ROBUST H_∞ CONTROL OF A DVD DRIVE UNDER PARAMETRIC UNCERTAINTIES

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Abstract: This paper is devoted to the control system design and implementation of an industrial DVD-video drive. A standard H_∞ approach is proposed to control the linear displacement of the optical head actuator along the disc radius, and to reduce the effect of external disturbances affecting the system, like eccentricity and vertical deviations. Uncertainty model, based on a parametric description of the DVD mechanism, and norm-bounded real perturbations are considered, and an H_∞ controller is designed by following industrial oriented control objectives. An a-posteriori performance and robustness analysis is finally performed, without applying μ-synthesis tools.
Since in the existing industrial solution the digital signal processor (DSP) provides finite precision of digital computation and rounding errors, controller order reduction is performed to allow its practical implementation and test robust stability and performance.

1 Introduction

Optical disc drives are widely used today to hold music, store data or to record digital movies. Even though improvements are observed in obtaining shorter data time access, higher storage capacity and information density on the disc, little has been done to improve the optical pick-up performances and their tolerances with respect to parameters variation along the production phase, actuators aging and different optical gains of the discs. Therefore, due to higher storage capacity and disc rotational speed, the positioning controllers must be more accurate in order to cope with considerable parameter tolerances [6]. The design of the controller can be formulated in an H_∞ setting, if its performance specifications are taken into account and norm-bounded parametric uncertainties are assumed. There are several studies concerning application of H_∞ and H_2 norm-based control design to a CD mechanism, via multi-objective LMI design technics, in order to reach performance and robustness specifications [4]. Other studies concern multi-variable control of a CD

player by using μ-synthesis or a description of real parametric perturbations [7], but none has been published about real parametric perturbations in DVD players in the H_∞ framework.

The aim of this paper is to propose a simple, but accurate method to perform H_∞ norm-based control design for a DVD-video player. To avoid conservatism and increase performance, a parametric uncertainty representation is chosen, and perturbations are restricted to be real. To implement the solution on the industrial application, the order of the controller is reduced without loosing performances and robustness. Then a comparison, in term of error signal Power Spectral Density between the achieved solution and the existing industrial one, is presented.

The paper is organized as follows: in Section 2 the DVD mechanism is presented, together with a linear model of the optical pick-up. Performance specification are described in Section 3. Section 4 is devoted to nominal and uncertainties models of the plant, and in Section 5 the H_∞ control design is described, as well as an order reduction procedure. A frequency analysis is proposed to point out improvements due to the resulting controller. Robust stability and performance analysis are presented in Section 6 and simulation and experimental results in Section 7. Some concluding remarks end the paper.

2 System Description

The DVD player is an optical data storage device able to reproduce high-quality video and audio from binary coded information, recorded as a spiral shape track, of impressed pits, on a reflective disc. In fig 1 a schematic view of the DVD mechanism is shown.
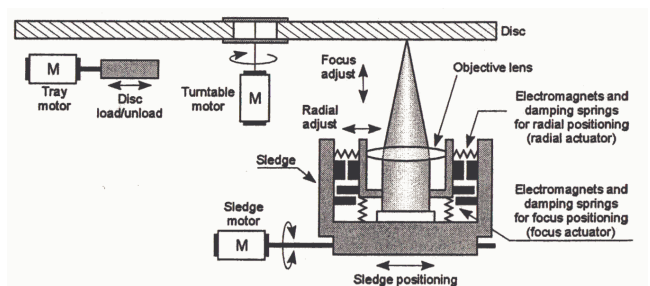

Figure 1: Schematic view of the DVD mechanism.

The system is composed by a turn-table DC motor, and an optical pick-up that retrieves data from the disc. A diode located in the pick-up emits a laser beam which is guided through optics to the disc surface. An objective lens, suspended by two parallel leaf springs, can be moved in a vertical direction, to give a focusing action, and in radial direction, to perform the track following. The reflected light is then detected by the pick-up, and data convoyed on the beam are converted in digital electric signals. Since only light touches the disc, four photo-diodes generate a current which, in the linear area is proportional to the distance between the focus point and the signal layer. Thereby the photo-diodes can be model by a constant gain. Due to the absence of the physical contact between the pick-up and the disc, feedback control is necessary to control the position of the laser spot with respect to the disc surface 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 disc layer, and the radial loop which allows the laser to follow the tracks. In the current industrial solution, provided by STMicroelectronics, the radial and the focus directions are controlled using two independent SISO schemes since, as pointed out in [3], the relatively low dynamic interaction between the two control loops allows to consider them as decoupled. An internal DSP is used to process position errors and supply control signals to actuator drivers. Although this device is very cheap and simple to program, it provides finite precision of digital computation rounding errors and quantization effects, that have to be considered during the controller implementation phase.

The goal of the control design is to minimize the amplitude of the position error between the laser spot and the real track position, in the radial and in the vertical directions, despite the presence of internal and external disturbances. The most important disturbances present in optical disc mechanisms are due to the rotation of the disc, eccentricity and track irregularities, shocks and mechanical vibrations, and positioning sensing noise. A way to decrease the driver's sensitivity to disturbances is to develop a more robust servo control system so that the laser spot stays on track all the times. This paper is focused on tracking following control problem, since it is the most critical and tricky. The design of the focus control loop is conceptually similar, but control requirements are weaker [1]. In fig 2 the block diagram of the control loop is shown.
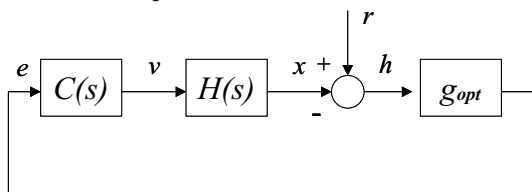

Figure 2: Block diagram of the DVD mechanism.

This scheme can be applied to focus and radial loop. $H(s)$ is the transfer function of the mechanical actuator, which is controlled by the voltage v and generates the laser spot on the disc. The optical head position, denoted with x, is determined by the displacement of the objective lens and should coincide, at any moment, with the disc reflective layer (in case of the focus control loop) or with the center of the read-out track (in case of radial loop). Since the actual track position r is not available from measurements, it can be considered as a disturbance signal acting at the output of the plant [5]. g_{opt} is the gain of the optical pick-up mechanism which converts the difference error h, between the track position r and the head position x, into an electrical signal e. The laser spot must follow the disc deviations despite the presence of disturbances, that influence its position. $C(s)$ denotes the controller transfer function.

Focus and radial actuators are constituted by a lens attached to the pick-up body by two parallel leaf spring, and moved in vertical and radial direction by a voice coil and a magnet. The control-oriented mathematical model of the actuator is derived from technical specifications as follows [8] :

$$H(s) = \frac{\frac{K_e}{mL}}{s^3 + \left(\frac{R}{L} + \frac{D}{m}\right)s^2 + \left(\frac{DR}{mL} + \frac{k}{m} + \frac{K_e^2}{mL}\right)s + \frac{kR}{mL}}$$

(1)

where $m\ [Kg]$ is the mass of the moving parts of the actuator, $R\ [\Omega]$ and $L\ [H]$ are the DC resistance and the impedance of the voice coil motor, $D\ [Ns/m]$ is the viscosity coefficient, $k\ [N/m]$ is the spring modulus , and K_e $[Wb/m]$ is the magnetic flux density per unit of effective coil length.

3 Performance Specifications

Disc specifications, contained in [2], prescribe values for the maximum deviations from nominal position x_{max}, for the scanning point maximum acceleration $\ddot{x}_{max}$, and for the maximum allowable value of the position error h_{max}. In table 1 these values are presented for a disc scanning velocity $v_a = 3.49m/s$ and $f_{rot} = v_a/2\pi d$, where d is the optical head position with respect to the disc center hole.

Table 1: *Standardized radial and vertical deviations from nominal position of the track specified at the disc scanning velocity $v_a = 3.49m/s$, and $f_{rot} = v_a/2\pi d$.*

Parameters and conditions	Radial	Focus
x_{max} for $f \leq f_{rot}$	$\pm 50\mu m$	$\pm 0, 3mm$
$\ddot{x}_{max}$ for $f_{rot} \leq f \leq 1.1KHz$	$1.1m/s^2$	$8m/s^2$
h_{max} for $f_{rot} \leq f \leq 1.1KHz$	$\pm 0.022\mu m$	$\pm 0.23\mu m$

In what follows disc specifications are translated in the frequency-domain. The deviation $x(t)$ in the acceleration zone can be modelled as a harmonic, and the max acceleration $\ddot{x}_{max}(t)$ is obtained as follows :

$$x(t) = A\sin(\omega t) \Rightarrow |\ddot{x}_{max}(t)| = A\omega^2 \qquad (2)$$

where A is the maximum amplitude of the radial deviation from the track.

For $f \leq f_{rot}$ the lowest corner frequency is given by :

$$f_L = \frac{1}{2\pi}\sqrt{\frac{\ddot{x}_{max}}{x_{max}}} = \frac{1}{2\pi}\sqrt{\frac{1.1}{50 * 10^{-6}}} \simeq 23.1 Hz \qquad (3)$$

Above f_L the amplitude is limited by the specified maximum acceleration up to the highest corner frequency :

$$f_H = \frac{1}{2\pi}\sqrt{\frac{\ddot{x}_{max}}{h_{max}}} = \frac{1}{2\pi}\sqrt{\frac{1.1}{0.022 * 10^{-6}}} \simeq 1125.4 Hz \quad (4)$$

The disc specifications are given for a disc rotating at a constant linear velocity. When the disc rotates at higher speeds, say $N v_a$, the corner frequencies f_L and f_H must be linearly shifted by the over-speed factor N and the focus and radial accelerations have to be multiplied by the factor N^2.

The restrictions on the radial deviation can be represented graphically in the frequency domain, as shown later in fig 9, where the disc specifications are given as requirements for the output sensitivity function :

$$S(s) = \frac{1}{1 + g_{opt}C(s)H(s)} \qquad (5)$$

In order to fulfill disc specifications, $S(s)$ has to lie below the disc templates defined in [2].

The control system performance is also characterized by the closed-loop bandwidth f_t, whose value is fixed in [2] to be equal to :

$$f_t = \frac{N}{2\pi}\sqrt{\frac{4.5\ddot{x}_{max}}{h_{max}}} \qquad (6)$$

According to table 1, $f_t = 3.5 KHz$ for the radial loop when $N = 1.5$, as in the industrial application.

4   Nominal and uncertainty model

To allow an accurate and non conservative representation of the actual DVD system, a simple frequency-domain model of real parametric uncertainty is computed using real norm-bounded perturbations.

The nominal model of the plant is obtained considering the values of physical parameters of a DVD pick-up, which is used in the industrial application. Then, its worst-case behavior is analyzed by taking into account the variation of each parameter in an interval of values, as indicated in the pick-up data-sheet. The nominal values of the actuator physical parameters, together with their percentage variation, are shown in table 2. Let us

Table 2: *Values of the radial actuator physical parameters together with their % variation.*

Parameters	Value	% Variation
R [Ω]	6.5 ± 1	15%
L [μH]	18 ± 6	33%
m [g]	0.33 ± 0.033	10%
k [N/m]	35.227 ± 7.054	20%
K_e [Wb/m]	0.0618 ± 0.0343	45%
D [Ns/m]	0.0141 ± 0.0021	15%

consider $G_0(j\omega) = g_{opt}H(j\omega)$ as the nominal plant transfer function, where g_{opt} is chosen in a way that the system bandwidth f_t matches the value prescribed in [2].

Then, the multiplicative uncertainty model $G_\Delta(j\omega)$ is described by the following equation :

$$G_\Delta(j\omega) = G_0(j\omega)[1 + W_i(j\omega)\Delta(j\omega)] \qquad (7)$$

where $|\Delta(j\omega)| \leq 1 \ \forall \omega$ represents the normalized real perturbations and $W_i(j\omega)$ is the uncertainty weight.

The dependency of the plant model from the variation of each of its physical parameters is analyzed, and the following relative error function is computed :

$$l_i(j\omega) = \max_\omega \left| \frac{G_\Delta(j\omega) - G_0(j\omega)}{G_0(j\omega)} \right| \qquad (8)$$

The rational weight $W_i(j\omega)$ is found in a way that [9] :

$$|W_i(j\omega)| \geq l_i(j\omega), \forall \omega \qquad (9)$$

Relative errors $l_i(j\omega)$, together with the rational weight $W_i(j\omega)$, are plotted in fig 3.
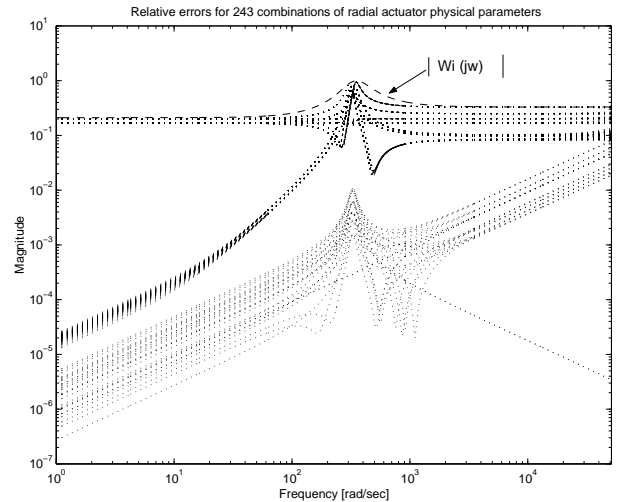

Figure 3: Relative plant errors $l_i(j\omega)$ (dotted line) and rational weight $W_i(j\omega)$ (dashed line) for 243 combination of the radial actuator physical parameters.

The weighting function $W_i(j\omega)$ is chosen equal to a fourth order transfer function in a way that it includes the set of all possible plant models.

5 H_∞ control approach

5.1   Some background on H_∞ control

This part states the problem in a similar way to [9] where more details can be found.

H_∞ control is formulated using the general control configuration (I) in figure 4, where $P(s)$ is the generalized plant model, w is the exogenous input vector, u is the control output vector, z is the controlled output vector, e is the measurement vector. The control design then consists in finding a controller $K(s)$ for a generalized plant $P(s)$ such that, based on the information given by e, the control signal $u (= K(s)e)$ ensures internal stability of the

closed-loop system and counteracts the influence of w on z, thereby minimizing the closed-loop transfer norm from the exogenous inputs (w) to the controlled outputs (z). Given γ, a pre-specified attenuation level, a H_∞ suboptimal control problem is to design a controller that internally stabilizes the closed-loop system and ensures:

$$\|T_{zw}(s)\|_\infty \leq \gamma \tag{10}$$

$T_{zw}(s)$ is the closed-loop transfer matrix from w to z. In general, some weights are considered on the controlled outputs (including the actuator force). They represent the performance specifications in the frequency-domain. P thus includes the plant model G and the considered input and output weights (W_p, W_u) as in figure 4 (II). The H_∞ control problem is then referred to as a mixed sensitivity problem, W_p and W_u thus appearing in (10) as weights on the sensitivity functions.
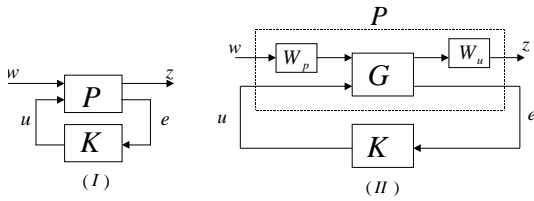

Figure 4: General control configuration.

The usual way of solving the H_∞ control problem is the use of Riccati equations or LMI. This leads to the design of the control law u that is solution of the suboptimal problem (10). A bisection algorithm is then used to approach the minimal value of γ.

5.2 H_∞ control design applied to a DVD player

In the case of DVD player, robustness aspects and shape of some of the relevant closed-loop transfer functions are taken into account to specify an H_∞ criterion (10) to minimize. In fig 5 the scheme of the generalized servo loop considered for this design is shown.
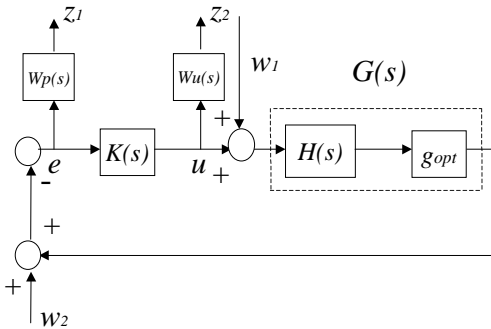

Figure 5: Control scheme for the H_∞ controller design.

The transfer functions W_p and W_u represent the design weighting functions, w_1 and w_2 are the exogenous inputs, z_1, z_2 are the performance outputs, e is the measurement output and u is the control input. $G(s) = g_{opt}H_d(s)$ with $H_d(s) = g_d H(s)$ are the plant and the actuator+driver

gain transfer functions respectively, and

$$T(s) = \frac{g_{opt}K(s)H_d(s)}{1 + g_{opt}K(s)H_d(s)}, \quad S(s) = \frac{1}{1 + g_{opt}K(s)H_d(s)}$$

are the well known sensitivity functions. The problem in fig 6 consist then in finding a $\gamma > 0$ and a controller $K(s)$ that ensures closed-loop internal stability, i.e :

$$\|T_{zw}\|_\infty = \left\| \begin{array}{cc} -W_pGS & -W_pS \\ -W_uT & -W_uKS \end{array} \right\|_\infty \leq \gamma \tag{11}$$

The weighting functions (W_p, W_u) should be chosen to reflect the design objectives (i.e. performance specifications) and knowledge of the disturbances and sensor noise. W_u is the weight on the control output, that can be affected by disc eccentricity or defects w_1, and W_p represents the weight on the error signal, that is affected by sensor noise w_2.

In (11) the goal is to minimize the amplitude of the error signal limiting the effort of the controller. Hence, the advantage of solving (11) is that using only two weights W_p and W_u, we force the frequency response of all the closed-loop transfer functions T, S, KS and GS to stay below pre-specified templates, in order to achieve performance specification and robustness objectives. Notice that, due to the implementation constraints, we do not include in fig 5 the uncertainty weight W_i that would increase the controller order. The considered methodology is to apply robust stability and performance tests a posteriori. In fig 6 the general control configuration in LFT form is shown.
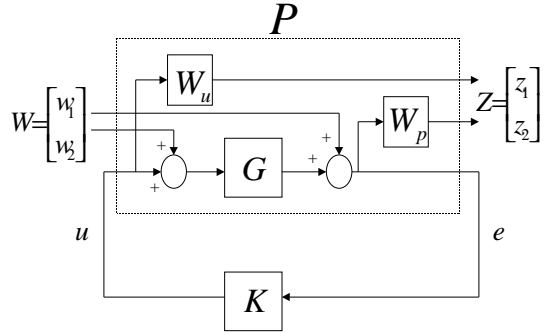

Figure 6: General control configuration in LFT form.

The weighting functions have been chosen according to industrial performance specifications.

$\mathbf{W_p}$: the inverse of the weighting function $W_p(j\omega)$ is used to impose a performance specification in terms of the sensitivity function S. We choose :

$$W_p(j\omega) = \frac{(j\omega/M_s + \omega_b)}{(j\omega + \omega_b A_s)} \tag{12}$$

where $M_s = 2.8183$ to introduce a margin of robustness on the the peak of S, $\omega_b = 2\pi250$ $[rad/sec]$ to have a sensible attenuation of disturbances up to $250Hz$ and $A_s = 2.2*10^{-2}$ to reduce the steady-state position error.

4

W_u: the control output u is weighted according to the actuator limitations. $W_u(j\omega)$ is set equal to :

$$W_u(j\omega) = \frac{(j\omega + \omega_{bc}/M_u)}{(j\omega\varepsilon + \omega_{bc})} \quad (13)$$

and we choose the following values : $M_u = 0.630957$ to impose limitations on the maximum value of the controller output signal, $\omega_{bc} = 2\pi 30e^3$ [rad/sec] to limit the effect of measurement noise and plant uncertainties at high frequencies, and $\varepsilon = 0.01$ to ensure a high-frequency controller gain of $-40dB/$decade.

Using the chosen weighting functions, the H_∞ control problem has a solution for $\gamma_{min} = 2.87$, and a 5th order controller is obtained. In [7] and [4] high-order weighting functions W_p and W_u are chosen, in order to achieve a very performing H_∞ controller and fulfill system performance specifications. However, due to implementation constraints, we had to limit to 3 the maximum order of the synthesized controller.

5.3 Implementation constraints and Controller order reduction

In the actual industrial solution the position control loops are implemented by using a dedicated DSP, which computes the discrete-time transfer functions with a fixed sampling frequency of $f_s = 123.45\ Khz$.

Although this device is simple to program, it provides arithmetic functions calculation with finite precision, rounding errors and quantization effects. That is why, during the controller design step, becomes fundamental to limit the controller order, to reduce the program length and the quantization effects. Another important point is represented by the choice of the coefficients used to implement digital filters : they must be in a pre-specified range, to reduce rounding errors and saturation effects.

An order reduction procedure, based on a truncated balanced realization of controller's state-space model [9], is then applied on the achieved 5th order controller, in order to allow its practical implementation on the industrial benchmark. However, the obtained reduced-order controller is not adapt for implementation, because its static gain is too high to avoid that saturations don't occurs in the DSP internal registers. For this reason, we had to reduced the controller dc-gain, keeping unchanged its poles and zeros. After discretization, the final controller has order 3, and is implemented in real-time application. The Bode diagram of the lead-lag controller, together with the designed 5th and the implemented 3th order controllers is shown in fig 7.

6 Robust stability and performance analysis

Generally a control system is robust if it is insensitive to differences between the actual real system and the model used to design the controller. In addition to nominal stability and performance, the objectives of any control system include :
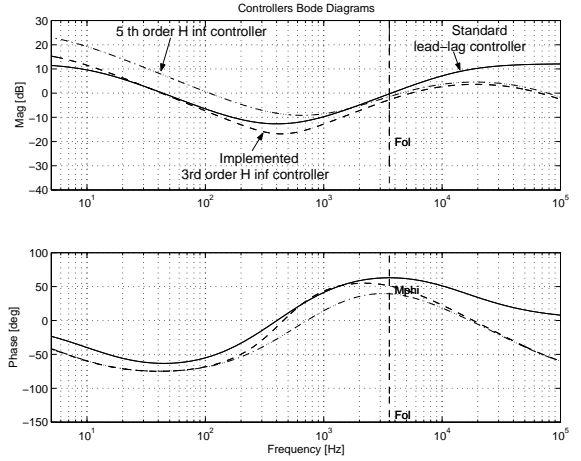

Figure 7: Bode diagram of the radial loop controllers. Standard lead-lag controller (solid line), H_∞ 5th order controller (dash-dotted line), H_∞ 3th order controller (dashed line) implemented on the industrial benchmark.

Robust Stability (RS). The system is stable for all perturbed plants around the nominal model up to the worst-case model uncertainty.
Robust Performance (RP). The system satisfies the performance specifications for all perturbed plants about the nominal model up to the worst-case model uncertainty. The scheme of a general feedback system with input multiplicative uncertainty is presented in fig 8.
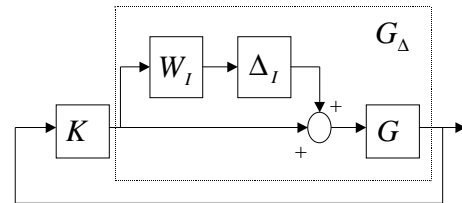

Figure 8: System with multiplicative uncertainty.

Using the small gain theorem, the condition for Robust Stability (RS) is given by [9] :

$$RS \iff |T| < \frac{1}{|W_I|}, \quad \forall\omega \quad (14)$$

Considering the performance specifications in term of the sensitivity function only, the condition for Robust Performance (RP) is obtained as [9] :

$$RP \iff (|W_pS| + |W_IT|) < 1, \quad \forall\omega \quad (15)$$

As pointed out in [9], equations (14), and (15) represent, for a SISO system, the direct application of μ-conditions for (RS) and (RP).

7 Simulation and experimental results

In the current application, we are interested in parametric uncertainties.
In particular the resistance, the inductance and the mass

of the voice coil motor are badly known. As it can seen in table 2, the first two are the most varying parameters, depending on environmental conditions (temperature, humidity, etc...) and on device's aging. The other parameters will vary due to industrial manufacturing only.

Simulation and experimental results show that (RS) is satisfied, since the closed-loop system remains stable for the chosen uncertainty set, as presented in fig 9. In this figure simulation results are obtained by using the actuator linear model and the computed controller, and experimental results by measuring the transfers Bode diagram with a dynamic signal analyzer, as described in [8]. Since real-time measurement are only available under closed-loop conditions, measurements of the loop sensitivity function are highly affected by noise at low frequencies, as it can see from fig.9 where the measured and the computed sensitivity functions don't match together in $[0, 400]$ Hz. Fig 10 shows that (15) is satisfied, i.e. (RP) is achieved. Finally, in fig 11 is presented the tracking error signal power density spectra (PSD) of the synthesized H_∞ controller (solid line) and of the standard lead-lag controller (dashed line), used in the current industrial solution. Measurements have been acquired by using the worst-case disc (test disc having nominal eccentricity of $\epsilon = 150$ μm) and for a disc rotational frequency $f_{rot} = 33Hz$. From this figure it appears that the H_∞ controller provides the same level of periodic disturbance rejection as the standard lead-lag, for a fixed rotational frequency.
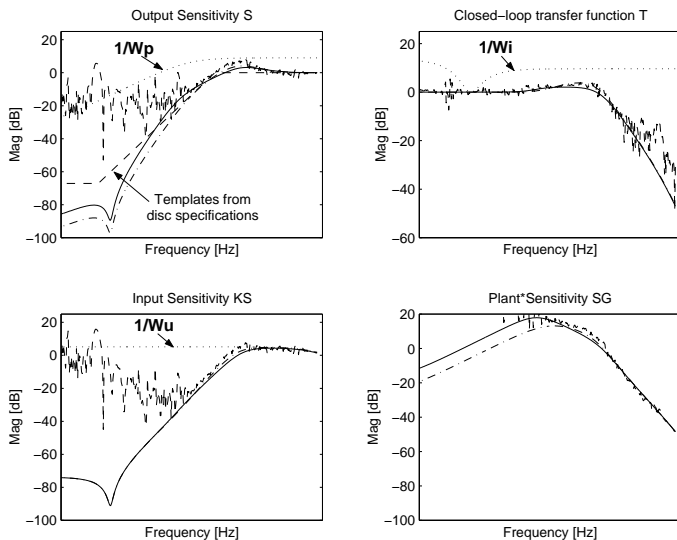

Figure 9: Measurements (dotted line), simulation with the 3rd order controller (solid line), simulation with the 5th order controller (dash-dotted line), weighting functions (dotted line).

8   Conclusions

This paper has dealt with H_∞ control design for a DVD video player, under industrial performance specifications and real parametric uncertainties. Simulation and experimental results show that (RS) and (RP) are achieved for large variation of actuator parameters (R, L and m), whose value is strongly dependent from environmental condition and system aging. We have also presented a comparison between the standard lead-lag [8] and the
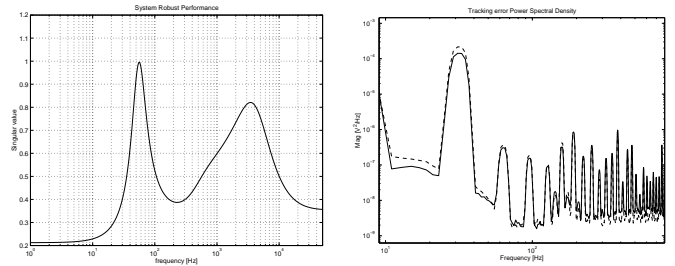

Figure 10: System robust performance, given by (15).

Figure 11: Tracking error signal PSD [8].

computed H_∞ controller, in term of periodic disturbance attenuation on the position error signal. The synthesized H_∞ controller gives the same results of the standard lead-lag controller, and this is due, in our opinion, to the limitations on the order of weighting functions W_p and W_u, and to the reduced order of the controller we had to consider for implementation. Moreover, we have provided a general and straightforward methodology for a DVD system control design, that is more suitable for unknown parameter variations and real-time implementation.

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