POLE PLACEMENT/SENSITIVITY FUNCTION SHAPING AND CONTROLLER ORDER REDUCTION IN DVD PLAYERS (FOCUS CONTROL LOOP)

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Abstract

The problem considered in this paper is the robust controller design for the focus control loop of DVD-video drive. For low-speed players, is known that this problem can be solved by means of simple lead-lag regulators. For high-speed players the disturbance rejection is more difficult problem than for CD players because of higher performance requirements. The control scheme proposed here is based on the design of robust digital controllers using the combined pole placement/sensitivity function shaping method to reduce the effect of repetitive disturbances. Controller order reduction is performed to allow its practical implementation. Experimental results, obtained on a real system in STMicroelectronics laboratories, illustrate the performance of the proposed algorithms for the focus control loop.

1 Introduction

Control of DVD player represents today a challenge for IC manufacturers and for consumer micro-controller device producers. A demand emerging from the current multi-media applications is to obtain a shorter data time access, high information density recorded on the disk, good periodical disturbance rejection, and good shock resistance. These new features require an improvement of the follow-up capability of the laser beam focussing in order to avoid loosing the disk information layer and the stability of the focus control loop, without decreasing the disk rotational speed.

Concerning DVD players, to our knowledge, only recently few papers have been dedicated to a narrow-band disturbance suppression in a high-speed DVD players system. In [3], the notch and funnel filters are used for the estimation of the rotating speed of a DVD player, in order to implement a control scheme which selectively cancels narrow-band disturbances. The work [2] proposes a control architecture for track following using the notch filtering and multirate control.

A combined pole placement/sensitivity function shaping methodology have not been used to control design till now although this method offers the possibilities on the periodic disturbance rejection. This paper treats mainly the control design of the focus loop. The controller is based on experimental results obtained on a real system in STMicroelectronics laboratories. The same method have been successfully used in tracking control loop design, [4].

The paper is organized as follows: in section 2, a disturbance sources incoming to the system and specification requirements are explained. Control methodology is presented in section 3. Control design for DVD player is shown in section 4 and section 5 presents performance analysis of the proposed controllers.

2 Problem statement

2.1 Focus control loop

In fig. 1 a block diagram of the focus control loop is shown. A peculiar feature of this servo loop is that the absolute position of the optical pick-up can not be measured. The only measure available for control purposes is the focus error e_F, in the neighborhood of the information layer. Moreover, notice that input/output measures of the plant u_F, e_F can be collected only in closed-loop working condition.

2.2 Disturbances sources

A large percentage of the internal disturbances are synchronous with the spindle frequency f_rot and its harmonics including oscillations in the disk media. Fig. 8 illustrates the power spectrum of the focus error signal e_F, at given rotational frequency $f_\mathrm{rot} = 15\,\mathrm{Hz}$, that has been acquired on the real DVD system in STMicroelectronics laboratories. One can see that main disturbances are given by the first and the second harmonic components of disk rotational frequency f_rot.

The external disturbances affecting drives are typically envi-

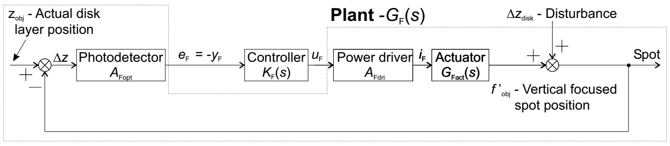

Figure 1: Configuration of the focus control loop.

ronmental shocks and vibrations, whether from a moving vehicle, a factory floor environment, a computer under a desk being kicked, or simply the motion of a laptop computer. For streaming media such as DVD/CD, they are usually overcome by data buffering in the portable players or cars. More detail information on the presented disturbances sources of both the DVD/CD players are in [1] and its references.

2.3 Focus servo specification

The specification contained in [5], mainly for the over-speed factor $N = 1$, prescribes two maximal deviations Δz_{low}, Δz_{high} from the nominal position of the disk and the maximal acceleration a of the scanning point at given frequencies, as briefly presented in table 1. f_{c} is specified by (1), where the coefficient α is equal to 1.5 in order to increase the maximal axial acceleration a.

The desired closed loop bandwidth f^{BW} is not specified in [5] but it is approximately equal to the cross-over frequency of the open loop f_{c}.

$$f_{\mathrm{c}} = \frac{N}{2\pi}\sqrt{\frac{3\,\alpha\,a}{\Delta z_{\mathrm{high}}}} = \frac{1}{2\pi}\sqrt{\frac{3\times 1.5\times 8}{0.23\times 10^{-6}}} = 2\,\mathrm{kHz} \qquad (1)$$

An additional information, concerning the closed loop performances, can be given from the rise time t_{r} of the closed loop step response, defined as the time it takes for the output y_{F} to first reach $90\,\%$ of its final value. t_{r} usually verifies the following equation

$$t_{\mathrm{r}} \simeq \frac{2.3}{2\pi f_{\mathrm{c}}} = \frac{2.3}{2\pi\, 2\times 10^{3}} = 0.183\,\mathrm{ms} \qquad (2)$$

Another important parameter for focusing is so-called focus depth Δz_{max}that establish maximal disk displacement between actual disk information layer and the position of the focused laser spot of the objective lens. Δz_{max} is defined by

$$\Delta z_{\mathrm{max}} = \frac{\lambda}{2NA^{2}} \qquad (3)$$

The numerical value $\Delta z_{\mathrm{max}} \doteq 0.903\,\mu\mathrm{m}$ is given by DVD parameters: laser wavelength $\lambda = 650\,\mathrm{nm}$ and numerical aperture of the objective lens $NA = 0.6$. The focus servo should therefore control the objective lens within $\pm\Delta z_{\mathrm{max}}$ to avoid loosing the data read-out signal at every time during playing.

The actual (spindle) rotational frequency f_{rot} of the disk is given by

$$f_{\mathrm{rot}} = \frac{N v_{\mathrm{a}}}{2\pi x}, \qquad (4)$$

Table 1: Focus servo specification for the DVD, $N = 1$.

	Parameter	Range (Hz)	Value
Δz_{low}	Max. deviation from nominal position	$f_{\mathrm{rot}} \leq 23.1$	$\pm 0.3\,\mathrm{mm}$
a	Max. vertical acceleration	$f_{\mathrm{rot}} > 23.1$	$8\,\mathrm{m/s^2}$
Δz_{high}	Max. deviation from nominal position	$f_{\mathrm{rot}} > 2000$	$\pm 0.23\,\mu\mathrm{m}$
f_{c}	Crossover frequency of the open loop		$2\,\mathrm{kHz}$
f^{BW}	Desired closed loop bandwidth		$\approx f_{\mathrm{c}}$
x_{ini}	Min. radius	$f_{\mathrm{rot}} = 23.1$	$24\,\mathrm{mm}$
x_{fin}	Max. radius	$f_{\mathrm{rot}} = 9.6$	$58\,\mathrm{mm}$
v_{a}	Scanning velocity		$3.49\,\mathrm{m/s}$
Δz_{max}	Focus depth		$0.903\,\mu\mathrm{m}$

where v_{a} is the scanning velocity and x is the distance between the disk rotational axis and the falling laser beam, $x \in \langle x_{\mathrm{ini}},\, x_{\mathrm{fin}}\rangle$, (see fig. 2).

2.4 The aims of the controllers design

The goal of the focus controller design is to minimize the amplitude of the focus displacement Δz, measured by the focus error signal e_{F}, during playback.

The periodical disturbances are mainly given by the rotational frequency f_{rot}, that is not constant during playback, (see expression (4)), because a constant linear velocity (CLV) is used to read the data recorded on the disk. These disturbances are mainly caused by the disk eccentricity Δx_{disk}, disk warping, disk thickness variation. Fig. 2 shows the geometry of the vertical deviation sources.

It is clear that the vertical deviation of the turning disk Δz_{disk} is not constant along the whole scanned track on the disk, (Δz_{disk} depends on the laser beam position x_{laser} from the rotation axis of the spindle). Therefore at the starting radius of the data zone x_{ini}, (where $f_{\mathrm{rot}} = 23.1\,\mathrm{Hz}$), the vertical deviation Δz_{ini} is *smaller* than the vertical deviation Δz_{fin} at the maximum radius of the data zone x_{fin} (where $f_{\mathrm{rot}} = 9.6\,\mathrm{Hz}$).

Hence, the different requirements on the disturbance rejection can be given in frequency domain. The sensitivity function shaping method is a useful tool to design controllers satisfying these system requirements.

3 Control design methodology

3.1 Pole placement & sensitivity function shaping

The standard digital control configuration obtained with polynomial RST controlleris presented in fig. 3. Part T of RST

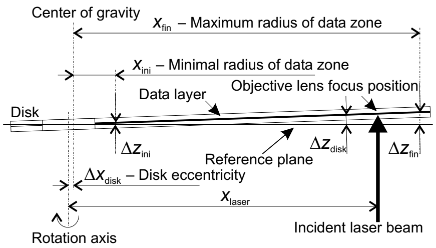

Figure 2: Sources of vertical deviation on the DVD disk, mainly caused by disk warping and disk tracking eccentricity.

structure has been omitted because the control design in the focus loop of DVD/CD players only contains the disturbance rejection.

Pole placement method have been used to design the controller's parts RS. The linear-time-invariant model of the plant is described by the transfer function

$$\begin{aligned} G(q^{-1}) &= \frac{q^{-d}\,B(q^{-1})}{A(q^{-1})} \\ &= \frac{q^{-d}\left(b_1\,q^{-1} + \cdots + b_{n_B}\,q^{-n_B}\right)}{1 + a_1\,q^{-1} + \cdots + a_{n_A}\,q^{-n_A}}, \end{aligned} \tag{5}$$

where q^{-1} is the backward time shift operator, d is the pure time delay, $T_{\text{s}} =$ the sampling period and sampling frequency $f_{\text{s}} = 1/T_{\text{s}}$.

Experience shows that simple linear model of DVD/CD system leads to sufficient high-performance controllers, [2], given by specifications presented in section 2.3 and in [5]. A more complex controllers, based on the high order model, have higher performance but they are practically useless. It is given from the constrainers during controllers implementation where the low-order controllers are still preferred.

The RS controller has the following transfer function

$$\begin{aligned} K(q^{-1}) &= \frac{R(q^{-1})}{S(q^{-1})} = \frac{R^{'}(q^{-1})\,H_{\text{R}}(q^{-1})}{S^{'}(q^{-1})\,H_{\text{S}}(q^{-1})} \\ &= \frac{r_0 + r_1\,q^{-1} + \cdots + r_{n_{\text{R}}}\,q^{-n_{\text{R}}}}{1 + s_1\,q^{-1} + \cdots + s_{n_{\text{S}}}\,q^{-n_{\text{S}}}}, \end{aligned} \tag{6}$$

where $H_{\text{R}}(q^{-1})$ and $H_{\text{S}}(q^{-1})$ denote the fixed parts of the controller (either imposed by the design or introduced in order to shape the sensitivity functions). $R^{'}(q^{-1})$ and $S^{'}(q^{-1})$ are solutions of the Bezout equation

$$AS^{'}H_{\text{S}} + BR^{'}H_{\text{R}} = P, \tag{7}$$

where P represents the characteristic polynomial (closed loop poles).

The four sensitivity functions $S_{ij}(K, G)$ are defined as follows: The output sensitivity function $S_{\text{yp}}(q^{-1}) = \dfrac{y(t)}{p(t)} = \dfrac{AS^{'}H_S}{P}$, input sensitivity function $S_{\text{up}}(q^{-1}) = \dfrac{u(t)}{p(t)} = -\dfrac{AR^{'}H_R}{P}$, output sensitivity function with respect to an input disturbance

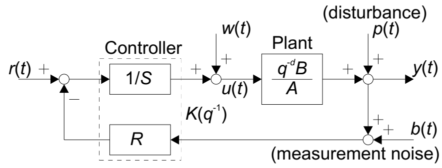

Figure 3: The closed loop system with RS controller.

$S_{\text{yw}}(q^{-1}) = \dfrac{y(t)}{w(t)} = \dfrac{q^{-d}BS^{'}H_S}{P}$ and complementary sensitivity function $S_{\text{yr}}(q^{-1}) = \dfrac{y(t)}{r(t)} = \dfrac{q^{-d}BR^{'}H_R}{P}$.

In our case, not only robustness (the modulus margin ΔM, delay margin $\Delta\tau$ and phase margin $\Delta\phi$) but also the performances specifications, [5], have to be check. Fortunately, the robustness requirements are related to sensitivity functions. Therefore the sensitivity function shaping is a useful tool to the controller design in case of DVD/CD players.

3.2 Controller order reduction

Controller order reduction is a very important issue in many control application, either because the size of the controller is limited by hardware and computation time or because simpler controllers are easier to implement. What is most important is that controller reduction should aim to preserve the required closed loop properties as far as possible. One of useful methodology, which is used here, is the balanced reduction method in state space domain that using a Gramian of the balanced state-space realization.

3.3 Generalized stability margin

The resulting reduced order controller should stabilize the nominal model and should give sensitivity functions which are closed to the nominal ones in critical frequency regions to ensure performance and robustness. One way to verify the stability margin of the whole system is the generalized stability margin $b(K, G)$ defined from all sensitivity functions

$$b(K,G) = \begin{cases} \left\| \mathbf{T}(K,G) \right\|_{\infty}^{-1} & \text{if } (K,\,G) \text{ is stable,} \\ 0 & \text{otherwise,} \end{cases} \tag{8}$$

where

$$\mathbf{T}(K,G) = \begin{bmatrix} S_{\text{yr}} & S_{\text{yw}} \\ -S_{\text{up}} & S_{\text{yp}} \end{bmatrix},$$

in which S_{yr}, S_{yw}, S_{up} and S_{yp} have been defined is section 3.1. The generalized stability margin gets higher the more $b(K, G)$ value is achieved.

Table 2: Parameters of the plant in focus control loop.

Symbol	Parameter
R_{F}	Coil resistance
L_{F}	Coil inductance
K_{Fe}	Back efm constant
M_{F}	Actuator moving mass
D_{F}	Dumping constant
K_{Fs}	Elastic constant
K_{Ff}	Force constant
A_{Fdri1}	First power driver gain
A_{Fdri2}	Second power driver gain
A_{Fopt}	Optical gain & remanent gains

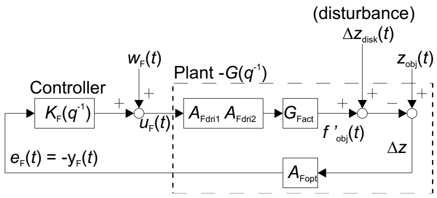

Figure 4: Focus closed loop of the DVD.

4 Control design

4.1 Plant model

A simplified, linear transfer function of the focus control loop $G_{\mathrm{F}}(s)$ is derived from the physical equations of focus system as follows.In table 2 its parameters are presented.

$$G_{\mathrm{F}}(s) = \frac{\frac{K_{\mathrm{Ff}}}{M_{\mathrm{F}} L_{\mathrm{F}}} A_{\mathrm{Fdri1}} A_{\mathrm{Fdri2}} A_{\mathrm{Fopt}}}{s^3 + \left(\frac{R_{\mathrm{F}}}{L_{\mathrm{F}}} + \frac{D_{\mathrm{F}}}{M_{\mathrm{F}}}\right) s^2 + \left(\frac{D_{\mathrm{F}} R_{\mathrm{F}}}{M_{\mathrm{F}} L_{\mathrm{F}}} + \frac{K_{\mathrm{Fs}}}{M_{\mathrm{F}}} + \frac{K_{\mathrm{Ff}} K_{\mathrm{Fe}}}{M_{\mathrm{F}} L_{\mathrm{F}}}\right) s + \frac{K_{\mathrm{Fs}} R_{\mathrm{F}}}{M_{\mathrm{F}} L_{\mathrm{F}}}} \tag{9}$$

The discrete transfer function of the focus system $G_{\mathrm{F}}(q^{-1})$ is given by conversion from the continuous-time to the discrete-time using a zero-order hold and the sampling period T_{s}, (a clock period of the Digital Signal Processor (DSP)), by the following expression:

$$G_{\mathrm{F}}(q^{-1}) = \frac{b_1 q^{-1} + b_2 q^{-2} + b_3 q^{-3}}{1 + a_1 q^{-1} + a_2 q^{-2} + a_3 q^{-3}} \tag{10}$$

Here $d = 0$, see (5). The other numerical values for $B(q^{-1})$ and $A(q^{-1})$ polynomial coefficients are not presented for reason of confidentiality.

4.2 Standard controllers

The second order lead-lag controller $K_{\mathrm{act}}(q^{-1})$, given by (11), is used in many actual DVD/CD applications as a standard controller structure.

$$K_{\mathrm{act}}(q^{-1}) = g_0 \frac{\left(1 - c_1\, q^{-1}\right)\left(1 - c_2\, q^{-1}\right)}{\left(1 - d_1\, q^{-1}\right)\left(1 - d_2\, q^{-1}\right)} \tag{11}$$

This standard second order lead-lag controller ($K_{\mathrm{act}}(q^{-1})$: $n_{\mathrm{R}} = 2, n_{\mathrm{S}} = 2$) is actually replaced by a third order ($K_{\mathrm{RS3}}(q^{-1})$: $n_{\mathrm{R}} = 3, n_{\mathrm{S}} = 3$) or a fourth order ($K_{\mathrm{RS4}}(q^{-1})$: $n_{\mathrm{R}} = 4, n_{\mathrm{S}} = 4$) controller in order to meet higher performance on the disturbance rejection.

The aim of this work is to provide a methodology to design the third (or fourth) order controllers that improve the actual performance on the disturbance rejection and fulfil the realization constrains in actual DVD platform.

4.3 New controller design

The third order RS controller $K_{\mathrm{RS3}}(q^{-1})$ and the fourth order RS controller $K_{\mathrm{RS4}}(q^{-1})$ are designed for DVD-video player, for over-speed factor $N = 1.5$. The rotational frequency f_{rot} at the data zone starting radius x_{ini} is 34.7 Hz while one at the data zone maximum radius x_{fin} is 14.4 Hz. The controller design should take also into account that on the DVD/CD disk the data area increases proportionally to the square of the disk radius.

When the over-speed factor N is bigger than 1, the break rotational frequency in performance specification $f_{\mathrm{cor}} = 23.1$ Hz, must be linearly shifted by the same factor N. Therefore the minimum sensitivity

$$S_{\mathrm{low}} = 20 \log \left(\frac{|\Delta z_{\mathrm{high}}|}{|\Delta z_{\mathrm{low}}|} \right) = -62.31\,\mathrm{dB} \tag{12}$$

is required at frequency $f_{\mathrm{rot}} = 23.1 \cdot 1.5 = 34.7$ Hz.

To suppress the periodical disturbances, mainly caused by disk warping together with the disk eccentricity at rotational frequency f_{rot}, a small modification on the $|S_{\mathrm{yp}}|$ template has been done:

1. $f_{\mathrm{rot}} = 34.7$ Hz:
   $|S_{\mathrm{yp}}| = S_{\mathrm{low}} - 18$ dB$= -80.31$ dB
2. $f_{\mathrm{rot}} = 14.4$ Hz:
   $|S_{\mathrm{yp}}| = 20 \log \left(\frac{|\Delta z_{\mathrm{high}}|}{|\Delta z_{\mathrm{low}}|} \cdot \frac{x_{\mathrm{ini}}}{x_{\mathrm{fin}}} \right) - 18$ dB$= -87.97$ dB
3. $f_{\mathrm{rot}} \in \langle 14.4\,\mathrm{Hz}, 34.7\,\mathrm{Hz} \rangle$:
   $|S_{\mathrm{yp}}|$ = linear interpolation between $|S_{\mathrm{yp}}|$ at two given frequencies: $f_{\mathrm{rot}} = 14.4$ Hz and $f_{\mathrm{rot}} = 34.7$ Hz
4. $f_{\mathrm{rot}} > 34.7$ Hz: $|S_{\mathrm{yp}}|$ is given by specification in [5] where the upper and lower limits on the $\left| \frac{1}{1 + H_s} \right|$ are defined

The low limit at the rotational frequency $f_{\mathrm{rot}} = 34.7$ Hz have been toughened up rather 18 dB. The low limit at the rotational frequency $f_{\mathrm{rot}} = 14.4$ Hz have been linearly increased with respect on the ratio of the data zone radiuses $\left(\frac{x_{\mathrm{ini}}}{x_{\mathrm{fin}}}\right)$, to take into account data distribution on the disk, and shifted rather 18 dB too.

The specification requirements (defined by the DVD disk and by normalized servo) with our modification are illustrated

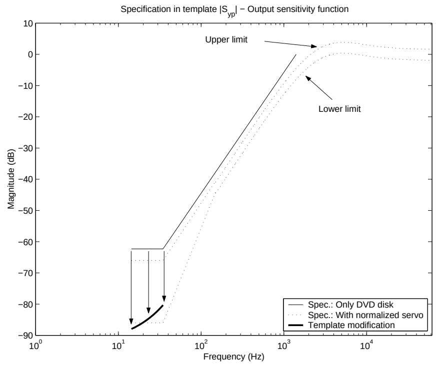

Figure 5: Desired template for the modulus of the output sensitivity function S_{yp} for focus loop, $N = 1.5$.

as the output sensitivity function modulus $|S_{\mathrm{yp}}|$ templates in fig. 5.

The controller design of the fourth order controller K_{RS4} has been realized using the following specifications:

- P (closed loop poles):
  - a pair of complex poles near the model's slowest vibration frequency $f_{\mathrm{D}} = 52\,\mathrm{Hz} \rightarrow 70\,\mathrm{Hz}$ but well damped $\xi_{\mathrm{D}} = 0.098 \rightarrow 0.98$
  - three multiple real poles $\gamma_{\mathrm{F}} = 0.867$ for keeping in the $|S_{\mathrm{yp}}|$, $|S_{\mathrm{up}}|$ templates
- H_{S}: a pair of complex poles $f_{\mathrm{S}} = 19.5\,\mathrm{Hz}$, $\xi_{\mathrm{S}} = 0.1$ to ensure disturbance rejection in the frequency range $f_{\mathrm{rot}} \in \langle 14.4\,\mathrm{Hz}, 34.7\,\mathrm{Hz}\rangle$
- H_{R}: a real zero $\gamma_{\mathrm{R}} = 0.239$ to lower the magnitude of the input sensitivity function $|S_{\mathrm{up}}|$ at high frequencies where the gain of the system is low
- The resulting controller has the orders $n_{\mathrm{R}} = 5$ and $n_{\mathrm{S}} = 7$. Therefore the balanced reduction method has been used to obtain a controller structure $n_{\mathrm{R}} = 4$ and $n_{\mathrm{S}} = 4$.
- Check the sensitivity functions $|S_{\mathrm{yp}}|$, $|S_{\mathrm{up}}|$, $|S_{\mathrm{yr}}|$ again. End the design procedure if the requirements on the sensitivity functions were satisfied.

The same procedure has been used to the third order RS controller K_{RS3} design except balanced reduction. Nevertheless, the restrictions on the resulting controller gives smaller performance in the frequency range $f_{\mathrm{rot}} \in \langle 14.4\,\mathrm{Hz}, 34.7\,\mathrm{Hz}\rangle$. The controllers are designed using the recently developed software tool "ppmaster" [6], developed in MATLAB®environment.

5 Performance analysis

5.1 Focus loop: Simulation experiments

Results are shown for the actual controller K_{act} and the designed fourth order RS controller K_{RS4}.

The disturbance rejection at the rotational's frequencies is illustrated by the output sensitivity function modulus $|S_{\mathrm{yp}}|$ in fig. 6. Notice that the perturbations suppression at $f_{\mathrm{rot}} = 22\,\mathrm{Hz}$ have

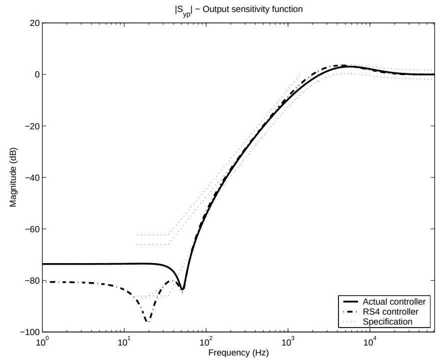

Figure 6: Output sensitivity function, focus loop.

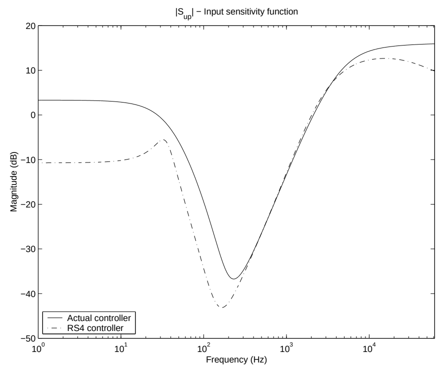

Figure 7: Input sensitivity function, focus loop.

been achieved by the H_S polynomial choice. Fig. 7 presents the input function. The lower peak in $|S_{\mathrm{yp}}|$ and lower values of $|S_{\mathrm{up}}|$ in low frequencies for the controller K_{RS4} than for actual controller K_{act} are seen.

One can see in table 4 that the rise time is satisfied in both cases but the overshot is about $7\,\%$ higher for the system with fourth order controller K_{RS4}.

A good control order reduction methodology and a good generalized stability margin of third/fourth order designed controllers $K_{\mathrm{RS3}}/K_{\mathrm{RS4}}$ are shown in table 3, where the parameters of reduced controllers are n_{R}, n_{S}, $b(K,G)$ and the ones of non-reduced controllers are $\widehat{n_{\mathrm{R}}}$, $\widehat{n_{\mathrm{S}}}$, $\widehat{b(K,G)}$.

The comparison of the performances of various reduced controllers is shown in table 4. The peak value of the disk displacement $\Delta z_{\mathrm{p},22}$, obtained by the focus closed loop model, for $f_{\mathrm{rot}} = 22\,\mathrm{Hz}$ and the sinusoidal disturbance amplitude $\Delta z_{\mathrm{disk}} = 0.44\,\mathrm{mm}$ is presented at last column in table 4. The peak to peak value Δz_{p} is not measurable in practise, but the simulation illustrates the improvement in the periodic disturbance rejection.

5.2 Focus loop: Real-time measurements

Real-time measurements are done with the third order RS controller K_{RS3} because the fourth order controller is not implementable into a DSP controller structure in actual DVD-video

Table 4: Comparison of the various reduced controllers, $N = 1.5$, focus loop.

$K(q^{-1})$	$n_{\rm R}$ $(-)$	$n_{\rm S}$ $(-)$	$\lvert S_{\rm yp}\rvert_{\max}$ (dB)	$\lvert S_{\rm yp}\rvert_{14.4}$ (dB)	$\lvert S_{\rm yp}\rvert_{34.7}$ (dB)	$\lvert S_{\rm up}\rvert_{\max}$ (dB)	$t_{\rm r}$ (μs)	Overshot (%)	$\Delta\tau$ (μs)	$\Delta\phi$ (degree)	$\Delta z_{\rm p,22}$ (μm)
$K_{\rm act}$	3	3	3.02	-73.5	-74.9	16.1	72.9	25	48.0	51.6	0.093
$K_{\rm RS3}$	3	3	3.28	-80.2	-82.5	15.5	72.9	31	46.4	48.5	0.041
$K_{\rm RS4}$	4	4	3.45	-88.0	-80.3	12.3	81.0	32	48.9	46.1	0.011
Spec.			3.85	-66.0	-66.0		122.5				0.903

Table 3: Comparison of the controller order reduction and generalized stability margin, $N = 1.5$, focus loop.

$K(q^{-1})$	$n_{\rm R}$ $(-)$	$n_{\rm S}$ $(-)$	$\widehat{n_{\rm R}}$ $(-)$	$\widehat{n_{\rm S}}$ $(-)$	$b(K,G)$ $(-)$	$\widehat{b(K,G)}$ $(-)$
$K_{\rm act}$	3	3	3	3	0.15563	
$K_{\rm RS3}$	3	3	4	4	0.16476	0.16476
$K_{\rm RS4}$	4	4	5	5	0.23351	0.23294

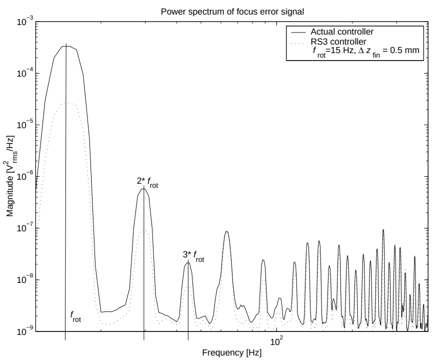

Figure 8: The measured power spectrum density of the focus error signal $e_{\rm F}$ for tested disk with very small disk eccentricity $\Delta x_{\rm disk}$, but with high disk vertical deviation at the disk outer edge $\Delta z_{\rm fin} = 0.5\,$mm, $f_{\rm rot} = 15\,$Hz.

player platform.

The disturbance elements of the focus error signal $e_{\rm F}$, in frequency domain at two different rotational frequencies $f_{\rm rot}$, are illustrated in figs. 8 and 9, where the power spectrum of the focus error signal $e_{\rm F}$ has been acquired on the real DVD system with the 3rd-order controller $K_{\rm RS3}$. These results point out that the obtained improvements are still influenced by disk rotational frequency $f_{\rm rot}$.

6 Conclusion

This paper has dealt with combined pole placement/sensitivity function shaping control design connected with controller order reduction for the focus control loop of DVD-video player, under industrial performance specifications. Modifications on the output sensitivity template have been explained and directly fulfill in controllers design to obtain improvement in term of periodic disturbances. Final comparison of the actual and designed controllers illustrate that new controllers provide better system performances and robustness than the actual controllers. Nevertheless, the presented disturbance rejection is impossible to obtain with more controller order reduction.

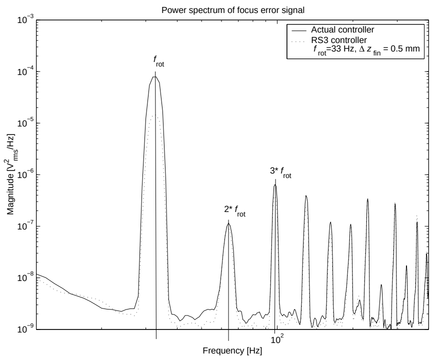

Figure 9: The same as in fig. 8 but for $f_{\rm rot} = 33\,$Hz.

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