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ROBUST H$_\infty$ CONTROL IN CD PLAYERS TO SUPPRESS EXTERNAL DISTURBANCES AND DEFECTS ON THE DISK

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ABSTRACT

This paper deals with the design and implementation of robust $\mathcal{H}_\infty$ controllers in order to suppress external disturbances and defects on the disk. Due to the conflictive requirements concerning the bandwidth of the closed loop to suppress external disturbances and defects on the disk, two independent $\mathcal{H}_\infty$ controllers are designed where norm-bounded uncertainties are assumed. The controllers are evaluated through an experiment showing better performance than a classical PID controller.

1. INTRODUCTION

CD players or more generally speaking, Optical Disk Drives (ODD), are mainly characterized by the absence of the physical contact between the pick-up and the disk. Feedback control is necessary to control the position of the focus point of the laser in order to read the data. Two main control loops can be identified: the focus loop which maintains the focus point of the laser on the signal layer, and the radial loop which follows the track.

Due to the different applications in which the ODD can be applied, several challenges emerge. Disturbances can roughly be classified in two groups, external disturbances: like shocks and acoustic feedback from speakers. And defects on the disk: like scratches, finger prints and dust. The first group requires a higher closed loop bandwidth than the second group. If the closed loop has a high bandwidth the controller can have a good performance in suppressing external disturbances but it might follow the defects on the disk, like scratches instead of the track in the signal layer. This imposes conflictive requirements to the closed loop bandwidth of the system. Besides the disturbances the closed loop can be exposed to, the controller must be able to cope with loop changes caused by e.g. the aging of the actuators, parameter variations along the production of ODD and different optical gains of the disks. The design of the controller can be formulated as a $\mathcal{H}_\infty$ control problem where norm-bounded uncertainties are assumed [1], [2]. Due to the conflictive requirements concerning the bandwidth of the closed loop to suppress the disturbances of the two above mentioned groups, two focus $\mathcal{H}_\infty$ controllers are designed. The weight matrices of the exogenous inputs are used as tuning parameters and the multiplicative uncertainty is modeled in a weight matrix in order to make the design of the controllers simpler. These are implemented and show better performance than a PID controller.

2. MODEL OF THE FOCUS SYSTEM

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

$$\frac{X(j\omega)}{V(j\omega)} = \frac{\frac{B\cdot l}{m\cdot R}}{(j\omega)^2 + \left(\frac{(B\cdot l)^2}{m\cdot R} + \frac{C}{m}\right)\cdot j\omega + \frac{K}{m}} \quad (1)$$

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

The absolute distance cannot be measured directly. The intensity of the reflected laser is measured by the photo-diodes and these generate a current, which in the linear area, is directly proportional to the distance between the focus point and the signal layer thereby the photo-diodes can be modeled by a constant gain. Figure 1 depicts a block diagram of the closed loop focus system where $G(s)$ is the plant, $K(s)$ the controller, K_p is the gain of the photo-diodes and the error $e'(s)$ is the difference between the position of the signal layer w(s), considered as noise, and the actual position of the focus point x(s).

As the bandwidth of the focus controller is typically placed between 1 [kHz] and 2 [kHz], [6], it is important to have an accurate uncertainty model around this area. That is the reason why there is focused on an uncertainty model between 100 [Hz] and 10 [kHz] in this paper. In this frequency area the focus model described in equation 1 can then be simplified to equation 2:

$$\frac{X(j\omega)}{V(j\omega)} = \frac{A}{(j\omega)^2} \quad (2)$$

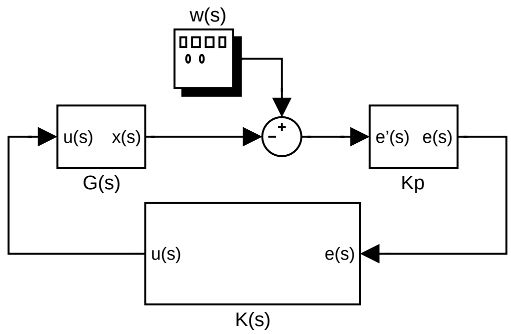

Fig. 1. Closed loop of focus system.

where A is the gain, which can vary, according to the data sheet, between 16.46 to 32.87, hence the nominal model can be expressed as follows:

$$G_{nom}(j\omega) = \frac{24.67}{(j\omega)^2}$$

The multiplicative uncertainty model $G_\Delta(j\omega)$ is then described by equation 3,

$$G_\Delta(j\omega) = G_{nom}(j\omega)(1 + \Delta(j\omega) \cdot l_m(\omega)) \qquad (3)$$

where $\Delta(j\omega)$ is the uncertainty of the focus system, satisfying the inequality $|\Delta(j\omega)| \leq 1$ and $l_m(\omega)$ is the maximal uncertainty, in this case 0.33.

3. DESIGN OF $\mathcal{H}_\infty$ CONTROLLER

In order to design the controller, the weight matrices of the external disturbances $W_d(j\omega)$ and the defects on the disk $W_s(j\omega)$ must be determined. By analyzing the frequency spectrum of the focus error while the CD player is exposed to external disturbances and defects on the disk a good insight can be obtained to design $W_d(j\omega)$ and $W_s(j\omega)$. $W_d(j\omega)$ is modeled as a low-pass filter:

$$W_d(j\omega) = K_d \cdot \frac{1}{\left(\frac{1}{\omega_d} j\omega + 1\right)^2} \qquad (4)$$

Defects on the disk like scratches can be considered as measurement noise which usually are high frequent. $W_s(j\omega)$ is therefore modeled as a high-pass filter.

$$W_s(j\omega) = l_m \cdot \frac{\left(\frac{1}{\omega_{s1}} j\omega + 1\right)}{\left(\frac{1}{\omega_{s2}} j\omega + 1\right)} \qquad (5)$$

In order to make the design of the controllers simpler, the model uncertainty $\Delta(j\omega) l_m(\omega)$ is included in the weight matrix $W_s(j\omega)$.

Figure 2 shows the open loop focus system, where $G(s)$ describes the dynamics of the focus motor, K_i and $K_o(s)$ describe the input amplifier, output amplifier and anti aliasing filter, $W_s(s)$ and $W_d(s)$ are the weight matrices which together with ε_1 and ε_2 are used as tuning parameters of the $\mathcal{H}_\infty$ controller.

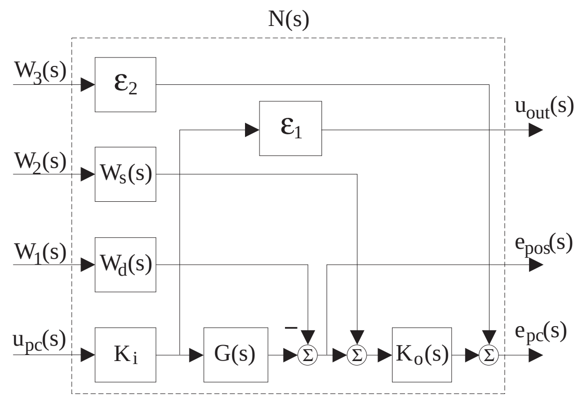

Fig. 2. Open loop of the focus system.

The system can then be represented as a partitioned matrix, as shown below:

$$N(s) = \left[\begin{array}{c|cc} A & B_1 & B_2 \\ \hline C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{array}\right] \qquad (6)$$

In terms of the NΔ-structure the requirements for stability and performance can be summarized as follows [3]:

1. Nominal stability
NS $\Leftrightarrow$ N is internally stable

2. Nominal performance
NP $\Leftrightarrow \| S(j\omega) W_d(j\omega) \|_\infty < 1$

where $S(j\omega)$ is the sensitivity function.

3. Robust stability
RS $\Leftrightarrow | W_s(j\omega) T(j\omega) | < 1$

where $T(j\omega)$ is the complementary sensitivity function.

4. Robust performance
RP $\Leftrightarrow |S(j\omega) W_d(j\omega)| + |W_s(j\omega) T(j\omega)| < 1 \qquad \forall\omega$

Once the norm is selected and the weight matrices are designed the $\mathcal{H}_\infty$ optimal controller can be obtained by expression 7,

$$K(s) = arg \min_{K(s) \in \mathcal{K}_s} \| F_l(N(s), K(s)) \|_{\mathcal{H}_\infty} \qquad (7)$$

which minimizes the peak of the maximum value of $|F_l(N(s), K(s))|$. In practice, it is not necessary to find an optimal controller. It is sufficient finding a sub-optimal controller, which can be calculated by using the function `hinfopt` in the Robust Toolbox of Matlab with $N(s)$ as entry. This function finds a stabilizing controller satisfying the following inequality,

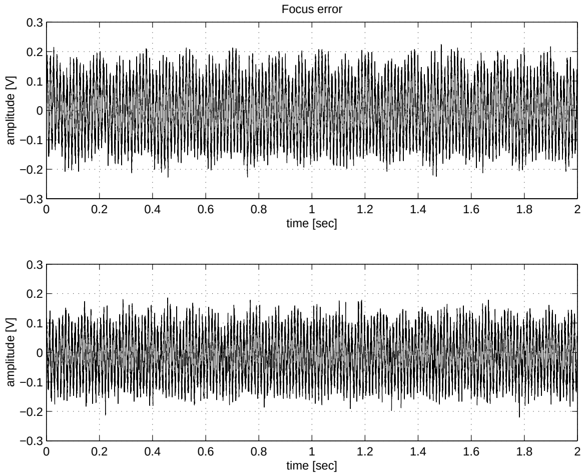

Fig. 3. Focus error with a PID (upper graph) and $\mathcal{H}_\infty$ controller (lower graph) when the CD-player is exposed to a disturbance frequency of 100 [Hz].

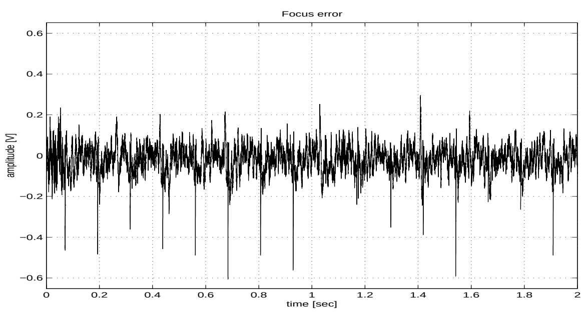

Fig. 4. Focus error with a $\mathcal{H}_\infty$ controller with a disk that has a non reflective scratch of aprox 1.3 [mm] and a reflective scratch of aprox 0.9 [mm].

$$\parallel F_l(N(s), K(s)) \parallel_{\mathcal{H}_\infty} < \gamma \qquad (8)$$

where γ must be $\gamma < 1$ in order to guarantee robust performance.

4. DISCUSSION OF THE EXPERIMENTS

The designed focus controllers were implemented in a 300 MHz Pentium PC with a I/O card which has 12-bit A/D and D/A converters. Direct Access Memory (DMA) was used to avoid CPU overload. In order to implement the controllers it was necessary to reduce the $\mathcal{H}_\infty$ controller order from a 5th to a 4th order and to have a relatively low sampling frequency F_s =20 [kHz] due to the limited calculation speed of the PC. The sampling frequency for this kind of systems is however usually around 50 [kHz] [4],[5].

Due to the conflictive requirements concerning the bandwidth of the closed loop to suppress external disturbances and defects on the disk, as mentioned before in the paper, two $\mathcal{H}_\infty$ controllers are implemented. The bandwidth of the weight matrices are adjusted such that the bandwidth of the closed loop is augmented to cope with external disturbances and reduced to cope with e.g. scratches on the surface of the disk.

Two experiments were therefore performed. The first one, where the CD-player was placed in a vibration board and exposed to a disturbance frequency of 100 Hz. $W_d(j\omega)$, ε_1 and ε_2 had following values:

```
Kd=15000
wd=17.5929
E1=9.0e-10
E2=100000
```

The upper graph in figure 3 shows the focus error of a PID controller tuned to suppress external disturbances and the lower graph in the same figure shows the focus error of the $\mathcal{H}_\infty$ controller. The $\mathcal{H}_\infty$ controller is able to damp the external disturbances slightly better. The $\mathcal{H}_\infty$ controller could be tuned to damp the disturbances better, loosing however robustness due to the following relation,

$$S(j\omega) + T(j\omega) = I$$

where it can be seen that there exists a trade-off between robustness and performace.

Figure 4 shows the focus error of the other $\mathcal{H}_\infty$ controller with following values:

```
lm=0.33
ws1=636.1725
ws2=1131000
E1=9.0e-10
E2=100000
```

which is able to cope with a non reflective scratch of aprox 1.3 [mm] and a reflective scratch of aprox 0.9 [mm]. The music could be reproduced without audible anomalies. It was not possible to implement a PID controller which was able to cope with these two scratches. The degrees of freedom in a PID controller are more limited than in a $\mathcal{H}_\infty$ controller, which explains why the PID controller cannot have a low bandwidth to cope with the scratches, a high gain at low frequencies to suppress disturbances from unbalanced disks, at the same time as the stability constraints are satisfied.

5. CONCLUSION

In this paper the design and implementation of two robust $\mathcal{H}_\infty$ controllers on the focus system has been presented. Minor differences were observed between the PID and the $\mathcal{H}_\infty$ controller when suppressing external disturbances. The $\mathcal{H}_\infty$ controller tuned to cope with defects on the disk showed though positive results. The ideal situation would be to control the focus error with the $\mathcal{H}_\infty$ controller tuned to suppress external disturbances, and when a defect on the disk is detected, the controller is replaced with the $\mathcal{H}_\infty$ controller tuned to cope with defects on the disk.

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