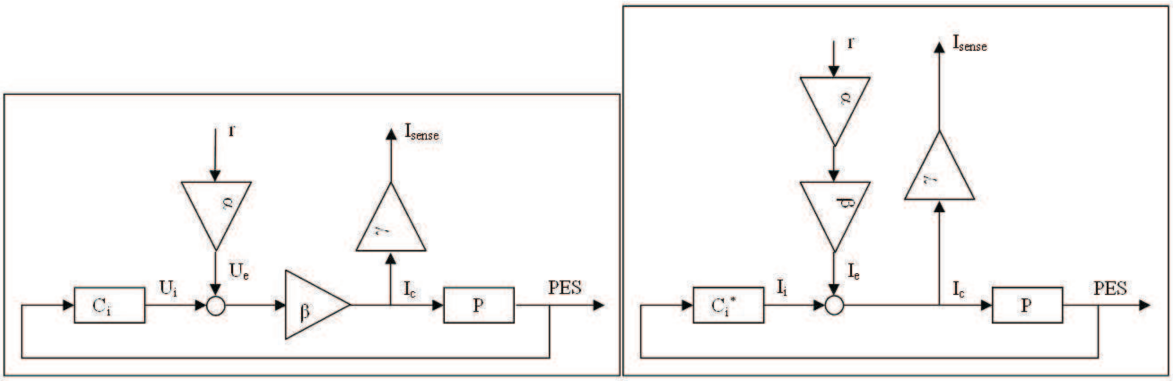


Figure 3.1: simplified model of the system. The left scheme deals with the power amplifier as a separate part, the right figure considers the power amplifier as part of the controller.

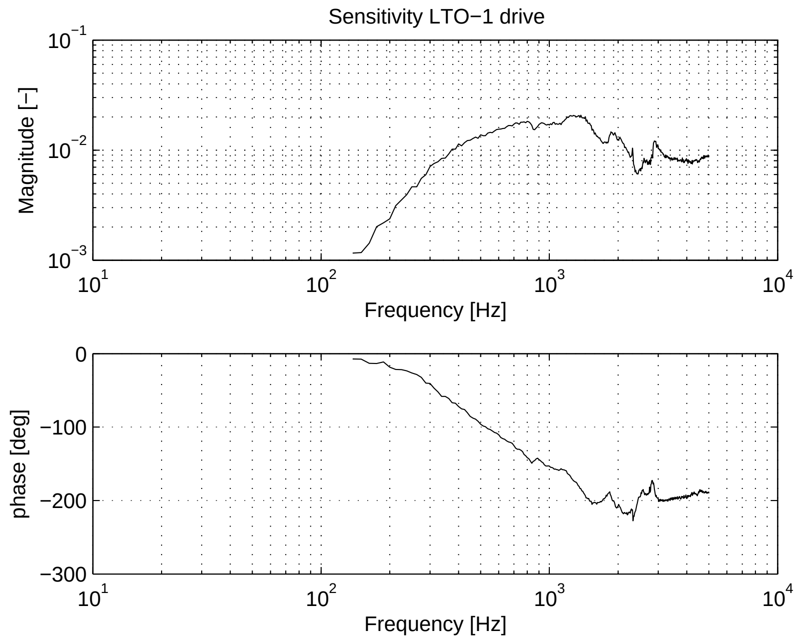
Although it is not possible to get a good closed loop measurement for the whole frequency range in one shot. It is possible to get several good measurements over a small frequency range using a chirp signal with different start end end frequencies closer together. Those separate measurements can be combined afterwards to get a good measurement over a larger frequency range. This has been done for both the Sensitivity and the Process Sensitivity and for both the LTO-1 and the LTO-3 tape drive as can be seen in figure 3.2 and figure 3.3. The frequency range differs for each graph, because it was not possible to get a good coherence for each transfer function over the same domain. These measurements were done with the controller gain at the default value.
These measurements can be used to calculate the plant dynamics using the following equation (3.3).

$$\frac{\alpha\beta PS}{\alpha\beta\gamma S} = \frac{P}{\gamma} \tag{3.3}$$

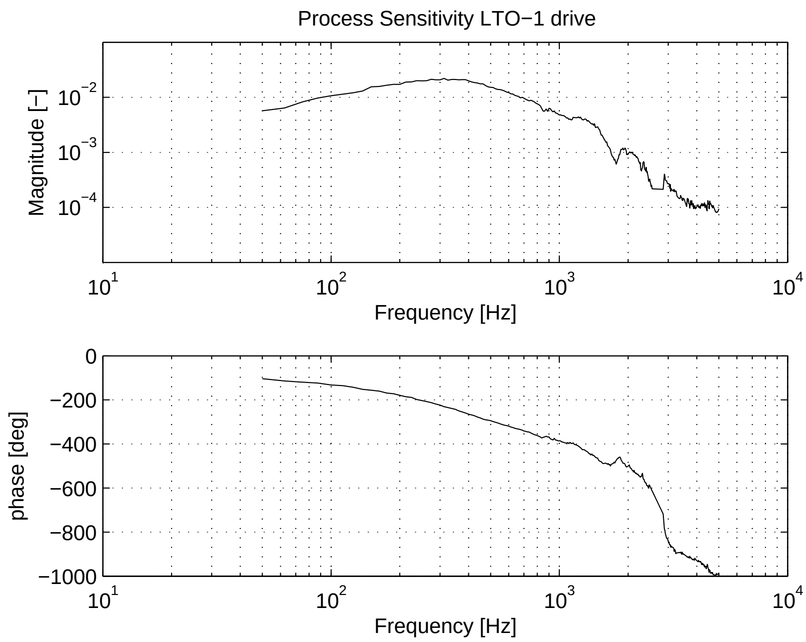
For control purposes however one is not interested in P divided by γ, but in P times α times β as can be seen after closing the loop between PES and r. Using equation (3.4) and multiplying its result with the previous result will give the desired frequency response. The results can be seen in figure 3.4.

$$\begin{aligned} \lim_{\omega\to\infty} \quad & \frac{1}{1+C(\omega)P(\omega)} = 1 \\ \lim_{\omega\to\infty} \quad & \frac{\alpha\beta\gamma}{1+C_i^*(\omega)P(\omega)} = \alpha\beta\gamma \end{aligned} \tag{3.4}$$

This equation holds assuming that α, β and γ are frequency independent. Moreover it is not certain that one is able to measure the transfer function for frequencies high enough for the sensitivity to go to a constant value. Figure 3.4 shows beside the calculated plant transfer function data also the models that are fitted on this data. These models are fitted on the data using the FREQID toolbox in Matlab and are based on a least squares optimization. Both models are ninth order state space models.

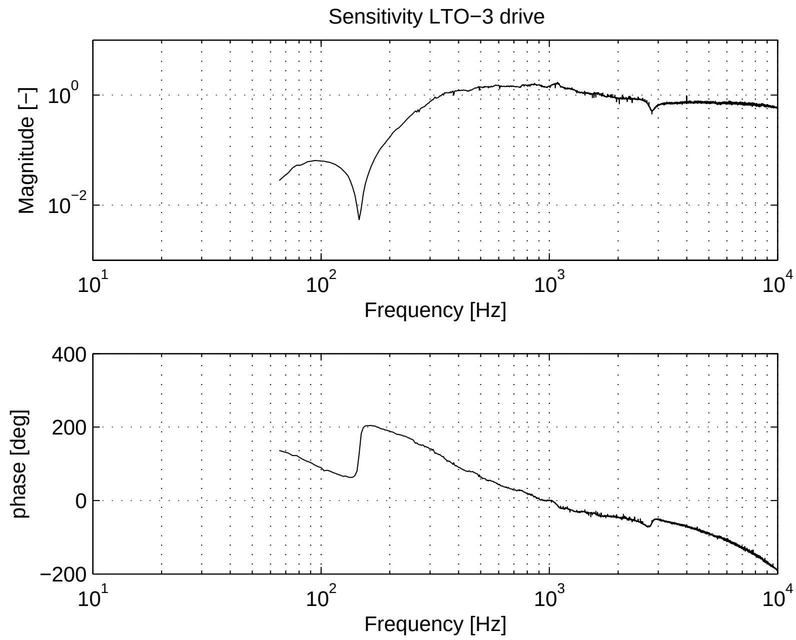


(a)

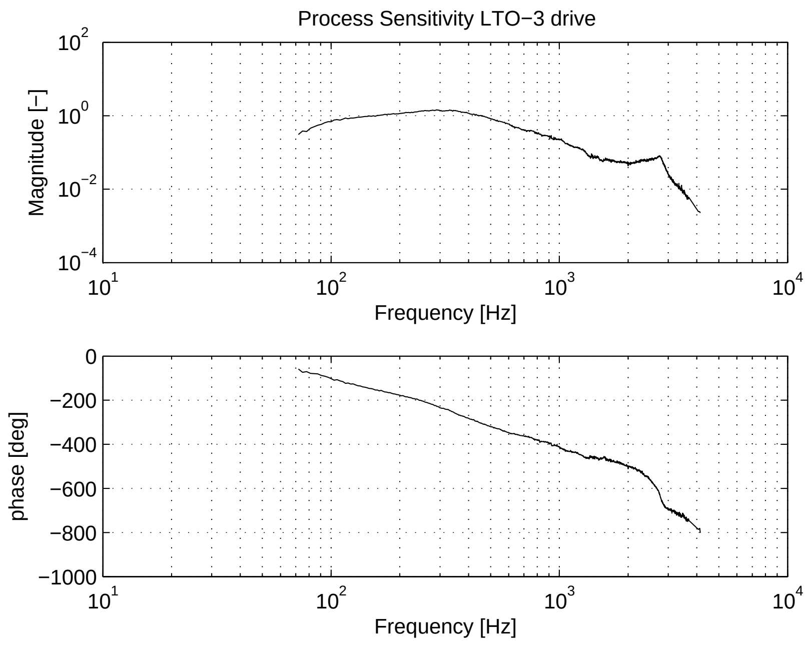


(b)

Figure 3.2: a) Sensitivity measurement LTO-1 drive. b) Process Sensitivity measurement LTO-1 drive.

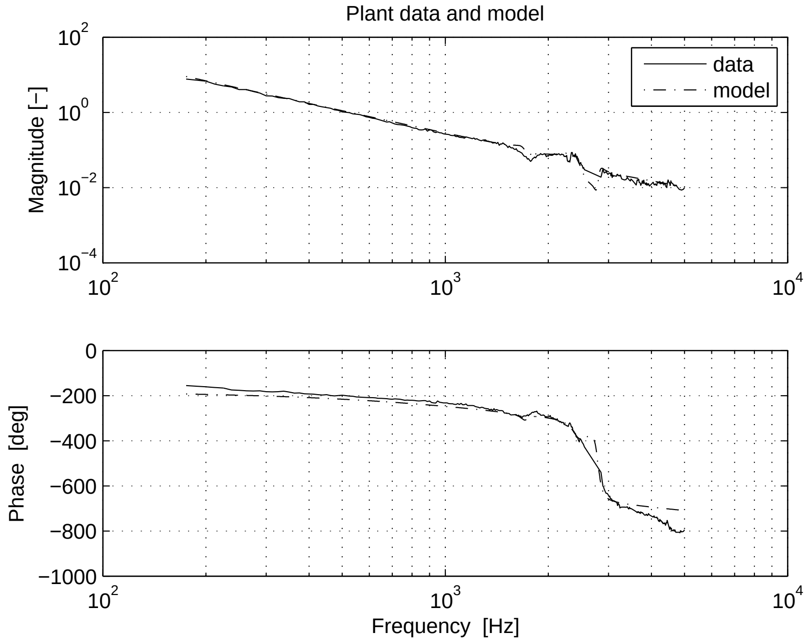


(a)

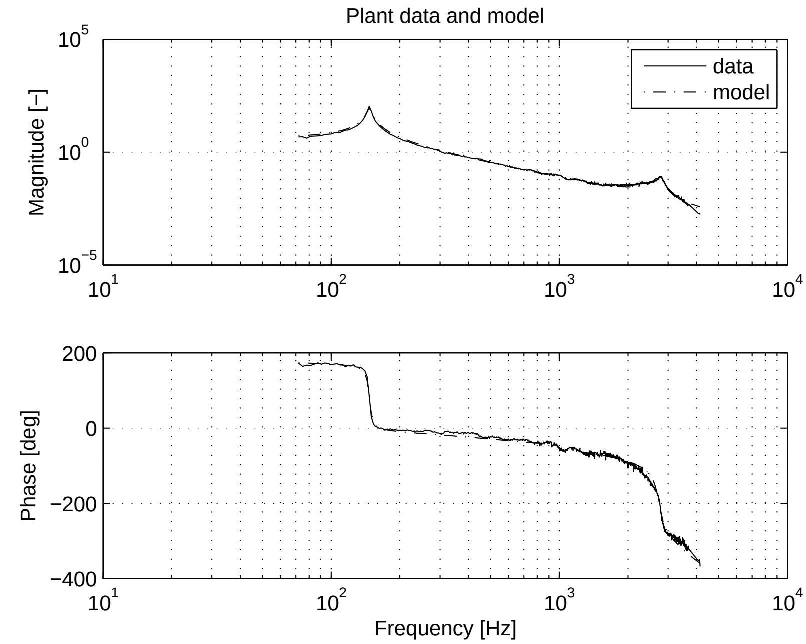


(b)

Figure 3.3: a) Sensitivity measurement LTO-3 drive. b) Process Sensitivity measurement LTO-3 drive.



(a)



(b)

Figure 3.4: a) Plant data and model of the LTO-1 tape. b) Plant data and model of the LTO-3 tape.

Chapter 4

Control Design

The control design will be discussed in this chapter. The control design is focused on the LTO-1 drive, but the techniques mentioned can of course be applied to the LTO-3 drive as well. The first approach for control design is loop shaping. After that a loop shaping design with $H\infty$ synthesis will be presented. Finally, a model of the main periodic disturbances caused by lateral tape motion is presented. In order to design controllers that suppress disturbances at certain frequencies instead of suppressing all low frequent disturbances as conventional controllers do. The design of these controllers will be done in continuous time. The implementation however will be done in discrete time. This will lead to problems which will be dealt with in chapter 5. In this chapter it will be assumed that the implementation of the controllers is ideal. The controllers will be fit on the model shown in figure 3.4.

4.1 Loop Shaping

The design should satisfy a robustness margin. This is a maximum modulus margin of 6 db in the Sensitivity transfer function. In order to satisfy this requirement and be able to place the bandwidth, 0 db crossing of the open loop transfer function, as high as possible, standard loop shaping techniques are used. The first step is to add a lead filter, to add phase lead to the open loop transfer function. The zero and the pole of the lead filter are placed as high as possible to just satisfy the robustness requirements. Moreover an integrator is added at low frequencies to suppress the low frequent disturbances. Then the gain is adjusted to make sure the open loop 0 db crossing is at the desired frequency. After doing so one will notice that a peak in the plant model at around 1600 Hz is the limiting factor for meeting the robustness margins. Therefore a notch filter at that frequency is added to increase the gain margin of the open loop transfer function. Adding a notch filter however costs phase. To deal with this phase loss a skew notch is added which will give phase lead but unfortunately also adds gain at high frequencies. So it is a matter of trade offs. After a process of trial and error for pole and zero placements and choosing damping factors, a controller was designed meeting the required robustness margins (4.1). The open loop transfer function and the accompanying sensitivity function are shown in figure 4.1. The phase lead at the cross over frequency (550 Hz) is 35 degrees and the maximum peak is 6 db in the Sensitivity FRF.

$$\begin{aligned} C(s) &= 57 \cdot \frac{\frac{1}{275\cdot\pi}s+1}{\frac{1}{4400\cdot\pi}s+1} \cdot \frac{0.005s+1}{s} \cdot \frac{\frac{1}{(3348\cdot\pi)^2}s^2+\frac{1.2}{3348\cdot\pi}s+1}{\frac{1}{(3348\cdot\pi)^2}s^2+\frac{1.98}{3348\cdot\pi}s+1} \cdot \frac{\frac{1}{(1600\cdot\pi)^2}s^2+\frac{1.4}{1600\cdot\pi}s+1}{\frac{1}{(2800\cdot\pi)^2}s^2+\frac{1.4}{2800\cdot\pi}s+1} \\ &= Gain \cdot leadfilter \cdot integrator \cdot notch \cdot skew\ notch \end{aligned} \tag{4.1}$$

The measured sensitivity for the internal controller is also plotted in figure 4.1. To be able to compare those figures, the measured FRF is divided by $\alpha\beta\gamma$ as described in equation (3.4). There is not much improvement in performance comparing the Sensitivity function of the loop shape design to the measured data. That is because the implemented controller was probably designed using the same techniques. So to improve the performance of the LTO-1 drive other approaches should be tried.

4.2 Loop Shaping with H_∞ Synthesis

This loop shaping with H_∞ synthesis control design technique has been introduced by McFarlane and Glover in [1]. The main idea of this approach is to shape the plant with input and/or output weighting functions (equation (4.2)). After which a controller is synthesized that minimizes the four closed loop transfer functions using the H_∞ norm (equations (4.3) and (4.4)). In this process the stability margin ϵ is minimized. If $\epsilon_{max} \lll 1$ however, other input and output weighting filters should be chosen. The final controller can be constructed combining this H_∞ controller with the input and output weighting filters (equation (4.5)). $\tilde{M}_s$ is a normalized coprime factor of the shaped plant.

$$P_s = W_2 P W_1 \tag{4.2}$$

$$\epsilon_{max}^{-1} \triangleq \inf_{C \text{ stabilizing}} \left\| \begin{bmatrix} I \\ C \end{bmatrix} (I - P_s C)^{-1} \tilde{M}_s^{-1} \right\|_\infty \tag{4.3}$$

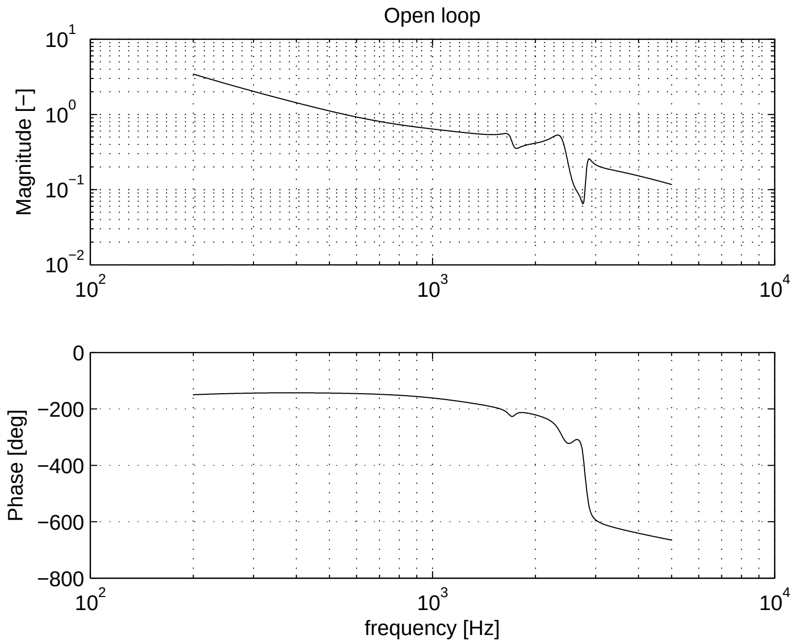
$$\left\| \begin{bmatrix} I \\ C_\infty \end{bmatrix} (I - P_s C_\infty)^{-1} \tilde{M}_s^{-1} \right\|_\infty \leq \epsilon^{-1}, \; \epsilon \leq \epsilon_{max} \tag{4.4}$$

$$C = W_1 C_\infty W_2 \tag{4.5}$$

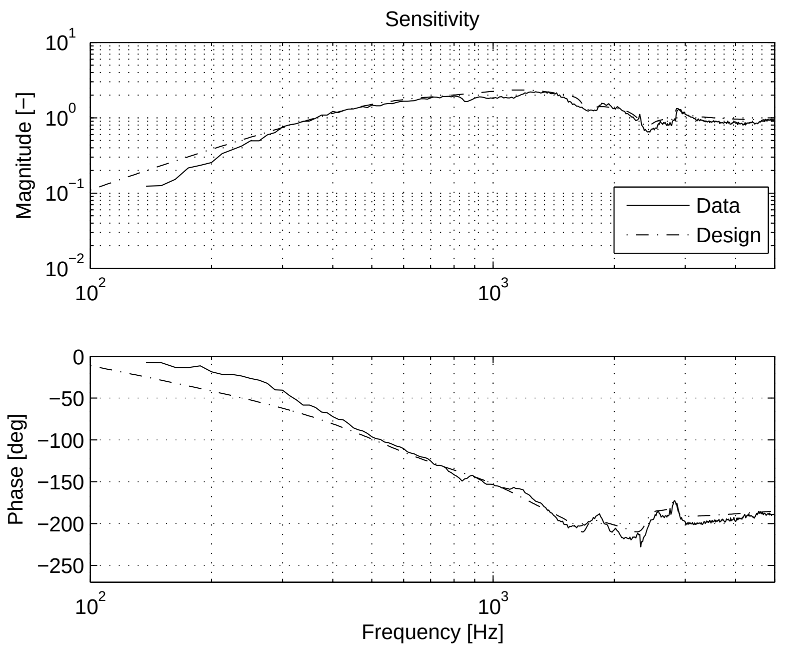
The freedom in the design of this controller is in the choice of the shaping filters for the plant. In the case of the LTO-1 drive, which is a SISO system, there is no separation needed between the two filters. The general approach for designing the shape filter is to give a desired shape to the open loop magnitude, after which the H_∞ will further optimize the 4-block problem in (4.3) to reduce the peaking of the closed loop transfer functions. Reducing peaking will also improve the overall robustness margins. In this case a low frequent integrator combined with a lead filter is chosen as input filter for the plant. The open loop FRF and sensitivity are shown in figure 4.2. The loop shaping controller using H_∞ synthesis is compared to the normal loop shaping controller, because the normal loop shaping controller was comparable to the implemented controller as can be seen in figure 4.1. The order of the controller was reduced using balanced truncation, getting rid of three insignificant states, finding a ninth order controller. Applying the same robustness margins to this controller, the phase lead at the cross over frequency (700 Hz) is 48 degrees and the maximum gain margin is 6 db in the Sensitivity transfer function.

4.3 Modeling periodic disturbances

A drawback of both control designs presented so far in this chapter, is that all low frequent disturbances are suppressed at the cost of high frequent disturbance amplification. However this high frequent amplification is bounded by the robustness margins, this is not ideal. It would be better to suppress the disturbance at exactly the frequencies they occur at. In order to do so, a model of the periodic disturbances will be presented. The main source of disturbances is the Lateral Tape

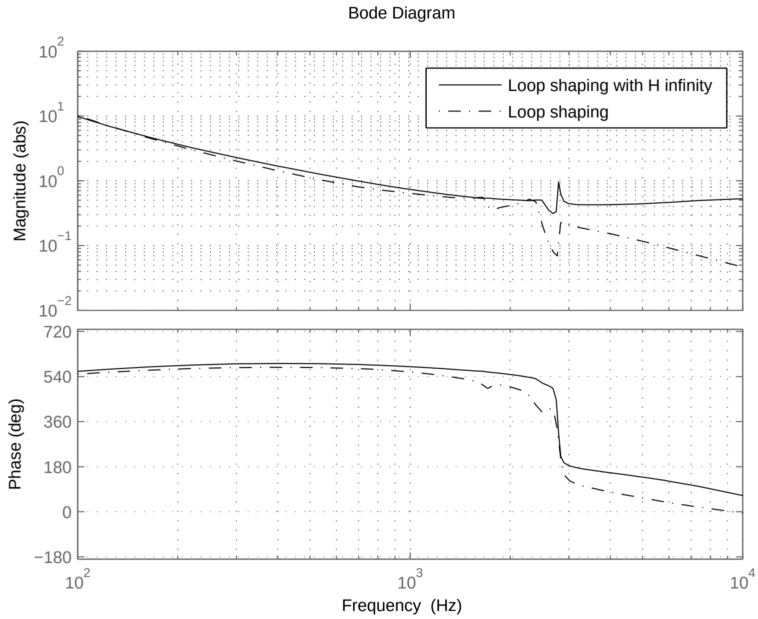


(a)

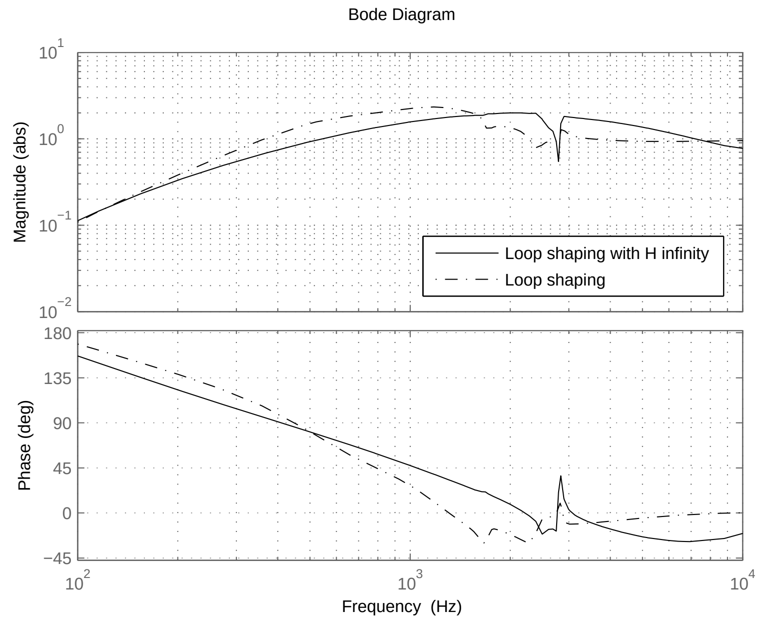


(b)

Figure 4.1: a) open loop model of loop shape controller with plant model. b) Sensitivity model of loop shape controller with plant model compared to the measured sensitivity function.



(a)



(b)

Figure 4.2: a) open loop model of H_∞ controller with plant model. b) Sensitivity model of H_∞ controller with plant model compared to loop shape sensitivity function.

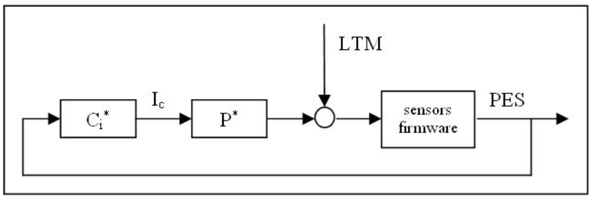


Figure 4.3: Model of the closed loop system with LTM as input signal

Motion (LTM). Those disturbances add up to the PES just after the plant (figure 4.3). Notice that the plant (P^*) in this case does not include the sensors and the firmware as described in section 2.2. The LTM is computed as follows:

1. A time sequence of the PES is measured
2. The PES is transformed into frequency domain using a Fourier transformation
3. The PES frequency data is multiplied with the inverse of the Sensitivity to obtain the frequency domain LTM data
4. The frequency domain LTM data is transformed into time domain using an inverse Fourier transformation

Assumed is that the sensors and firmware are frequency independent and thus only affect the gain. The Sensitivity used at step three should be like equation (4.6) but this gain due to the sensors and firmware (δ) is unknown. The qualitative analysis of the LTM is nevertheless not affected and the measured sensitivity can be used to compute the LTM.

$$LTM \rightarrow PES \quad : \quad \frac{\delta}{1 + C_i^* P} = \delta S \tag{4.6}$$

For further analysis, the power spectral density of the LTM is determined. To do so, the LTM data is divided into frames, with each frame containing a certain part of the data. If the spectral density is then computed for every frame and the results are shown in order, the change of the spectral density of the LTM over time can be studied. Three different kinds of disturbances can be identified in this way, namely: random noise, a non moving disturbance and moving disturbances The first kind of disturbance looks like random noise. This noise comes in bursts and has frequencies up to 50 Hz. The second one is a pulsating disturbance at one specific frequency (65 Hz). The last kind consists of 2 sets of moving disturbances: one series of harmonic disturbances changing to higher frequencies and one series of harmonic disturbances changing to lower frequencies. The peaks of the harmonics have been tracked to see the change in frequency. This is shown in figure 5.1. The non moving disturbance can be explained as a beating effect. Two different disturbances (v_1 and v_2) with slightly different frequencies sometimes amplify each other and sometimes damp each other. Equation (4.7) describes this beating phenomenon in the tape drive and can be due to slight differences in the bearings and geometry of the spools.

$$\begin{aligned} v_1(t) &= \sin(\omega t) \\ v_2(t) &= \sin((\omega + \epsilon)t) \\ v(t) &= v_1(t) + v_2(t) = 2\sin((\omega + \frac{\epsilon}{2})t)\cos(\frac{\epsilon}{2}t) \end{aligned} \tag{4.7}$$

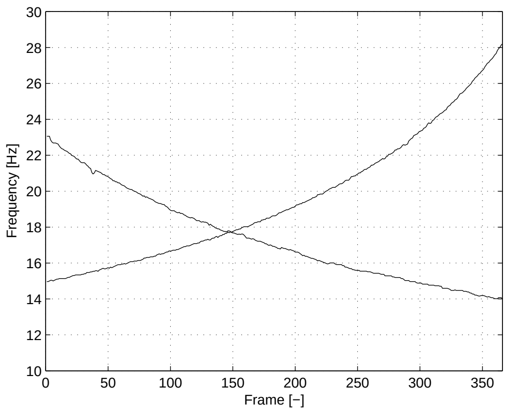


Figure 4.4: Change in frequency of the harmonics. One series changing to higher frequencies and one series changing to lower frequencies over time

The moving disturbances can be due to a change in angular velocity of the reels. The tape speed is kept constant, thus when the reel winds up more tape, the radius increases and the angular velocity should decrease. The angular velocity of the empty (θ_e) and full (θ_f) reel can be described as function of tape speed (V), starting reel radius (r_0) and tape thickness (τ) as in equation (4.8) respectively equation (4.9).

$$\dot{\theta}_e = \frac{V}{\sqrt{r_0^2 + \frac{\tau}{\pi}Vt}} \tag{4.8}$$

$$\dot{\theta}_f = \frac{V}{\sqrt{r_0^2 - \frac{\tau}{\pi}Vt}} \tag{4.9}$$

$$\tag{4.10}$$

It would be helpful during the design of a controller if these identified disturbances could be simulated. This can be done for example in Simulink. The noise and the non moving disturbance can be simulated in a straightforward way. The only difficulty is to simulate a disturbance, y, with a time dependent frequency, $\omega(t)$. This can be simulated as shown in equation (4.11).

$$\begin{aligned} y &= \cos(\psi(t)) \\ \psi(t) &= 2\pi \int \omega(\tau) d\tau \end{aligned} \tag{4.11}$$

Chapter 5

External Control Implementation

In this chapter an external controller will be implemented. This has been tried for the LTO-1 drive, but in the process of experimenting, the input signal grew too big at a certain moment in time which probably caused some damage to the electronics inside the LTO-1 drive. After that it was not possible to do the same measurements anymore at that specific drive. Therefore the implementation of the external controller in this chapter will focus on the LTO-3 drive. Some choices made in this chapter are not optimal. This has unfortunately to do with a lack of time because of that. First some problems designing the external controller will be taken care off. Then a few points of attention concerning the implementation of an external controller will be discussed and finally some results will be presented.

5.1 Design of an external discrete controller

The block diagram for the implementation of the external controller is shown in figure 5.1. The internal controller is still in there, but the gain can be set to zero after which that loop will vanish. The block diagram shows clearly that the earlier opposed transfer function of $\alpha\beta P$ would not be sufficient for control purposes. First of all, the conversion of voltage to micrometer (κ) should be added. But more important is that both an extra digital analogue converter (DA) and an analogue digital (AD) converter are necessary to implement an external controller. The AD converter is reasonable fast and can be neglected for the time being. The DA converter however causes a time delay (τ) of half the sample time. This is due to the concept of zero order hold. This time delay should be taken care of, because it causes phase loss. One way to take this phase loss into

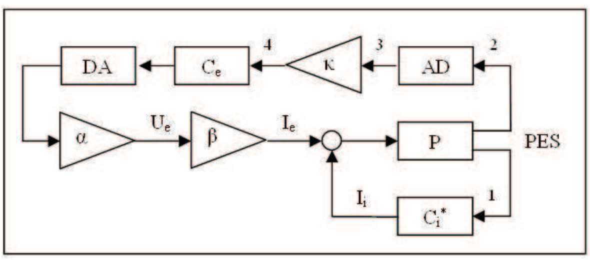


Figure 5.1: Schematic of the implementation of an external controller, with PES1,3:digital PES in volt, PES2: analogue PES in volt, PES4: digital PES in micrometer

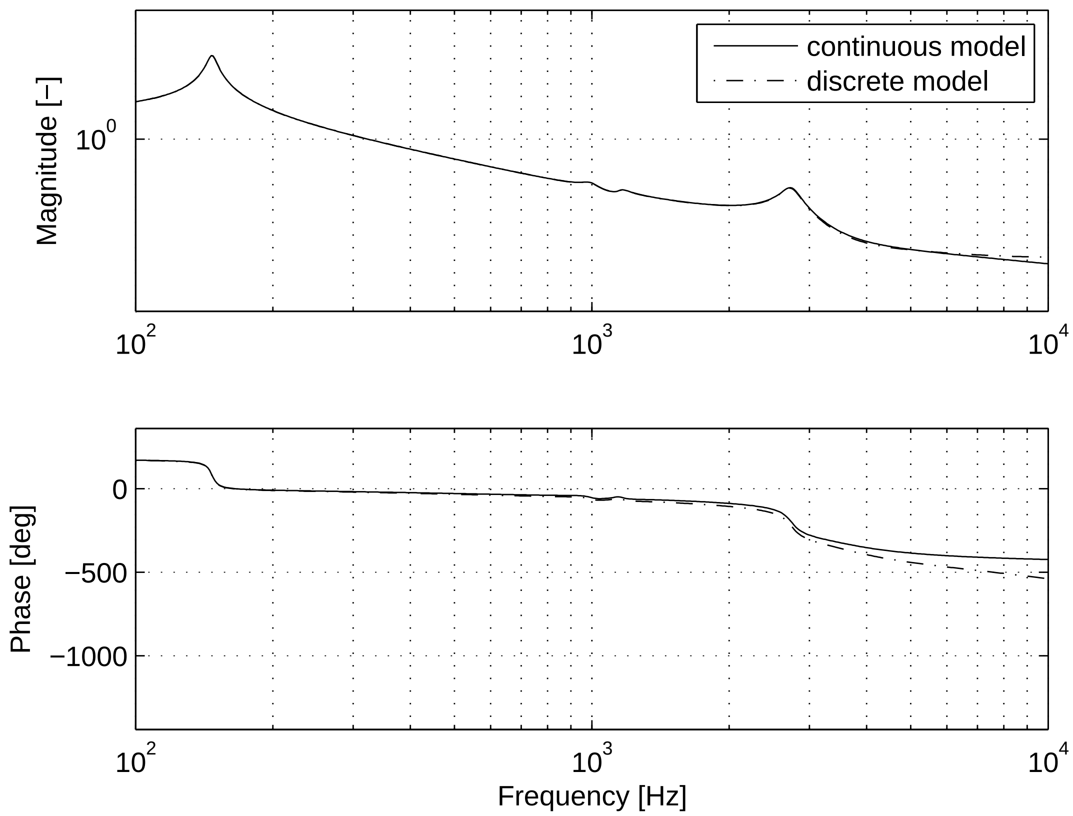
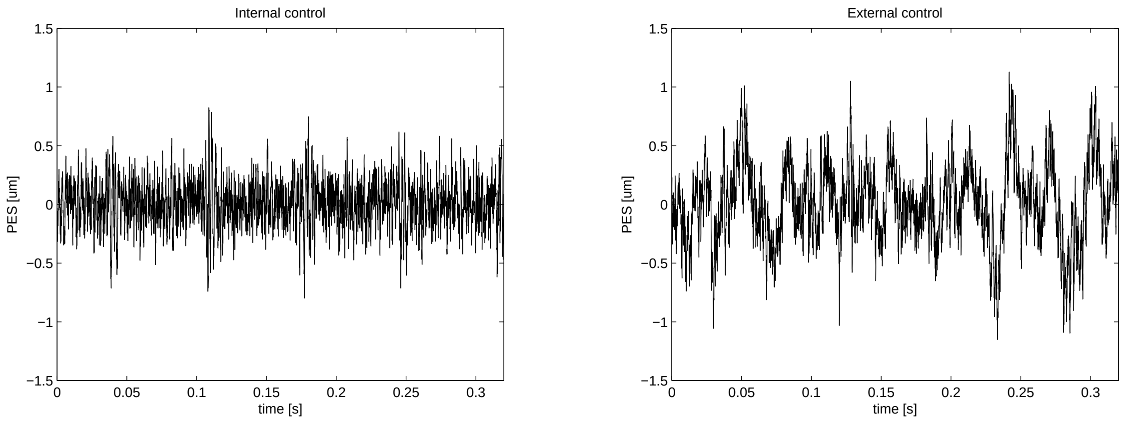


Figure 5.2: Continuous ($\alpha\beta\kappa P$) and discrete model ($\alpha\beta\kappa P_{zoh}$) of the LTO-3 plant dynamics

account is to consider the DA converter as part of the plant. This can be modeled by converting the continuous time plant model to a discrete time model using a zero order hold algorithm (P_{zoh}). Another way to model the DA converter with its time delay is shown in equation (5.1), where ω is the frequency in rad/s.

$$DA = e^{\tau j\omega} \tag{5.1}$$

The original and discrete plant models are shown in figure 5.2. The sample frequency for this discrete model is 20 kHz. There is not much difference in amplitude between the continuous and discrete model, but the discrete model has less phase. The controller should be designed on this model. The controller that will be designed should at least have one step time delay, for it is not possible to use the input measurement of the current time step for the calculation of the output for that same time step. To do so an extra pole should be added to the controller. This will cost some phase lead but is necessary. The controller that will be implemented should not have a pure integrator (pole on the unity circle). This will make the controller marginal stable and can cause the control signal to drift when the PES signal is not properly conditioned. This will be explained some more in the next section.



(a) (b)

Figure 5.3: PES error signal for the internal controller (a) and the external controller (b)

5.2 Implementation of an external discrete controller

The external controller will be implemented using the Matlab Simulink real time windows target. For data acquisition a National Instruments I/O board is used. The system will sample at 20 kHz, faster sampling, if even possible, is not required because the LTO-3 drives samples its PES signal also at 20 kHz. A drawback of this fast sample rate is that our system is not able to handle two inputs and an output at such a fast sample rate. However two inputs are not really necessary, it would be helpful while identifying the implemented system when everything is up and running. The PES signal has an offset of 1.25 V. This value should be subtracted before the control signal is calculated. Moreover the AD converter of the data acquisition board adds an offset (0.06 V) to the PES signal too. This value should be subtracted as well. If this is not taken care of properly, the control signal will drift to an offset value. The tape drive however can only handle voltages up to 0.5 V so this drift should be minimized.

5.3 Results

The controller that is implemented was not designed for performance, only to stabilize the plant and to test the principle. Figure 5.3 compares the PES signal for the internal controller with the PES signal for the external controller. The high frequent error signal is comparable in magnitude, but the external controller does not suppress the low frequent disturbances as good as the internal controller does. The error signal is reasonable small and the head can keep on track with the external controller which was the main goal for this experiment. Now it is possible to identify the implemented controller to check whether the controller behaves as expected or not. To identify the Sensitivity a disturbance signal should be added to the external control signal. Unfortunately the LTO-3 drive has only one injection point and our system can not handle two input signals. The data acquisition board however uses a differential input to minimize noise on the signals. This can be used to subtract an analogue signal from another analogue signal at the input port. In the same manner it is possible to subtract a noise signal from the PES signal and identify the Control Sensitivity as shown in figure 5.4 and described in equation (5.2). The AD converter is

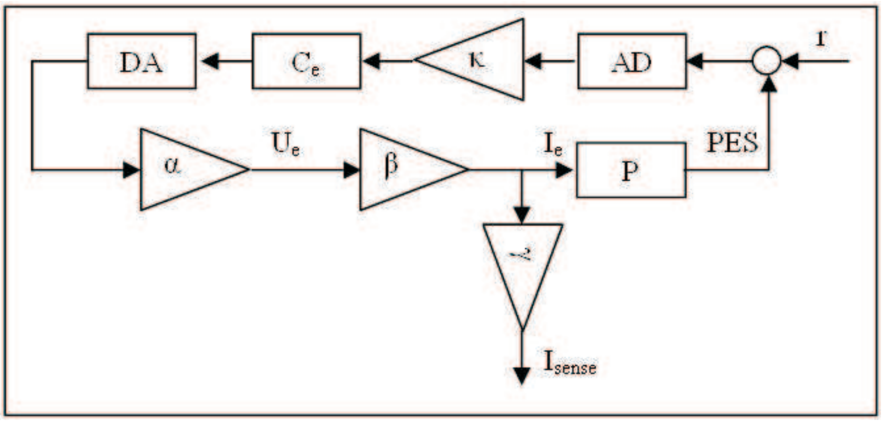


Figure 5.4: Block scheme to identify the Control Sensitivity of the external controller. A reference signal is subtracted from the PES signal at the input board

neglected in this equation.

$$\begin{aligned} -r \rightarrow I_{sense} : \frac{-\kappa C_e DA\alpha\beta\gamma}{1 - C_e P^*_{zoh}} &= -\kappa DA\alpha\beta\gamma CS \\ P^*_{zoh} &= \kappa DA\alpha\beta P \end{aligned} \tag{5.2}$$

The results of the Control Sensitivity measurement are shown in figure 5.5. Moreover the frequency response of the model has been plotted. For the frequencies where the measurement had a good coherence, the model matches the measurement. To check whether the model is also good for the other frequencies, more measurements should be taken and combined the same way as mentioned in section 3.2. Assuming that the model is also good for the lower frequencies, all future controllers should be designed on the model as given in equation (5.2).

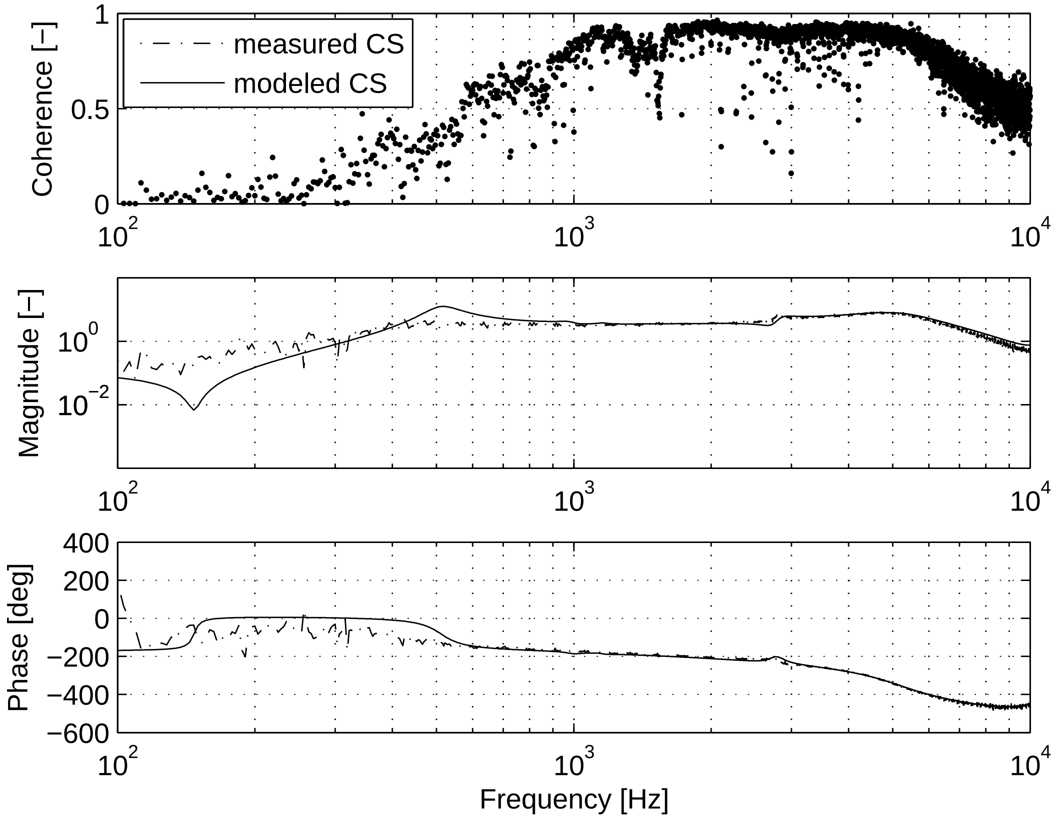


Figure 5.5: Measurement and model of the Control Sensitivity of an external controller

Chapter 6

Conclusion

In order to let the tape drive run on an external controller, the controller should be designed on a model of the tape drive dynamics, which can be identified using several measurements. This model should also include a time delay, caused by the DA converter, and several gains, due to volt to meter conversion and gain differences on the input and output signals. The controller will be a discrete time controller and should have at least one step time delay, for it is impossible to implement it otherwise. This can be done by adding a pole. Moreover this controller should not have a pure integrator to prevent the control signal from drifting. It turned out that it is possible to let the tape drive run on such an external controller. To improve the performances of the drive, new control designs are presented. Nevertheless it will probably be hard to actually increase the performance, because the external controller has to deal with more time delay than the internal controller does. It turned out that classical loop shaping would not be enough to improve the performance. Probably because the internal controller was designed using that technique. However the performance can be improved theoretically using a loop shaping with H_∞ synthesis technique as described in [1]. Another way to improve the performance is to suppress only those frequencies which are identified in the lateral tape motion. A model for this lateral tape motion is given in this report, but is not yet used to design a controller. This report has shown that it is possible to let a tape drive run on an external controller, but there are still more things to do:

- Take more identification measurements on the external controller closed loop system to assure the right models are used
- Try to implement the controller based on the loop shaping with H_∞ synthesis technique and see whether the performance increases or not
- Design an implement a controller based on the lateral tape motion model

Bibliography

[1] Duncan McFarlane and Keith Glover. A loop shaping design procedure using h_∞ synthesis. *IEEE transactions on automatic control*, 37(6):759–769, June 1992.