ROBUST DESIGN OF SMITH PREDICTIVE CONTROLLER FOR MOMENT MODEL SET

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Abstract: The paper presents a simple and systematic procedure for automatic tuning of dead time compensating controllers (DTC). It integrates a simple identification experiment providing process characteristic numbers and a robust design method for an exactly defined model family. This family contains all transfer functions having (a) the given a priori form of lag/dead time transfer function (b) the experimentally obtained moment characteristic numbers. The independently interesting result of this paper is the explicit description of the value set for the model family. *Copyright © 2005 IFAC*

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1. INTRODUCTION

Dead times between inputs and outputs are common phenomena in many industrial processes and cause considerable difficulties in effective control of them. For more details see for example (Richard, 2003).

Smith (1958) suggested a dead-time compensation scheme called Dead Time Compensator (DTC) or Smith predictor. The Smith predictor whose parameters are tuned using common frequency based design criteria gives an excellent performance when an exact process model is available but yields robustness troubles when even small mismatches occur because of the more complicated Nyquist curve shape at high frequencies (Palmor, 1980). Nevertheless, a properly tuned DTC can outperform conventional controllers while achieving the same robustness. It is shown in many simulations and experimental studies (Lee *et al.*, 1996; Åström and Hägglund, 2001). There exist many semi-empirical DTC design methods which attempt to overcome these robustness problems (Morari and Zafiriou, 1989; Santacesaria and Scattolini, 1993; Ingimundarson and Hägglund, 2001; Mataušek and Kvaščev, 2003) but the range of their applicability is usually not well defined.

This paper presents a simple and systematic DTC tuning procedure which never fails under given assumptions. Furthermore, the procedure can be easily automated. The key concepts introduced are process characteristic numbers (the first three moments of the process transfer function) and the exactly defined model set containing all transfer functions that are consistent with the a priori form of the lag/dead time transfer function and with the experimentally obtained characteristic numbers. Using these concepts an exact robust design problem can be formulated and solved.

The paper is organized as follows: In Section 2 the process characteristic numbers, their properties and a simple identification experiment are introduced. In Section 3 the model set is defined and several associated concepts are presented. The parametrization of all ultimate transfer functions is given in Section 4 while Section 5 describes basic concepts of the robustness regions method for DTC design. Section 6 introduces the DTC robust design problem involving

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the robustness region method and the ultimate transfer function parametrization as its basic concepts. Finally, an example can be found in Section 7 and conclusions are summarized in Section 8.

2. PROCESS CHARACTERISTIC NUMBERS

The process transfer function $P(s)$ can be characterized by its moment sequence

$$m_i = \int_0^\infty t^i h(t)dt, \qquad i = 1, 2, \ldots, \tag{1}$$

where $h(t)$ is the corresponding process impulse response. The first few moments describe the low frequency properties of the process well because of the fact that the first elements of the Taylor series

$$F(s) = f_0 + f_1 s + f_2 s^2 + \ldots \tag{2}$$

are determined by

$$f_i = \frac{1}{i!} P^{(i)}(0) = (-1)^i \frac{1}{i!} m_i. \tag{3}$$

For processes with the monotonous step response it turns out that the only first three moments may be sufficient for a rough low frequency process model. Further, the numbers m_0, m_1, m_2 can be converted into another triplet of characteristic numbers

$$\kappa = m_0, \;\; \mu = \frac{m_1}{m_0}, \;\; \sigma^2 = \frac{m_2}{m_0} - \frac{m_1^2}{m_0^2} \tag{4}$$

with the following meanings: κ is the static gain of the process, μ and σ are the mean and variance of the 'density function' $h(t)/\kappa$, respectively. In our context, μ is usually called the resident time (Åström and Hägglund, 1995) and σ^2 is some measure for the length of the process response. It is illustrated by the following three examples.

Example 1. The characteristic numbers of the first order system $1/(\tau s + 1)$ are $\kappa = 1, \mu = \tau, \sigma^2 = \tau^2$.

Example 2. The characteristic numbers of the pure dead time e^{-Ds} are $\kappa = 1, \mu = D, \sigma^2 = 0$.

Example 3. The characteristic numbers of the zero-order hold (ZOH) system

$$F_{ZOH}(s) = \frac{1}{s}(1 - e^{-Ls}) \tag{5}$$

are $\kappa = L, \mu = L/2, \sigma^2 = L^2/12$. Note that the ZOH system (5) converts the input Dirac pulse into the unit rectangle pulse with the length L.

It is easy to prove the following lemma.

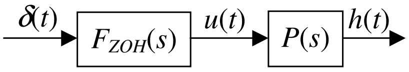

Fig. 1. Hypothetical series connection for determination of process characteristic numbers.

Lemma 1. Let the transfer function $P_i(s)$ has characteristic numbers $\kappa_i, \mu_i, \sigma_i^2,\ i = 1, 2, \ldots, m$, given according to (1) and (4), then for the characteristic numbers κ, μ, σ^2 of the transfer function

$$P(s) = P_1(s) P_2(s) \cdot \ldots \cdot P_m(s) \tag{6}$$

it holds

$$\begin{aligned} \kappa &= \kappa_1 \kappa_2 \cdot \ldots \cdot \kappa_m, \\ \mu &= \mu_1 + \mu_2 + \ldots + \mu_m, \\ \sigma^2 &= \sigma_1^2 + \sigma_2^2 + \ldots + \sigma_m^2. \end{aligned} \tag{7}$$

From Lemma 1 and Examples 1 and 2 it emerges that the transfer function of the monotonous process

$$P(s) = \frac{K_p e^{-Ds}}{(\tau_1 s + 1) \cdot \ldots \cdot (\tau_n s + 1)} \tag{8}$$

has the following characteristic numbers

$$\begin{aligned} \kappa &= K_p, \\ \mu &= D + \tau_1 + \tau_2 + \ldots + \tau_n, \\ \sigma^2 &= \tau_1^2 + \tau_2^2 + \ldots + \tau_n^2. \end{aligned} \tag{9}$$

Now, the way how the characteristic numbers κ, μ, σ^2 can be obtained from a real identification experiment will be described. For this purpose, consider the hypothetical series connection $H(s) = F_{ZOH}(s)P(s)$, depicted in Fig. 1, where F_{ZOH} is given by (5) and $P(s)$ is a process transfer function.

The impulse response $h(t)$ of this series connection is clearly identical with the response of the process $P(s)$ to the rectangle pulse

$$u(t) = \left\langle \begin{array}{l} 1, \text{ for } t \in [0, L] \\ 0, \text{ elsewhere} \end{array} \right. \tag{10}$$

as it follows from Fig. 1. Thus, the characteristic numbers $\kappa_H, \mu_H, \sigma_H^2$ of the transfer function $H(s)$ can be computed from the response of the process $P(s)$ to the rectangle pulse (10) according to (1) and (4). Now, Lemma 1 and Example 3 give the following expressions for the process characteristic numbers

$$\begin{aligned} \kappa &= \frac{\kappa_H}{L}, \\ \mu &= \mu_H - \frac{L}{2}, \\ \sigma^2 &= \sigma_H^2 - \frac{L^2}{12}. \end{aligned} \tag{11}$$

3. MODEL SET

In this section the model set of all lag/dead time transfer functions with the order n and the given characteristic numbers κ, μ and σ^2 is defined.

Definition 1. (Model Set). Let a fixed n and the characteristic numbers κ, μ, σ^2 be given. A process transfer function $P(s)$ is called *unfalsified* (or an element of the model set $\mathcal{S}^n(\kappa, \mu, \sigma^2)$) if it is consistent with the two following conditions:

(i) (A priori Hypothesis)

$$P(s) = \frac{K_p}{(\tau_1 s + 1) \cdot \ldots \cdot (\tau_n s + 1)}, \qquad (12)$$

where $K_p > 0, \tau_i \geq 0,\ i = 1, 2, \ldots, n.$

(ii) (Interpolation Conditions) The transfer functions $P(s)$ has characteristic numbers κ, μ, σ^2.

Remark 1. The condition (i) of Definition 1 expresses the fact that the whole set of all real poles stable systems of the order at most n is a priori admissible. It means that all systems (8) with the pure dead time are included for the case $n \to \infty$.

Lemma 2. The model set $\mathcal{S}^n(\kappa, \mu, \sigma^2)$ is not empty iff

$$\frac{1}{n} \leq \frac{\sigma^2}{\mu^2} \leq 1. \qquad (13)$$

Moreover, there exist infinitely many members of the model set $\mathcal{S}^n(\kappa, \mu, \sigma^2)$ if the both strict inequalities hold in (13).

The proof is given in (Večerek, 2004).

4. PARAMETRIZATION OF ALL ULTIMATE TRANSFER FUNCTIONS

Definition 2. (Value Set) Let ω is a given frequency, then the set

$$\mathcal{F}^n(\kappa, \mu, \sigma^2; \omega) = \left\{ P(j\omega) : P(s) \in \mathcal{S}^n(\kappa, \mu, \sigma^2) \right\}$$

is called the value set of the model set $\mathcal{S}^n(\kappa, \mu, \sigma^2)$ at frequency ω. The symbol $\partial\mathcal{F}^n(\kappa, \mu, \sigma^2; \omega)$ denotes the boundary of the value set $\mathcal{F}^n(\kappa, \mu, \sigma^2; \omega)$.

Definition 3. (Ultimate Transfer Function) An unfalsified transfer function $P(s) \in \mathcal{S}^n(\kappa, \mu, \sigma^2)$ is said to be ultimate if there exist at least one frequency $\omega > 0$, such that

$$P(j\omega) \in \partial\mathcal{F}^n(\kappa, \mu, \sigma^2; \omega). \qquad (14)$$

Without loss of generality the normalized case of $\kappa = 1$ and $\mu = 1$ (obtained by gain and time normalization) can be considered. Note, that the model set $\mathcal{S}^n(1, 1, \sigma^2)$ contains more than one element iff

$$\frac{1}{n} < \sigma^2 < 1 \qquad (15)$$

as it follows from Lemma 2.

Theorem 1. Let (15) holds and k is maximal integer less than $\frac{1}{\sigma^2} + 1$, then the unfalsified transfer function $P(s)$ is ultimate iff it can be expressed in the form

$$P^{\alpha}_{\nu}(s) \triangleq \qquad (16)$$
$$\frac{1}{(\tau_\nu(\alpha)s + 1)^{n_1} (\vartheta_\nu(\alpha)s + 1)^{n_2} (\zeta_\nu(\alpha)s + 1)^{n_3}},$$

where $\nu = (n_1, n_2, n_3)$ is a multiindex ranging over the list which depends on k:

(i) If $k = 2$ then the respective list is the following:
$(1, 1, 1),\ (1, 2, 1),\ \ldots,\ (1, n-2, 1),$ (a)
$(n-2, 1, 1).$ (b)

(ii) If $k \in \{3, \ldots, n-1\}$ then the respective list is:
$(1, k-1, 1),\ (1, k, 1),\ \ldots,\ (1, n-2, 1),$ (a)
$(n-2, 1, 1),\ (n-3, 1, 2),\ \ldots$
$\ldots, (n-k+1, 1, k-2),$ (b)
$(n-k, 1, k-1),$ (c)
$(1, k-2, 1).$ (d)

(iii) If $k = n$ then the respective list is the following:
$(n-2, 1, 1),\ (n-3, 1, 2),\ \ldots$
$\ldots,\ (1, 1, n-2),$ (b)
$(1, n-2, 1).$ (d)

Moreover, the parameters $\tau_\nu(\alpha)$, $\vartheta_\nu(\alpha)$ and $\zeta_\nu(\alpha)$ are given by

$$\tau_\nu(\alpha) = \alpha,$$

$$\vartheta_\nu(\alpha) = \frac{1 - n_1\alpha}{n_2 + n_3} - \sqrt{n_3} \cdot$$
$$\cdot \frac{\sqrt{\sigma^2(n_2 + n_3) - (1 - n_1\alpha)^2 - n_1(n_2 + n_3)\alpha^2}}{\sqrt{n_2}(n_2 + n_3)},$$

$$\zeta_\nu(\alpha) = \frac{1 - n_1\alpha}{n_2 + n_3} + \sqrt{n_2} \cdot$$
$$\cdot \frac{\sqrt{\sigma^2(n_2 + n_3) - (1 - n_1\alpha)^2 - n_1(n_2 + n_3)\alpha^2}}{\sqrt{n_3}(n_2 + n_3)},$$

where α ranges over the interval $I_\nu = [a_\nu, b_\nu]$. The expression for the end point b_ν is

$$b_\nu = \frac{1}{n_1 + n_2 + n_3} - \frac{\sqrt{n_3}\sqrt{\sigma^2(n_1 + n_2 + n_3) - 1}}{\sqrt{n_1 + n_2}(n_1 + n_2 + n_3)}$$

and the expression for the end point a_ν depends on the type of a row to which ν belongs: If ν is in the row (a) or (c) then $a_\nu = 0$, if ν is in the row (b) or (d) then

$$a_\nu = \frac{1}{n_1 + n_2 + n_3}$$
$$- \frac{\sqrt{n_2 + n_3}\sqrt{\sigma^2(n_1 + n_2 + n_3) - 1}}{\sqrt{n_1}(n_1 + n_2 + n_3)}$$

The proof is given in (Schlegel, 2000).

Now, some nearly evident consequences of Theorem 1 are briefly stated. Let $\nu = (n_1, n_2, n_3)$ belongs to the list of multiindexes from Theorem 1, then the value set of the set $\{P^{\alpha}_{\nu}(j\omega) : \alpha \in I_\nu\}$ for fixed frequency ω is clearly a smooth curve called ν-arc. For each point of this ν-arc there exists just one corresponding ultimate transfer function in the form (16) and vice versa. The endpoints of the ν-arcs correspond with the ultimate transfer functions in the form

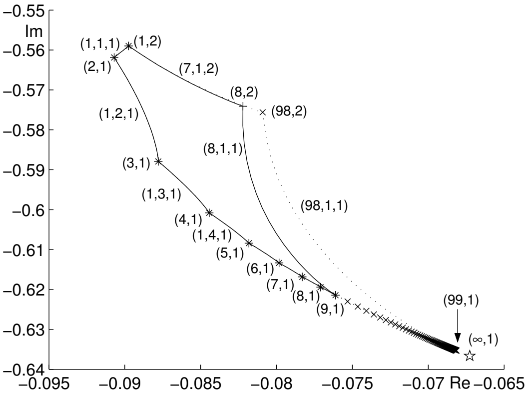

Fig. 2. The boundary of the value set $\mathcal{F}^n(\kappa, \mu, \sigma^2; \omega)$, $\omega = 2$, for $\kappa = 1$, $\mu = 1$, $\sigma = 0.6$ and $n = 10$ $(-)$, $n = 100$ $(\cdots)$, $n \to \infty$ $(\star)$. The ν-arcs and corners are marked by the corresponding triples (n_1, n_2, n_3) and pairs (m_1, m_2) respectively.

$$P(s) = \frac{1}{(\chi_1 s + 1)^{m_1} (\chi_2 s + 1)^{m_2}}, \qquad (17)$$

where

$$\chi_1 = \frac{1}{m_1 + m_2} - \frac{\sqrt{m_2}\sqrt{\sigma^2(m_1 + m_2) - 1}}{\sqrt{m_1}(m_1 + m_2)}$$

$$\chi_2 = \frac{1}{m_1 + m_2} + \frac{\sqrt{m_1}\sqrt{\sigma^2(m_1 + m_2) - 1}}{\sqrt{m_2}(m_1 + m_2)}$$

and (m_1, m_2), $m_1 \geq 1$, $m_2 \geq 1$, are ordered pairs of integers which range over the following list depending on the value k from Theorem 1:
If $k = 2$, then (m_1, m_2) belongs to the list

$$(1, 1), (2, 1), \ldots, (n - 1, 1).$$

If $k \in \{3, \ldots, n - 1\}$, then (m_1, m_2) belongs to the list

$$(k - 1, 1), (k, 1), \ldots, (n - 1, 1);$$
$$(n - 2, 2), (n - 3, 3), \ldots, (n - k + 1, k - 1);$$
$$(1, k - 1).$$

If $k = n$, then (m_1, m_2) belongs to the list

$$(n - 1, 1), (n - 2, 2), \ldots, (1, n - 1).$$

For simplicity, ultimate transfer functions in the form (17) will be called extreme.

Furthermore, it follows from Theorem 1 that the value set $\mathcal{F}^n(\kappa, \mu, \sigma^2; \omega)$, $\omega > 0$, defined by Definition 2, is bounded by a closed curve which consists of a finite number of ν-arcs specified in Theorem 1. The corners of this boundary curve are generated by the extreme transfer functions (17). This is illustrated in the Fig. 2.

In the following, the fact that the extreme transfer function (17) for $(m_1, m_2) = (n - 1, 1)$ converges to

$$P_0(s) = \frac{e^{-(1-\sigma)s}}{\sigma s + 1} \triangleq P_1(s) e^{-(1-\sigma)s}, \qquad (18)$$

when $n \to \infty$ will be used. The proof is simple and based on the identity $\lim_{n\to\infty} 1/(\frac{D}{n}s + 1)^n = e^{-Ds}$.

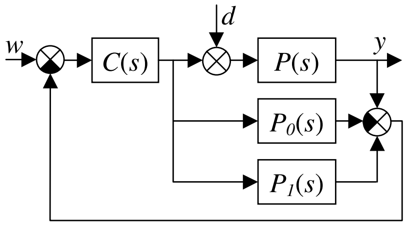

Fig. 3. Structure of DTC.

5. ROBUSTNESS REGIONS METHOD

The robustness regions metod is a graphical method allowing easy and straightforward design of two parameters of a fixed structure controller; it is a generalization of the D-partition method (Neimark, 1949). Basically, its objective is to isolate an area (region) in the controller parameter plane where a certain frequency domain design requirement is fulfilled for a certain process. While regions obtained for several processes and/or design requirements have a nonempty intersection there exists an area where all design requirements are satisfied for all processes considered. Afterwards, a point defining the optimal controller parameters is chosen from the area using some proper criterion. The principles of the method for PI(D) controller are treated in (Shafiei and Shenton, 1997; Schlegel *et al.*, 2003) in more details. In the following, the generalization of the metod for DTC is stated.

Consider a feedback control system in Fig. 3 in which $P(s)$ represents the process, $C(s)$ primary PI controller

$$C(s) = k\left(1 + \frac{1}{T_i s}\right) \triangleq k + \frac{k_i}{s}, \qquad (19)$$

in which k and T_i are the gain and the integral time constant respectively, $k_i \triangleq k/T_i$ is gain used in the following and

$$Z(s) \triangleq P_0(s) - P_1(s)$$

is the dead time compensator (Smith predictor) which consists of process models P_0 and P_1 defined by (18). The design specification is the index of an arbitrary chosen point c to the Nyquist plot of the respective open loop system in the complex plain. Almost arbitrary shaping of the Nyquist curve can be performed by involving more such points to the design procedure covering all usual frequency-domain design specifications (gain and phase margins, constraints on sensitivity functions peak values. . .).

Denote for simplicity

$$P(j\omega) \triangleq a + jb, \qquad Z(j\omega) \triangleq q + jr, \qquad d \triangleq \frac{k_i}{k}$$

Then, for open loop transfer function (Nyquist curve) $L(j\omega)$ of the system from fig. 3 it must hold

$$L(j\omega) = \frac{C(j\omega)P(j\omega)}{1 - C(j\omega)Z(j\omega)} = \\ = \frac{k(1 - j\frac{d}{\omega})(a + jb)}{1 - k(1 - j\frac{d}{\omega})(q + jr)} \tag{20}$$

Now, the goal is to isolate such regions in the controller parameter plane $k - k_i$ that the point c has the same index to the corresponding Nyquist curves in the complex plane for all points from a certain region. It is evident that for all points on the regions boundaries the corresponding Nyquist curve $L(j\omega)$ must pass through the point c in the complex plane. In other words it must hold

$$L(j\omega) = c \triangleq u + jv \tag{21}$$

at some frequency ω where $L(j\omega)$ is given by (20). The equation (21) has a unique solution for unknown controller parameters k and d:

$$k = \frac{\Upsilon}{\Psi}, \qquad d = \frac{\Xi}{\Upsilon}, \tag{22}$$

where

$$\begin{aligned} \Upsilon &= ua + qv^2 + qu^2 + bv, \\ \Psi &= a^2 + 2auq - 2avr + q^2v^2 + q^2u^2 + \\ &\quad 2bvq + 2rbu + b^2 + v^2r^2 + u^2r^2, \\ \Xi &= (ru^2 + bu - av + rv^2)\omega. \end{aligned}$$

The parametric curve $(k(\omega), k_i(\omega) = k(\omega)d(\omega))$ defined by (22) divides the parametric plane $k - k_i$ into several regions. All points of the given region fulfill the property that the point c has the same index to all corresponding Nyquist plots $L(j\omega)$. If such regions are plotted for several different points c a region can be isolated with $L(j\omega)$ properly shaped. This procedure can be performed for finite number of processes and points and then a 'satisfactory' region can be found where Nyquist plots $L(j\omega)$ of all systems are properly shaped.

Now, from the 'satisfactory' region where all the corresponding closed loop systems are stable and all the corresponding Nyquist curves are properly shaped, the optimal point which minimizes the disturbance rejection performance index

$$J = \frac{1}{k_i} \tag{23}$$

is chosen according to (Åström *et al.*, 1998).

6. ROBUST DTC DESIGN FOR THE MODEL SET

This section describes the design procedure of DTC for the model set $\mathcal{S}^n(1, 1, \sigma^2)$. Let n, the normalized σ, $0 < \sigma < 1$, and several frequency design specifications in the form of points c are given. The objective is to design a fixed DTC which fulfils the given specifications for all unfalsified transfer functions from the model set $\mathcal{S}^n(1, 1, \sigma^2)$. It is easy to prove that instead of $\mathcal{S}^n(1, 1, \sigma^2)$ it is sufficient to consider only its small subset containing all the ultimate transfer functions. In this way, much more easier and equivalent robust design problem is obtained because of Theorem 1. Since the set of all the ultimate transfer functions is infinite, it is necessary to use some its finite approximation for the computation e.g. set of all the extreme transfer functions (17) associated with the model set $\mathcal{S}^n(1, 1, \sigma^2)$. Though such approximation does not lead generally to the exact solution of the above problem, it turns out that the controller obtained in this way is at least very close to the exact solution.

Table 1. Coefficients of the DTC parameters approximation (24)

	a_0	a_1	a_2	a_3	a_4
k	0.213	-0.947	34.2	-65.0	37.7
k_i	2.22	-0.179	8.09	-16.2	13.1

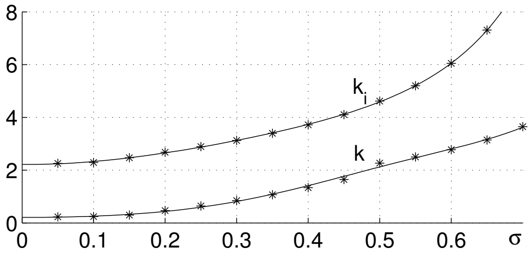

Fig. 4. Gains k and k_i of the controller (19).

7. EXAMPLE

In this example the model set $\mathcal{S}^n(1, 1, \sigma^2)$, $n = 100$, $\sigma \in [0, 0.8]$ is considered. The frequency domain robust specifications are following:

(a) For the maximum of sensitivity function

$$M_s \triangleq \max_{\omega \in [0, +\infty)} \frac{1}{1 + L(j\omega)}$$

it holds $M_s \leq 1.7$

(b) The open loop Nyquist plot $L(j\omega)$, $\omega > 0$, does not intersect the real axis in the interval $(0.6, +\infty)$.

Both of these specifications can be (approximatively) transformed to the form of four points c_i in the complex plane: $c_1 = -0.41, c_2 = -0.43 - 0.15j, c_3 = -0.49 - 0.29j, c_4 = 0.6$ as can be seen in Fig. 6. Solutions obtained for all extreme transfer functions of the model set for different values σ are depicted in Fig. 4 and approximated by

$$f(\sigma) = a_0 e^{a_1\sigma + a_2\sigma^2 + a_3\sigma^3 + a_4\sigma^4}, \tag{24}$$

where corresponding coefficients $a_0, a_1, \ldots, a_4$ are given in Tab. 1.

Figs. 5 – 7 treat the special case $\sigma = 0.4$. Fig. 5 presents the corresponding robustness regions. The optimal point used for controller design according to

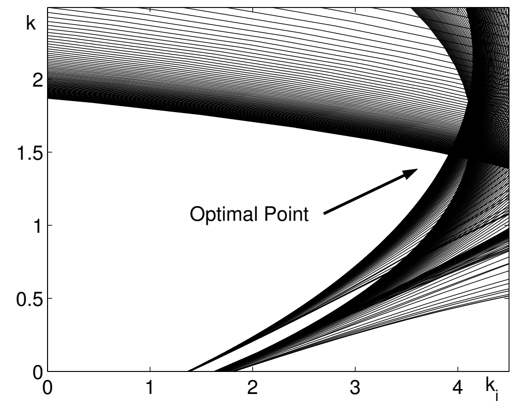

Fig. 5. Robustness regions in the parameter plain.

criterion (23) is emphasized by an arrow. Fig. 6 depicts the open loop Nyquist plots and Fig. 7 shows closed loop set-point and load disturbance step responses for all the extreme transfer functions.

8. CONCLUSIONS

This paper describes a new systematic tuning procedure for DTC which guarantees the fulfilment of all design specifications for arbitrary order lag/dead time process transfer functions. The procedure integrates all necessary steps from the simple identification experiment which provides just the three process characteristic numbers to the tuning formulae by which the robust parameters of the controller are computed. Notice, that the same tuning procedure can be used for tuning of DTCs for integrating processes (Večerek, 2004) and also for conventional PI(D) controllers.

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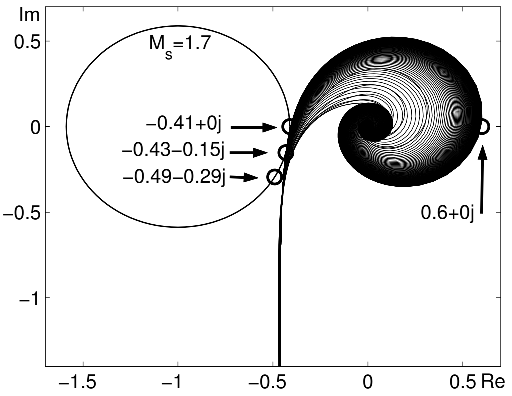

Fig. 6. Nyquist curves $L(j\omega)$ in the complex plain.

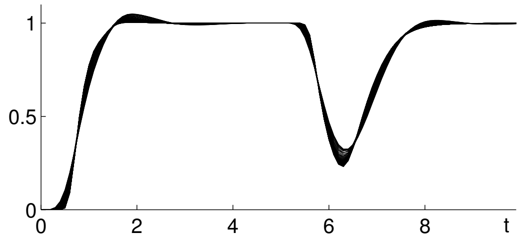

Fig. 7. Set point and load disturbance step responses.

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