A FREQUENCY DOMAIN DESIGN TECHNIQUE FOR ROBUST DECENTRALIZED CONTROLLERS

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Abstract: The paper proposes a new frequency domain approach to the design of robust decentralized controllers (DC) for continuous-time systems described by a set of transfer function matrices. To guarantee the nominal stability and the prespecified nominal performance, the recently developed DC design technique (Kozáková and Veselý, 2003) has been applied, adapted so as to guarantee the robust *M-Ḍ* structure based stability conditions modified for the closed-loop system under decentralized controller as well. Unlike the standard robust approaches to the DC, this technique allows the inclusion of the nominal interactions into the nominal model; thus the conservativeness of the robust stability conditions is relaxed.

Keywords: decentralized control, robust stability, unstructured uncertainty

1. INTRODUCTION

Complex systems are typical by multiple inputs and multiple outputs (MIMO systems). Usually, they arise as an interconnection of a finite number of subsystems. Multivariable controllers are used if strong interactions within the plant are to be compensated for. However, practical reasons often make restrictions on controller structure necessary or reasonable. In an extreme case, the controller is split into several local feedbacks and becomes a decentralized controller. Compared with centralized full-controller systems such a control structure brings about certain performance deterioration; however, this drawback is weighted against important benefits, e.g. hardware, operation and design simplicity, and reliability improvement (Skogestad and Morari, 1989; Hovd and Skogestad, 1993; 1994; Skogestad and Postlethwaite, 1996; Engell, 1998; Kozáková, 1998; Kozáková and Veselý, 2003; Schmidt and Jacobsen, 2003). Decentralized control (DC) design techniques remain probably the most popular among control engineers, in particular the frequency domain ones which provide insightful solutions and link to the classical control theory.

Development of decentralized control (DC) in the 70´ has attracted much attention. A survey of the main theoretical results can be found e.g. in Hovd and Skogestad (1994) and Viswanadham and Taylor (1988). With the come up of robust frequency domain approaches in the 80's, several practice-oriented techniques were developed (Skogestad and Morari, 1989; Hovd and Skogestad, 1993; 1994; Viswanadham and Taylor, 1988; Kozáková, 1998). The DC design comprises two steps: 1) selection of control configuration (pairing inputs with outputs); 2) design of local controllers for individual subsystems. In Step 2), two main approaches can be applied: independent design e.g. (Skogestad and Morari, 1989; Hovd and Skogestad, 1993; Kozáková, 1998) or sequential design e.g. (Viswanadham and Taylor, 1988). According to the independent design used in the sequel, local controllers are designed without considering interactions with other subsystems. The effect of interactions on the full system is assessed first and transformed into bounds for individual controller design to guarantee stability and a desired performance of the overall system. Main advantages with this approach are failure tolerance and direct local designs. The main limitation consists in that information about controllers in other loops is not exploited; therefore obtained stability and performance conditions are only sufficient and thus conservative.

The paper proposes an interactive graphical design technique of robust decentralized controllers for continuous-time uncertain systems. The core of it is the recently developed decentralized controller design method for specified performance (Kozáková and Veselý, 2003); applied for the nominal system it provides the required nominal performance. Moreover, this design method enables to consider the *full* transfer function matrix as the nominal system - unlike the existing robust DC approaches, according to which the nominal system is the diagonal part of the plant transfer matrix and the off-diagonal part is dealt with as uncertainty. In the framework of the proposed design technique, the DC design process has been adapted so as to simultaneously guarantee nominal performance and fulfillment of the *M-D* structure based robust stability conditions modified for the closed-loop under the decentralized controller considering the three most common types of unstructured uncertainty: additive, input multiplicative and output multiplicative uncertainty.

The paper is organized as follows: preliminaries and problem formulation are given in Section 2, development of the robust decentralized controller design techniques is presented in Section 3 and illustrated by an example in Section 4. Conclusions are given at the end of the paper.

2. PRELIMINARIES AND PROBLEM FORMULATION

Consider a MIMO system *G(s)* and the controller *R(s)* in a standard feedback configuration (Fig. 1)

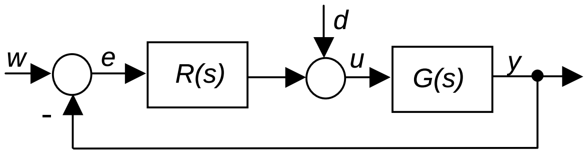


Fig. 1 Standard feedback configuration

where $G(s) \in R^{m\times l}$ and $R(s) \in R^{l\times m}$ are transfer function matrices and w, u, y, e, d are respectively vectors of reference, control, output, control error and disturbance of compatible dimensions. Only square matrices will be considered, i.e. $m=l$.

The return difference matrix $F(s) \in R^{m\times m}$ is

$$F(s) = [I + Q(s)] \qquad (2)$$

where $Q(s) \in R^{m\times m}$ is the open-loop transfer function matrix; in particular for the system in Fig.1 $Q(s) = G(s)R(s)$.

The *Nyquist D-contour* comprises the imaginary axis $s = jw$ and an infinite semi-circle into the right-half plane avoiding locations where *Q(s)* has jw -axis poles by small indentations around them; hence, unstable poles of *Q(s)* are those in the *open* right-half plane. *Nyquist plot* of a complex function $g(s)$ is the image of the Nyquist *D*-contour under *g(s);* $N[k, g(s)]$ denotes the number of anticlockwise encirclements of the point *(k, j0)* by the Nyquist plot of *g(s).*

The closed-loop characteristic polynomial of the system in Fig.1 is

$$\det F(s) = \det[I + Q(s)] = \det[I + G(s)R(s)] \qquad (3)$$

If *Q(s)* has n_q unstable poles, the closed-loop stability can be verified using the Generalized Nyquist Stability Theorem, e.g. (Skogestad and Postlethwaite, 1996).

<u>*Theorem 1*</u> *(Generalized Nyquist Stability Theorem)*
The feedback system in Fig. 1 is stable if and only if

1. $\det F(s) \neq 0 \qquad \forall s \in D$
2. $N[0, \det F(s)] = n_q \qquad (4)$

where n_q is the number of its open-loop unstable poles. □

Eigenvalues of $Q(s)$ are called *characteristic functions of* $Q(s)$ and are defined to be the set of *m* algebraic functions $q_i(s),\ i = 1,...,m$ (MacFarlane and Belletrutti, 1973; MacFarlane and Kouvaritakis, 1977; MacFarlane and Postlethwaite, 1977) given as

$$\det[q_i(s)I_m - Q(s)] = 0 \qquad i = 1,...,m \qquad (5)$$

Using characteristic functions of $Q(s)$, the closed-loop characteristic polynomial becomes

$$\det F(s) = \det[I + Q(s)] = \prod_{i=1}^{m}[1 + q_i(s)] \qquad (6)$$

Characteristic loci (CL) $q_i(s), i = 1,2,...,m$ are the set of loci in the complex plane traced out by the characteristic functions of *Q(s),* $\forall s \in D$.

A theorem equivalent to the *Theorem 1* has been derived in terms of the CL´s (DeCarlo and Saeks, 1981; MacFarlane and Postlethwaite, 1977).

<u>*Theorem 2*</u>

The closed-loop system with the open-loop transfer function matrix Q(s) is stable if and only if

1. $\det[I + Q(s)] \neq 0 \quad \forall s \in D$
2. $\sum_{i=1}^{m} N\{0, [1 + q_i(s)]\} = n_q \qquad (7)$

i.e. the sum of anticlockwise encirclements of (0, j0) contributed by the CL's of [I+Q(s)]has to be n_q. □

When designing a controller, a major source of difficulty is the plant model inaccuracy. To deal with it, the uncertainty model is used; instead of a single model, the behaviour of a class of models is considered. Let $\tilde{G}(s) \in P$ be any member of a set of possible plants P, $G(s) \in P$ be the nominal model of the plant. A simple uncertainty model is obtained using unstructured uncertainty, i.e. a full complex perturbation matrix D with dimensions compatible with those of the plant, and satisfying $\sigma_M[D(j\omega)] \le 1$ (Skogestad and Postlethwaite, 1996). We consider three common uncertainty forms and their related classes of models along with bounds on their scalar weights *w(s)* expressed in terms of bounds on the maximum singular value

$$\sigma_M[w(s)] \le \lambda(\omega) = \max_{\tilde{G} \in P} \sigma_M\{w(s)\}.$$

i. Additive uncertainty

$$\begin{aligned} &P_A : \tilde{G}(s) = G(s) + w_A(s) D_A(s) \\ &|w_A(s)| \le \lambda_A(\omega) \\ &\lambda_A(\omega) = \max_{\tilde{G} \in P_A} \sigma_M[\tilde{G}(s) - G(s)] \end{aligned} \qquad (8)$$

ii. Multiplicative input uncertainty

$$\begin{aligned} &P_I : \tilde{G}(s) = G(s)[I + w_I(s) D_I(s)] \\ &|w_I(s)| \le \lambda_I(\omega) \\ &\lambda_I(\omega) = \max_{\tilde{G} \in P_I} \sigma_M\{G^{-1}(s)[\tilde{G}(s) - G(s)]\} \end{aligned} \qquad (9)$$

iii. Multiplicative output uncetainty

$$\begin{aligned} &P_O : \tilde{G}(s) = [I + w_O(s) D_O(s)] G(s) \\ &|w_O(s)| \le \lambda_O(\omega) \\ &\lambda_O(\omega) = \max_{\tilde{G} \in P_O} \sigma_M\{[\tilde{G}(s) - G(s)] G^{-1}(s)\} \end{aligned} \qquad (10)$$

The standard feedback configuration in Fig.1 comprising the uncertain plant model $\tilde{G}(s)$ with any type of uncertainty can be rearranged into the $M - D$ structure, which is a tool for robust stability analysis.

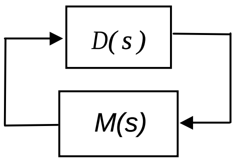


Fig. 2 $M - D$ structure

For the uncertainty types (8), (9), (10), the matrix *M(s)* has the following forms:

$$M_A = -\lambda_A(s) R(s)[I + R(s)G(s)]^{-1} \qquad (11)$$

$$M_I = -\lambda_I(s) R(s)[I + R(s)G(s)]^{-1} G(s) \qquad (12)$$

$$M_O = -\lambda_O(s) G(s) R(s)[I + G(s)R(s)]^{-1} \qquad (13)$$

<u>Theorem 3</u> *(Robust stability for unstructured perturbations , Skogestad and Postlethwaite, 1996)*

Assume that the nominal system M(s) is stable and the perturbations $D(s)$ are stable. Then the $M - D$ system in Fig. 2 is stable for all perturbations satisfying $\sigma_M[D(j\omega)] \le 1$ if and only if

$$\sigma_M[M(j\omega)] < 1, \quad \forall \omega \qquad (14)$$

□

<u>Problem Formulation</u>

Consider a system with *m* subsystems described by a set of *N* transfer function matrices $G^k(s),\ k = 1,\ldots,N$.

A robust decentralized controller to be designed is

$$\begin{aligned} &R(s) = diag\{R_i(s)\}_{i=1,\ldots,m} \\ &\det R(s) \ne 0 \quad \forall s \end{aligned} \qquad (15)$$

with $R_i(s)$ being transfer function of the ***i-th*** local controller. The designed controller has to guarantee stability and specified performance of the controlled plant over the entire opertaing range specified by the *N* transfer function matrices and described by either of the perturbed models (8), (9) or (10).

3. DEVELOPMENT OF THE ROBUST DECENTRALIZED CONTROLLER DESIGN TECHNIQUE

3.1 Choice of nominal model G(s)

In contrast to the existing robust DC approaches, in which always the diagonal model is considered as the nominal one, the proposed approach takes the full mean parameter value model as the nominal system.

3.2 Decentralized controller design (Kozáková and Veselý, 2003)

Consider the nominal model $G(s) \in R^{m \times m}$ with *m* subsystems, which can be split into the diagonal and the off-diagonal parts describing respectively models of decoupled nominal subsystems $G_d(s)$ and nominal interactions $G_m(s)$

$$G(s) = G_d(s) + G_m(s) \qquad (16)$$

where $\det G_d(s) \ne 0 \quad \forall s \in D$

The closed-loop comprising the nominal plant $G(s)$ and the decentralized controller $R(s)$ is stable if and only if conditions of Theorem 1 are met. Factorize $\det F(s)$ as follows

$$\begin{aligned} &\det F(s) = \det\{I + [(G_d(s) + G_m(s)]R(s)\} = \\ &= \det[R^{-1}(s) + G_d(s) + G_m(s)] \det R(s) = \\ &= \det F_1(s) \det R(s) \end{aligned} \qquad (17)$$

where $F_1(s) = R^{-1}(s) + G_d(s) + G_m(s) \qquad (18)$

<u>*Corollary 1*</u>

A closed-loop system comprising the system (16) and the decentralized controller (15) is stable if and only if $\forall s \in D$

1. $\det F_1(s) \ne 0$
2. $N[0, \det F_1(s)] + N[0, \det R(s)] = n_q \qquad (19)$

If $R(s)$ is stable, $N\{0, \det[R(s)]\} = 0$ and the encirclement condition (19) reduces to

$$\begin{aligned} &N[0,\ \det F_1(s)] = \\ &= N\{0,\ \det[R^{-1}(s) + G_d(s) + G_m(s)]\} = n_q \end{aligned} \qquad (20)$$

□

As $[R^{-1}(s) + G_d(s)]$ is a diagonal matrix related just to subsystems, using an appropriately chosen stable diagonal matrix $P(s) = diag\{p_i(s)\}_{i=1,\ldots,m}$ it is possible to stabilize the full system and improve its performance. Denote

$$R^{-1}(s) + G_d(s) = P(s) \qquad (21)$$

which yields

$$I + R(s)[G_d(s) - P(s)] = 0 \qquad (22)$$

or, on the subsystem level

$$1 + R_i(s)G_i^{eq}(s) = 0 \qquad i = 1,2,...,m \qquad (23)$$

where

$$G_i^{eq}(s) = G_i(s) - p_i(s) \quad i = 1,2,...,m \qquad (24)$$

is the transfer function of the *i-th* subsystem modified by $p_i(s)$ and called the transfer function of the *i-th equivalent subsystem* or simply the *equivalent transfer function*. Similarly, (23) is the *i-th equivalent characteristic equation* (Kozáková and Veselý, 2003)

Substituting into (18) we obtain

$$\det F_1(s) = \det[P(s) + G_m(s)] \qquad (25)$$

With (25) it is possible to formulate stability conditions for the closed-loop system under a decentralized controller in terms of the spectral Nyquist plot of $F_1(s)$.

<u>Corollary 2</u>

A closed-loop system comprising the system (16) and a stable decentralized controller (15) is stable if there exists a stable matrix $P(s) = diag\{p_i(s)\}_{i=1,...,m}$ such that each equivalent subsystem (24) can be stabilized by its related local controller $R_i(s)$, i.e. each equivalent closed-loop characteristic polynomial

$$CLCP_i^{eq} = 1 + R_i(s)G_i^{eq}(s) \quad i = 1,2,...,m$$

has stable roots and the two following conditions hold (in Condition 2, a. and b. are equivalent):

1. $\det[P(s) + G_m(s)] \neq 0 \qquad (26)$
2. a. $N[0, \det[P(s) + G_m(s)] = n_m$

   b. $\sum_{i=1}^{m} N[0, m_i(s)] = n_m \qquad (27)$

where $m_i(s), i = 1,...,m$ are characteristic functions of $M(s) = P(s) + G_m(s)$; n_m is the number of its unstable poles. □

3.3 Choice of $p_i(s), i = 1,...,m$

Guaranteeing performance of the closed-loop system under the decentralized controller

According to the independent design philosophy (Skogestad and Postlethwaite, 1996) $p_i(s), i = 1,...,m$ on the diagonal of the stable diagonal matrix (21) actually represent bounds for local controller designs. To guarantee closed-loop stability of the full nominal system they should be chosen such as to appropriately account for the interactions $G_m(s)$.

Substituting $P(s) = diag\{p_i(s)\}_{i=1,...,m}$ into (25) and equating to zero yields

$$\det F_1(s) = \det[p_i(s)I + G_m(s)] = 0, \quad i = 1,...,m \qquad (28)$$

which, compared with (5) defines the m characteristic functions $g_i(s), i = 1,...,m$ of the matrix $[-G_m(s)]$. In the sequel, just identical entries in the diagonal of $P(s) = p(s)I$ will be considered. Then

i. if choosing $p(s) = -g_{\mathbf{l}}(s)$ for a fixed $\mathbf{l} \in \{1,...,m\}$ then

$$\det F_1(s) = \prod_{i=1}^{m}[-g_{\mathbf{l}}(s) + g_i(s)] = 0 \qquad (29)$$

In that case the closed-loop system has some poles on the imaginary axis and no poles in the right half-plane, i.e. it is at the limit of instability.

ii. Using $(s - a)$, $a \geq 0$, $\forall s \in D$ in the arguments of all terms in (29),

$$p(s-a) = -g_{\mathbf{l}}(s-a), \text{ fixed } \mathbf{l} \in \{1,..,m\} \qquad (30)$$

$$\det F_1(s-a) = \prod_{i=1}^{m}[-g_{\mathbf{l}}(s-a) + g_i(s-a)] = 0 \qquad (31)$$

hence, the closed-loop system is at the limit of instability "shifted to $(-a)$", i.e. it has just poles with $Re\, s \leq -a$ and its degree of stability is a.

Thus, by specifying the degree of stability $a \geq 0$ for $P(s)$ we actually specify performance for the closed-loop system under the decentralized controlller in terms degree of stability.

Transfer functions of equivalent subsystems are

$$G_{i\mathbf{l}}^{eq}(s-a) = G_i(s-a) - p_{\mathbf{l}}(s-a), \ i = 1,2,...,m \qquad (32)$$

For this choice of $p_i(s), i = 1,...,m$ the encirclement stability conditions (26), (27) of *Corollary 2* can be restated in terms of the spectral Nyquist plot of $F_1(s)$

1. $\det F_1(s) = \prod_{i=1}^{m}[-g_{\mathbf{l}}(s-a) + g_i(s)] \neq 0 \qquad (33)$
2. $\sum_{i=1}^{m} N\{0, [-g_{\mathbf{l}}(s-a) + g_i(s)]\} = \sum_{i=1}^{m} N[0, m_{i\mathbf{l}}^{eq}(s-a)] = n_m \qquad (34)$

where

$$m_{i\mathbf{l}}^{eq}(s-a) \ i = 1,...,m, \ \mathbf{l} \in \{1,2,...,m\} \qquad (35)$$

are *equivalent characteristic functions* of $M(s) = [P(s) + G_m(s)]$.

The main theoretical results are summarized next.

<u>Lemma 1</u> *(Kozáková and Veselý, 2003)*

A closed-loop system comprising the system (16) and a stable decentralized controller (15) is stable with the degree of stability a if there exist such $a \geq 0$ and $g_{\mathbf{l}}(s)$, fixed $\mathbf{l} \in \{1,...,m\}$, that the two following conditions hold

1. $m_{i\mathbf{l}}^{eq}(s-a) = [-g_{\mathbf{l}}(s-a) + g_i(s)] \neq 0 \ \forall i, \forall s \in D$
2. *all equivalent closed-loop characteristic polynomials have stable roots.* □

To stabilize equivalent subsystems with a prespecified degree of stability $a \geq 0$ any graphical SISO frequency domain design technique can be applied for each subsystem independently. (e.g. Bode plots, Neymark D-partition method).

Guaranteeing performance and robust stability of the closed-loop system under the decentralized controller

With respect to the factorization of *F(s)* (17) and using (11), (12), (13) and (21), the respective forms of the general robust stability condition (14) have been derived for different uncertainty descriptions (8), (9), (10). Note that the set of perturbed plants consists of *N* transfer function matrices.

i. <u>*Additive uncertainty*</u>

$$\sigma_M\{[P(j\omega)+G_m(j\omega)]^{-1}\}= \\ =\sigma_m[P(j\omega)+G_m(j\omega)]<\frac{1}{\lambda_A(\omega)} \qquad (36)$$

where

$\sigma_m(\cdot)$ denotes the minimum singular value of the corresponding matrix and

$$\lambda_A(\omega)=\max_k \sigma_M[G^k(s)-G(s)], \quad k=1,\ldots,N$$

ii. <u>*Multiplicative input uncertainty*</u>

$$\sigma_M\{[P(j\omega)+G_m(j\omega)]^{-1}G(s)\}<\frac{1}{\lambda_I(\omega)} \qquad (37)$$

where

$$\lambda_I(\omega)=\max_k \sigma_M\{G^{-1}(s)[G^k(s)-G(s)]\} \quad k=1,\ldots,N\,.$$

iii. <u>*Multiplicative output uncertainty*</u>

$$\sigma_M\{G(j\omega)[P(j\omega)+G_m(j\omega)]^{-1}\}<\frac{1}{\lambda_o(\omega)} \qquad (38)$$

where

$$\lambda_O(\omega)=\max_k \sigma_M\{[G^k(s)-G(s)]G^{-1}(s)\} \quad k=1,\ldots,N$$

<u>*Corollary 3*</u>

A closed-loop system comprising the system (16) and a stable decentralized controller (15) is robustly stable and has a guaranteed performance in terms of the degree of stability α if there exist both such $\alpha\ge 0$ and $g_1(s)$, fixed $1\in\{1,\ldots,m\}$, that the following conditions are satisfied:

1. $m_{i1}^{eq}(s-\alpha)=[-g_1(s-\alpha)+g_i(s)]\neq 0\ \forall i,\ \forall s\in D$
2. *all equivalent closed-loop characteristic polynomials have stable roots.*
3. *either of the conditions (36), (37), (38) is satisfied for* $P(s)=[-g_1(s-\alpha)]$ □

The design procedure is described in the following illustrative example.

5. ILLUSTRATIVE EXAMPLE

Consider a laboratory plant consisting of two subsystems. Three plant models identified in 3 different operating points have been available, the resulting model is a set of 3 transfer function matrices $G^k(s),\ k=1,2,3$

- Nominal model is obtained using the mean parameter values of corresponding transfer functions entries

$$G(s)=\begin{pmatrix}\dfrac{0.1178s+4.766}{s^2+12.610s+9.689} & \dfrac{-0.023s-1.581}{s^2+16.870s+11.550}\\ \dfrac{0.124s+1.215}{s^2+9.770s+6.259} & \dfrac{1.306s+30.090}{s^2+13.750s+52.630}\end{pmatrix}$$

and has to be partitioned into the diagonal part (subsystems) and interactions

$$G(s)=G_d(s)+G_m(s)$$

- Nominal performance is specified in terms of the degree of stability $\alpha\ge 0$. Several values can be considered: $\alpha=[0\ \ 0.1\ \ 0.2\ \ 0.3\ \ 0.6\ \ 0.7]$ to simplify the final choice.
- The nominal system has two characteristic functions $g_1(s)$ and $g_2(s)$. The corresponding characteristic loci for the above specified α are in Fig. 3.

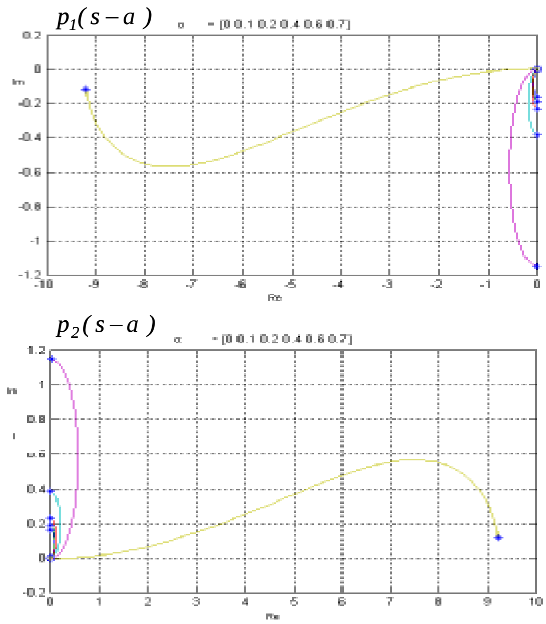


Fig. 3 Characteristic loci of $G_m(s-\alpha)$

- Choose e.g. $g_2(s-\alpha)$ to generate equivalent characteristic transfer functions

$$G_1^{eq}(s-\alpha)=G_1(s-\alpha)+g_2(s-\alpha),$$
$$G_2^{eq}(s-\alpha)=G_2(s-\alpha)+g_2(s-\alpha)$$

- The robust stability conditions (36), (37), (38) are satisfied for $\alpha=0.4$ and $P(s)=[g_2(s-0.4)]I$, the test is in Fig. 4

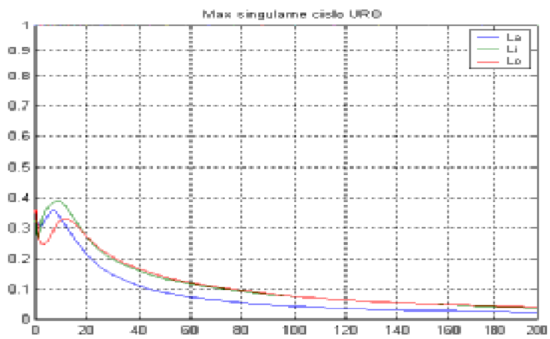


Fig. 4 Test of robust stability conditions for the closed-loop under the DC and uncertainty (8), (9),(10)

- PI controllers with the transfer function

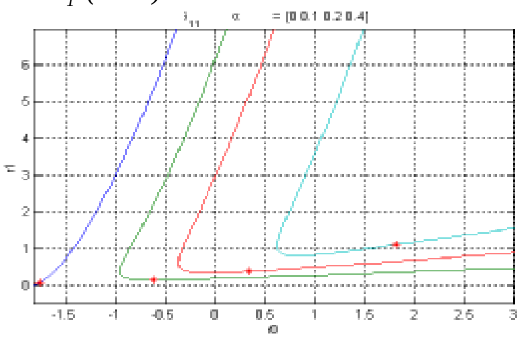
$$R(s) = r_0 + \frac{r_1}{s}$$

are designed for individual subsystems by means of the Neymark D-partition of the (r_0,r_1) plane applied to the equivalent closed loop characteristic polynomials. The resulting D-plots are in Fig. 5.

- Controller parameters have been chosen from the D-plots for $a = 0.4$ as follows

$$R_1(s) = 1.805 + \frac{1.083}{s} \qquad R_2(s) = 3.140 + \frac{1.835}{s}$$

$G_1^{eq}(s-a)$



$G_2^{eq}(s-a)$

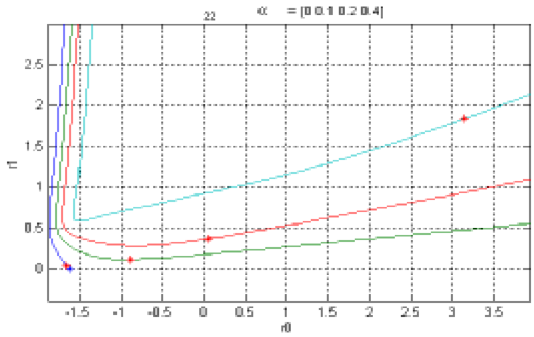


Fig. 5 Neymark D-plots for equivalent subsystems under local PI controllers

- Calculation of the closed-loop poles confirms achievement of the degree of stability 0.4. The set of closed-loop poles is

$$L = \{-0.3954 \pm 0.0791j; -0.6998 \pm 0.0244j; \\ -1.2038; -8.7308 \pm 8.1529j; -9.0808; \\ -11.2203; -16.1532\}$$

The designed decentralized controller simultaneously guarantees robust stability and performance in terms of degree of stability.

6. CONCLUSION

A new frequency domain approach to the design of robust decentralized controllers for continuous-time systems is proposed. To guarantee robust stability and performance, the recently developed DC design technique is applied (Kozáková and Veselý, 2003) being adapted so as to simultaneously guarantee a prespecified performance in terms of the degree of stability, and fulfillment of the *M-D* structure based robust stability conditions modified for the closed-loop system under decentralized controller. This design technique also enables including interactions in the nominal model, which considerably relaxes the *M-D* structure based robust stability conditions.

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