

Identification in view of control design of a CD player

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Identification in view of control design of a CD player[‡]

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Abstract. Electro mechanical servo systems, as encountered in consumer electronic products, have to keep pace with increasingly high performance demands. As the mechanical construction is a restricting factor regarding the limits of achievable performance, model based control design is proposed to enhance the bandwidth. System identification proves to be an adequate tool to produce nominal models and uncertainty models that are suitable for control design purposes. A method based on performing identification and control design in an iterative manner is proposed in order to systematically enhance the disturbance attenuation properties of a servo system. The proposed method is experimentally verified via application to a compact disc servo mechanism.

Keywords. Control design, system identification, compact disc player.

1 Introduction

A large number of applications of electro mechanical servo systems requires tracking with an increasingly high accuracy at a high speed. Especially in the field of consumer electronic products like audio and video systems the limits of achievable performance are more and more dictated by the mechanical construction of the servo system. In many cases this predominantly results in a desired enhancement of disturbance rejection of the servo system which may be achieved by control design. Design of control systems that establish an improved disturbance attenuation for electro mechanical constructions is however known to be hindered by the presence of resonance modes that are (in most cases) not exactly known. An additional aspect regarding consumer electronic products is the variability of system dynamics due to tolerances in the mass production process. This

motivates development of a tool that on one hand establishes an improved performance of existing constructions having variable dynamical properties and on the other hand explores the physical limitations of electro mechanical constructions in the stage of product development.

In case knowledge of resonance dynamics is sufficiently accurate a high bandwidth controller, designed based on this knowledge, is likely to provide a high bandwidth for the system without causing unstable behaviour. Therefore accurate knowledge of resonance modes is indispensable in the design of a high bandwidth control system. This motivates the use of model based control design as a tool to achieve an enhanced bandwidth for an electro mechanical servo system. Knowledge of resonance dynamics can adequately be described by a mathematical model which serves as a basis for control design. One way to construct such a model is to use relations based on first principles. In general these models are quite elaborate which inevitably leads to a controller of high dynamical order. If measurements can be taken from the system, models can also be obtained from experimental data utilizing system identification techniques. As experimental models are not

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based on the physical structure of the system, the order may be kept low in order to describe relations induced by measured data. Therefore experimental modelling is employed in this paper.

As the intended use of the model is control design, the identification problem we are confronted with is to come up with a low order model such that a resulting controller establishes a high performance for the true system. In literature (a.o. Gevers, 1993; Van den Hof and Schrama, 1995) it has been recognized that, in order to establish an enhanced performance for the system through model based control design, identification and control design should be performed in an iterative manner. The topic of this paper is to propose an iterative scheme of identification and control design for systematic enhancement of the closed loop bandwidth and to verify the method experimentally on the servo mechanism of a compact disc (CD) player. A specific feature of the proposed scheme is the utilization of uncertainty models, that may be obtained through recently developed identification techniques (see a.o. de Vries, 1994).

In section 2 the need for an iterative approach of identification and control design is elucidated in view of achieving an enhanced closed loop bandwidth. The identification of nominal models and uncertainty models is the subject of section 3. The control design method employed is a two-stage procedure that combines a loop shape design with robustness in view of resonance modes. This is the subject of section 4. Results obtained from an experimental set up of a CD player are presented and commented upon in section 5. Conclusions and remarks conclude the paper.

2 Model based performance enhancement

We consider a servo system consisting of an electro mechanical actuator, denoted as P_0 , and a controller C as depicted in the block scheme of figure 1. In many cases the actuator is marginally stable and must therefore operate in closed loop. The signal d represents a reference signal that is not available from measurement but is to be tracked by the actuator output y . As d is presumed to be unknown it is regarded as a disturbance acting on the servo system. The servo error is denoted by e .

The desired performance is achieved in case the tracking error satisfies $|e(t)| < \delta, \forall t$ where the value of δ is determined by physical system properties. Although the translation is not one-to-one, the performance spec is expressed in the frequency domain¹

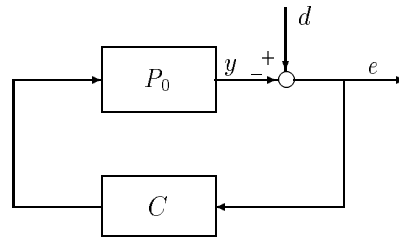


Fig. 1: Block scheme of an electro mechanical servo system

in terms of the following specification regarding the sensitivity function of the closed loop system:

$$\left| \frac{e}{d} \right| = |(1 + CP_0)^{-1}| \leq \beta^{-1}, \quad \forall \omega. \quad (1)$$

where β denotes the minimal disturbance rejection required for the system. We focus on the design of a controller C that establishes the specified disturbance rejection. To that end knowledge of P_0 as well as the disturbance d is indispensable which motivates the need for accurate models of both the actuator and the disturbance. Although it is acknowledged that disturbance modelling should be incorporated in the overall design, here we restrict attention to data based modelling of the actuator dynamics.

In literature the problem of identification of models that are suitable for high performance control design has received a great deal of attention (a.o. Gevers, 1993; Van den Hof and Schrama, 1995). It has been stressed that a model that provides a satisfactory description of the open loop system dynamics might provide a poor basis for control design, in the worst case resulting in controllers that destabilize the closed loop system. The main observation made is that system dynamics that govern the closed loop dynamics in conjunction with a controller often only marginally contribute to the open loop dynamics and vice versa.

This observation has resulted in a widely accepted strategy that identification of models suitable for control design should be performed in a closed loop situation, in the presence of a controller. To do closed loop identification we need a controller that emphasizes the dynamics that are relevant for control design. However, in order to find such a controller a model is required that encompasses control relevant dynamics. Here we are confronted with a circular reasoning that has motivated the proposition of algorithms where identification and control

¹The frequency argument ω is left out for brevity

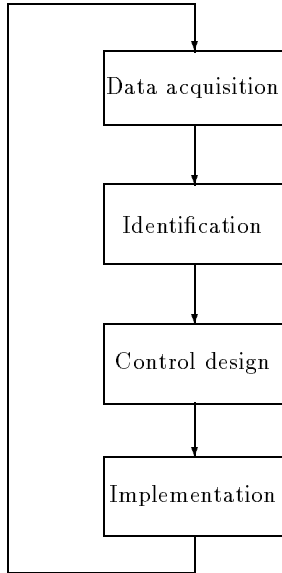


Fig. 2: Iterative approach of model based performance enhancement

design are performed in an iterative manner (Gevers, 1993; Van den Hof and Schrama, 1995; Lee *et al.*, 1995) in order to arrive at an enhanced performance. Basically such a procedure consists of the following steps: data acquisition, identification, control design and controller implementation; this is schematically depicted in figure 2.

In the sequel of this paper the separate steps of identification and control design are addressed. As the procedure is implemented on an experimental set up of a CD servo mechanism, the elaboration from here on is directed towards this application.

3 Identification

In figure 3 a block scheme of the experimental CD player is depicted where time domain signals r , u and e are available from measurement. The signal r is used for excitation, u and e are the input resp. output of the actuator, measured in the presence of a stabilizing controller.

The identification of a parametric model is concerned with estimation of parameters in a predetermined model structure. The data underlying the identification procedure is a frequency domain representation of measured time sequences by means of a discrete Fourier transform in conjunction with periodic excitation. The data are available as (complex valued) data points $\{r(e^{i\omega_j}), u(e^{i\omega_j}), e(e^{i\omega_j})\}$ at a finite number of user specified frequencies $\omega_j, j = 1, \dots, N$. The main motivation for trans-

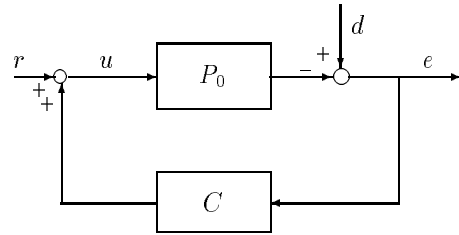


Fig. 3: Experimental configuration of a CD servo system

forming time domain data to the Fourier domain prior to identification is the possibility to establish a considerable compression of the amount of data. Moreover, a frequency domain data representation is compatible with the performance specification (1). Two features are characteristic for the identification problem addressed. Firstly, a model that is employed for control design should be obtained from measurements taken in the presence of a controller, as mentioned in section 2. Secondly, as the identification has to be performed in closed loop, straightforward application of open loop identification methods is hazardous. To that end the identification of a parametric model is performed following a so called indirect approach. A parametric model of the closed loop transfer $P_0(I + CP_0)^{-1}$ is estimated from $\{r(e^{i\omega_j}), e(e^{i\omega_j})\}$ by determining parameters, denoted θ , that minimize the following least squares criterion function:

$$\sum_{j=1}^N |\mathcal{W}(e^{i\omega_j})[e(e^{i\omega_j}) - R(e^{i\omega_j}, \theta)r(e^{i\omega_j})]|^2 \quad (2)$$

where

$$R(e^{i\omega}, \theta) := \frac{b_0 + b_1 e^{-i\omega} + \dots + b_n e^{-in\omega}}{1 + a_1 e^{-i\omega} + \dots + a_n e^{-in\omega}} \quad (3)$$

and \mathcal{W} is a frequency dependent weighting function. A model of the system is constructed from $R(e^{i\omega}, \theta)$, utilizing knowledge of the (stable) controller, as follows:

$$P(e^{i\omega}, \theta) = \frac{R(e^{i\omega}, \theta)}{I - CR(e^{i\omega}, \theta)}. \quad (4)$$

It is mentioned that a generalization of this approach is applied, allowing to deal with marginally stable controllers, as is indicated by Van den Hof and de Callafon (1996). The identification of a (low order) model $P(e^{i\omega}, \theta)$ suitable for control design in the SISO case amounts to specifying a suitable weighting \mathcal{W} in (2).

In addition to identification of nominal models, techniques have recently been developed (see a.o.

de Vries, 1994) to construct a data based measure of the deviation of a model with respect to the system. This results in so called uncertainty bounds that enable construction of a set of transfer functions to which the true system is presumed to belong. In case of identification of \hat{R} according to (2) a bound $\delta_R(\omega)$ is estimated which determines a set of transfer functions

$$\mathcal{R} = \{R | R = \hat{R} + \Delta_R, |\Delta_R| < \delta_R(\omega)\} \quad (5)$$

to which the true transfer function R_0 belongs. The motivation for employing uncertainty models in this specific model structure is that they are instrumental in predicting the closed loop dynamics for a set of systems in conjunction with any (stabilizing) controller, as is elaborated by Van den Hof *et al.* (1996). This is a potentially powerful technique to incorporate the aspect of variable system dynamics into the control design.

4 Control design

In this section a nominal control design procedure is presented that is proposed by McFarlane and Glover (1990). The design procedure is solely based on nominal models but has favourable robustness properties and consists of two consecutive stages. The first stage is the determination of a loop shape transfer function C_0 such that the nominal sensitivity function satisfies a minimum prespecified magnitude bound:

$$|(I + C_0 \hat{P})^{-1}| \leq \beta^{-1}, \quad \forall \omega. \quad (6)$$

The determination of C_0 is done by visual inspection of the Bode diagram and Nyquist contour of $C_0 \hat{P}$ where the structure of C_0 is predetermined in terms of a low order lead-lag compensator. Although loop shaping is an appealing technique due to the fact that compensators result from visual inspection, it is not a very robust technique for high bandwidth design especially in case resonance modes are present in the model \hat{P} . Therefore robustness properties are improved in the second stage which consists of a norm based control design, where a controller is determined such that the following criterion function is minimized

$$\|T(C_0 \hat{P}, C)\|_{\infty} \quad (7)$$

where $T(P, C)$ is a 2×2 matrix that comprises the closed loop transfer functions from r to $[e \ u]^T$ in the block scheme of figure 3, defined as²

$$T(P, C) := \begin{bmatrix} P \\ I \end{bmatrix} [I + CP]^{-1} [C \ I]. \quad (8)$$

²Note that the sensitivity is the (2, 2)-element of $T(P, C)$.

The final controller is found as the product of the results of both design stages $C_0 C$.

The rationale behind this two-stage design strategy is that in the loop shape step the presence of resonances may be disregarded as the desired robustness with respect to resonances is supposed to be dealt with in the second step. This may considerably facilitate the loop shape design in the sense that performance and robustness considerations are accounted for in separate design steps.

5 Application to a CD servo system

The separate steps of one iteration of model based performance enhancement as proposed in section 2 have been applied to an experimental CD player servo mechanism. The servo system, as is schematically depicted in figure 1, establishes track following of digital information stored on a rotating optical disc.

Attention is restricted to the radial part of the mechanism (Single Input Single Output case). Controller implementation and data acquisition are carried out utilizing a DSP signal processor (dSPACE GmbH, 1995) at a sample rate of 25 kHz. Measurements are taken of 40 time sequences of $\{r, u, e\}$ each containing 4096 data points where the excitation signal r is chosen as a random phased multisine, exciting the system at 99 logarithmically spaced frequencies between 100 Hz and 10 kHz. A 4th order compensator is present in the loop during measurement.

A nominal parametric model of order 10 is identified according to (2) together with an upper bound of model uncertainty. The frequency response and the nominal model are shown in the Bode diagram of figure 4. The nominal model seems to provide a rather poor description of the data in the low and high frequency region.

Based on this nominal model a 4th order lead-lag compensator C_0 is designed on visual inspection of Bode magnitude diagrams of the nominal sensitivity and the predicted sensitivity, constructed from uncertainty bounds. The compensator is adjusted to a higher bandwidth until the nominal sensitivity function will (inevitably) peak up at frequencies beyond the bandwidth. Figure 5 shows the Bode diagram of the measured sensitivity and the nominally designed sensitivity.

Besides visual inspection of the nominal sensitivity also the actually achieved sensitivity is evaluated in terms of lower and upper magnitude bounds of the sensitivity, constructed from estimated uncertainty bounds of the model; this is depicted in figure 6 together with the nominally designed sensitivity function. The design of the loop shape function is per-

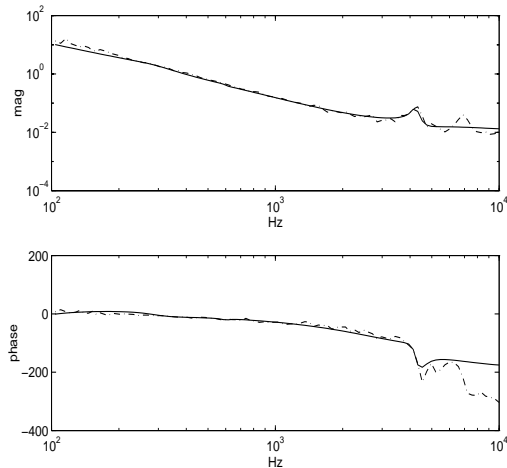


Fig. 4: Measured frequency response (dash-dot) and 10th order nominal model (solid) of the radial CD servo mechanism.

formed such that the nominal sensitivity magnitude remains within the bounds and the bounds are not too large.

To verify the validity of this closed loop system set the sensitivity frequency response measured with the loop shape compensator is added. The measured sensitivity is predicted quite well by the upper and lower magnitude bounds up to 4 kHz, while the designed sensitivity function is not captured by the bounds. This can be attributed to the fact that the (low order) nominal model lacks system dynamics which seem to be relevant in view of the newly designed controller.

The second stage of the control design is performed according to (7). The final controller C_0C is restricted to order 6 due to implementation limitations. This implies that the norm based design step produces controllers of order 2. To analyse the merits of the second control design step, the sensitivity function is measured with the enhanced controller (order 6). The Bode magnitude diagram in figure 8 shows the initial sensitivity function and the enhanced sensitivity. The loop shape compensator and the corresponding final controller are shown in figure 7.

In figure 9 the radial tracking error measured with the low bandwidth compensator and the enhanced compensator is shown. It is evident that increasing the bandwidth is a valid strategy in order to establish a reduction of the tracking error.

An important observation is that the loop shape design is a very crucial stage in the iterative approach. If the nominal design provides a relatively large increase of the bandwidth in comparison to the controller present during measurement (as is illustrated figure 5), then the nominal model may not reliably

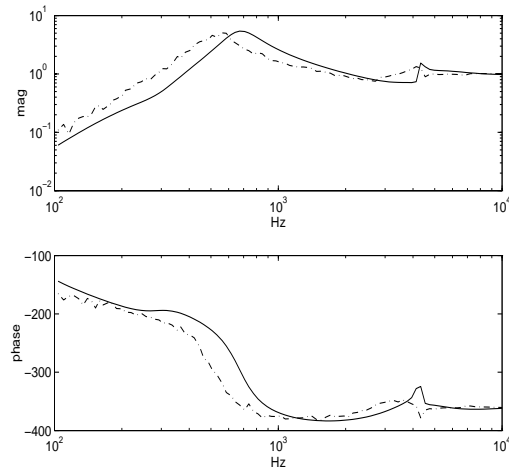


Fig. 5: Sensitivity function: enhanced loop shape design (solid) and measured with low bandwidth compensator in the loop (dash-dot).

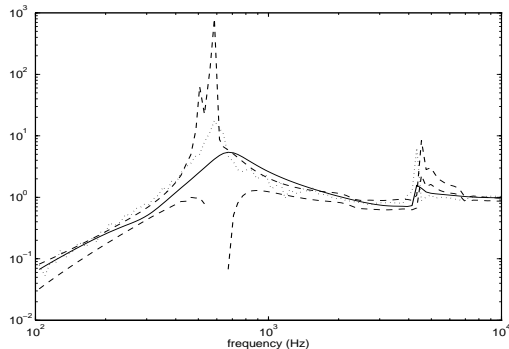


Fig. 6: Magnitude of sensitivity: nominal (solid), lower and upper bounds (dash) and measured (dot).

predict the actual sensitivity. This is in fact illustrated in figure 6 where the nominally designed sensitivity is not completely captured by the magnitude bounds; the nominal design appears not to be very robust. In the line of performing several iterations (here we have only considered one iteration) it is important to take small steps in the nominal loop shape design towards a higher bandwidth in order to maintain a robust design. This has yet to be verified.

6 Conclusions

To comply with increasing higher demands of servo systems as encountered in consumer electronic products, control design is used to obtain a high bandwidth. A crucial issue in designing a high bandwidth control system for electro mechanical servo systems is the presence of (unknown) resonance modes. As

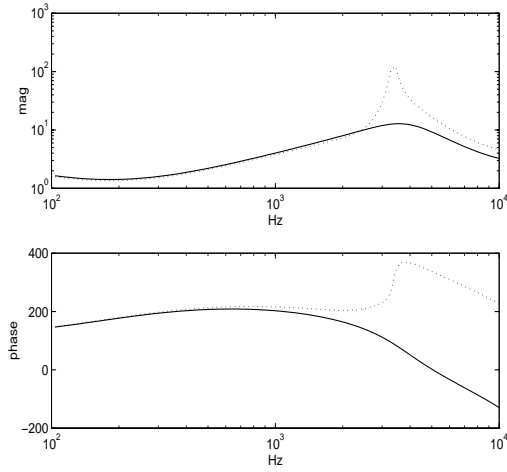


Fig. 7: Loop shape compensator C_0 (solid) and final controller C_0C (dot).

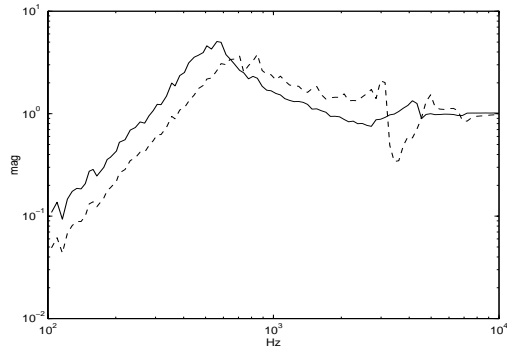


Fig. 8: Magnitude of sensitivity: initial compensator (solid) and enhanced compensator(dash).

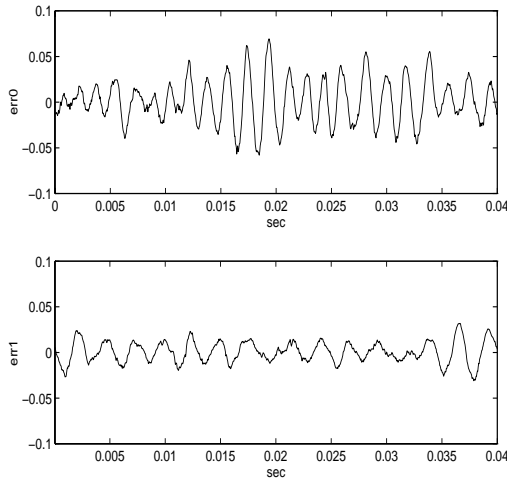


Fig. 9: Radial tracking error: initial compensator (upper) and enhanced compensator (lower).

knowledge of resonance dynamics is indispensable in view of high bandwidth design, model based control design is pursued. To that end system identification is employed to provide low order models that are suitable for control design purposes. In literature iterative procedures of identification and model based control design are proposed to establish an enhanced closed loop performance. Controllers are designed according to a two stage design procedure where nominal and robustness considerations are separated. The method is applied to a compact disc servo mechanism performing one iteration where the loop shape design appears to be a crucial step. From experimental results identification as a modelling tool and subsequent control design appear to be fruitful in order to arrive at an enhanced performance of the servo system.

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