*Journal of* ELECTRICAL ENGINEERING, VOL. 58, NO. 6, 2007, 313–317

# ROBUST CONTROLLER DESIGN: POLYNOMIALLY PARAMETER DEPENDENT LYAPUNOV FUNCTION APPROACH

**Vojtech Veselý** *

The paper addresses the problem of robust output feedback controller design with guaranteed cost and polynomially parameter-dependent quadratic stability for linear continuous-time and discrete-time polytopic systems. The proposed design method pursues the idea given by Ebihara *et al*, 2006. Numerical examples are given to illustrate the effectiveness of the proposed method.

K e y w o r d s: affine linear systems, polynomially parameter-dependent quadratic stability, robust controller, output feedback

## 1 INTRODUCTION

The robust stability analysis and robust controller design for linear systems subject to time-invariant uncertainties have attracted considerable attention in robust control theory. Undoubtedly, the Lyapunov theory is one of the main approaches to deal with this problem. Description of uncertain linear time-invariant systems using convex polytope-type uncertainty has found its natural framework in the linear matrix inequality (LMI) Boyd *et al* [3]. The first LMI stability analysis and robust controller design has been based upon the notion of quadratic stability. To reduce quadratic stability conservatism in the robust controller design procedure the parameter dependent Lyapunov function (PDLF) has been introduced (Apkarian *et al* [1], de Oliveira *et al* [11, 12], Henrion *et al* [9], Peaucelle *et al* [14] and others). In the existing studies, however, the PDLFs mostly employed are restricted to those affine in the uncertain parameters. To get around the conservatism arising from affine PDLFs, more recently, promising LMI based conditions using Polynomially Parameter-Dependent Lyapunov Function (PPDLF) have been proposed in [4, 10, 13].

In this paper we pursue the idea of Ebihara *et al* [4], where robust sufficient stability condition for the existence of such PPDLFs in terms of finitely many LMIs evaluated on the vertex of the polytope of continuous LTI system has been developed. The results in the present paper have been obtained by modifying the results of [4], to linear time-invariant discrete-time systems and adding to them the conditions which in the robust controller design ensure guaranteed cost in the $D\!-\!LMI$- region . We use the following notations in this paper. Matrix $P = P^\top > 0$ $(< 0)$ is positive (negative) definite. For a matrix $A \in R^{m\times n}$ with $rank(A) = r < n, A^\perp \in R^{n\times(n-r)}$ is a matrix such that $AA^\perp = 0$ and $(A^\perp)^\top A^\perp > 0$. $R_+$ denotes the set of nonnegative integers. $C$ denotes the complex plain. $He\{AB\} = AB + B^\top A^\top$.

## 2 PROBLEM FORMULATION AND PRELIMINARIES

We consider the following affine linear time-invariant uncertain systems

$$\begin{aligned} \delta x(t) &= A(\theta)x(t) + B(\theta)u(t)\,, \\ y(t) &= C(\theta)x(t)\,, \quad x(0) = x_0 \end{aligned} \tag{1}$$

where $x(t) \in R^n$ is the plant state; $u(t) \in R^m$ is the control input; $y(t) \in R^l$ is the output vector of the system; $A(\theta), B(\theta), C(\theta)$ are matrices of appropriate dimensions and

$$\begin{aligned} A(\theta) &= A_0 + A_1\theta_1 + \dots + A_s\theta_s\,, \\ B(\theta) &= B_0 + B_1\theta_1 + \dots + B_s\theta_s\,, \\ C(\theta) &= C_0 + C_1\theta_1 + \dots + C_s\theta_s \end{aligned} \tag{2}$$

where $\theta = [\theta_1 \dots \theta_s] \in R^s$ is a vector of uncertain and time-invariant real parameters with known lower and upper bounds. $\delta x(t)$ denotes the derivative operator for continuous time system or forward difference operator for discrete time system.

Note that, in order to keep the polytope affine property, either matrix $B(\theta)$ or $C(\theta)$ must be precisely known. In the following we assume that $C(\theta)$ is known and equal to matrix $C$. The following performance index is associated with system (1)

- continuous-time system

$$J = \int_0^\infty (x(t)^\top Qx(t) + u(t)^\top Ru(t))\mathrm{d}t\,, \tag{3}$$

- discrete-time system (with discrete time $t$)

$$J = \Sigma_0^\infty (x(t)^\top Qx(t) + u(t)^\top Ru(t)) \tag{4}$$

where $Q = Q^\top \geq 0, R = R^\top > 0$ are matrices of compatible dimensions.

* Institute of Control and Industrial Informatics, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, Bratislava, Slovakia; vojtech.vesely@stuba.sk

ISSN 1335-3632 

The problem studied in this paper can be formulated as follows: For a linear time-invariant (LTI) system described by (1) design a static output feedback controller with the gain matrix $F$ and control algorithm

$$u(t) = Fy(t) = FCx(t) \tag{5}$$

so that the closed loop system

$$\delta x = (A(\theta) + B(\theta)FC)x(t) = A_c(\theta)x(t) \tag{6}$$

is PPDQS in $D{-}LMI$ region with a guaranteed cost.

Definition 1. Consider the system (1). If there exists a control law $u^*$ and a positive scalar $J^*$ such that the closed loop system (6) is stable and the closed loop value cost function (3)or (4) satisfies $J \leq J^*$, then $J^*$ is said to be the guaranteed cost and $u^*$ is said to be the guaranteed cost control law for system (1).

The system represented by (6) is a polytope of linear affine systems which can be described by a list of its vertices

$$\delta x(t) = A_{ci}x(t), \quad i = 1, 2, \ldots, N \tag{7}$$

where $N = 2^s$ and

$$A_{ci} = A_{vi} + B_{vi}FC$$

where $A_{vi}$ and $B_{vi}$ are vertices corresponding to (2). The linear uncertain system described by (7) belongs to a convex polytopic set

$$\delta x(t) = A_c(\alpha)x(t) \tag{8}$$

where

$$S = \Big\{A_c(\alpha) \colon A_c(\alpha) = \sum_{i=1}^{N} A_{ci}\alpha_i\,,\ \sum_{i=1}^{N}\alpha_i = 1\,,\ \alpha_i \geq 0\Big\}.$$

Using the concept of Lyapunov stability it is possible to formulate the following definition and lemma.

Definition 2. System (8) is robustly stable in the uncertainty box (8) if and only if there exists a matrix $P(\alpha) = P(\alpha)^\top > 0$ such that

$$\begin{aligned} D(\alpha, r) = r_{11}P(\alpha) + r_{12}^*A_c^\top(\alpha)P(\alpha) + \\ r_{12}P(\alpha)A_c(\alpha) + r_{22}A_c^\top(\alpha)P(\alpha)A_c(\alpha) < 0 \end{aligned} \tag{9}$$

within a stability region in the complex plane defined as

$$D = \Big\{z \in C \colon \begin{bmatrix} 1 \\ z \end{bmatrix}^* \begin{bmatrix} r_{11} & r_{12} \\ r_{12}^* & r_{22} \end{bmatrix} \begin{bmatrix} 1 \\ z \end{bmatrix} < 0\Big\} \tag{10}$$

where the asterisk denotes the transpose conjugate, for all $\alpha$ such that $A_c(\alpha) \in S$.

Stability within region $D$ with PPDLM is denoted as D-PPDQS. Standard choices for $D$ are the left half-plane ($r_{11} = 0, r_{12} = 1, r_{22} = 0$) for continuous time systems or the unit circle ($r_{11} = -1, r_{12} = 0, r_{22} = 1$) for discrete time ones.

Lemma 1. *Consider the LTI system* (8) *with control algorithm* (5). *The control algorithm* (5) *is the guaranteed cost control law for $D{-}LMI$ region for system* (8) *if and only if the following condition holds.*

$$D(\alpha, r) + Q + C^\top F^\top RFC < 0 \tag{11}$$

According to [11] there is no general and systematic way to formally determine $P(\alpha)$ as a function of $A_c(\alpha)$. Such a matrix $P(\alpha)$ is called the parameter dependent Lyapunov matrix (PDLM) and for a particular structure of $P(\alpha)$ inequality (9) defines the parameter dependent quadratic stability (PDQS). A new formal approach to determine $P(\alpha)$ for real convex polytopic uncertainty can be found in the references, Apkarian *et al* [1], Bachelier *et al* [2], de Oliveira *et al* [11, 12], Peaucelle *et al*[14], Dettori and Scherer [7], Henrion *et al* [9] and references cited therein. In this existing studies, however, the PDLFs employed are restricted to those affine in the uncertain parameters in the form

$$\begin{aligned} P(\alpha) = \sum_{i=1}^{N} P_i\alpha_i\,, \quad \sum_{i=1}^{N}\alpha_i = 1\,, \\ P_i = P_i^\top > 0\,, \quad i = 1, 2, \ldots, N\,. \end{aligned} \tag{12}$$

To decrease the conservatism of (11) arising from affinely PDLF, more recently, the use of polynomial PDLF has been proposed in different forms. In Ebihara *et al* [4], the following PPDLM has been proposed:

$$P(\alpha) = G\big(M(\alpha), p\big)^\top \Pi_p(\alpha) G\big(M(\alpha), p\big) \tag{13}$$

Here

$$G(M(\alpha), p) = [I_n M(\alpha)^\top \ldots (M(\alpha)^p)^\top]^\top \in R^{(p+1)n \times n}\,,$$

$M(\alpha) \in R^{n\times n}$ is a given affine function of $\alpha \in R^N$, $\Pi_p(\alpha) \in R^{(p+1)n\times(p+1)n}$ is an affine function of $\alpha$ to be determined through design procedure. The parameter $p \in R_+$ is used to determine the degree of the PPDLMs on $\alpha$. In the present paper for developing the robust controller design procedure the PPDLM in the form of (13) will be used. The following lemma is used in the paper.

Lemma 2 (Skelton *et al* [16]). *Let matrices $E \in R^{n\times n}$ and $D \in R^{m\times n}$ be given such that $rank(D) < n$. Then, the following conditions are equivalent:*

- *The condition*
$$(D^\perp)^\top ED^\perp < 0 \tag{14}$$
*holds.*
- *There exists $\mu_1 \in R$ such that $E - \mu D^\top D < 0$ holds for all $\mu \geq \mu_1$.*
- *There exists $Z \in R^{n\times m}$ such that*

$$E + He\{ZD\} < 0\,. \tag{15}$$

## 3 MAIN RESULTS

In this paragraph we present main results to design a static output feedback for polytopic system (8) with control algorithm (5) which ensures guaranteed cost and PPDQS with Lyapunov matrix given by (13) in the D-region. The design procedure is based on Lemma 1) and Lemma 2. Using the idea of Ebihara *et al* [4], the inequality (11) with (13) can be rewritten, equivalently, in the following form:

$$M1^\top \begin{bmatrix} G11 & \Pi_p(\alpha) r_{12} \\ \Pi_p(\alpha) r_{12}^* & \Pi_o(\alpha) r_{22} \end{bmatrix} M1 < 0\,, \tag{16}$$

$$G11 = G_{n,p}(Q + C^\top F^\top RFC) G_{n,p}^\top + r_{11}\Pi_p(\alpha)\,, \tag{17}$$

where

$$M1 = \begin{bmatrix} G(M(\alpha), p) \\ G(M(\alpha), p) A_c(\alpha) \end{bmatrix}$$

$$G_{n,p} = G(0,p) \in R^{(p+1)n \times n}\,,$$

with

$$G(M(\alpha), p)^\top G_{n,p} = I_n$$

for any $M(\alpha)$and $p$. From (16) we see that for the last term the following equality holds (Ebihara *et al* [4]):

$$\begin{bmatrix} A_c(\alpha) G_{n,p} & -G_{n,p} \\ L(M(\alpha), p) & 0 \\ 0 & L(M(\alpha), p) \end{bmatrix} \begin{bmatrix} G(M(\alpha), p) \\ G(M(\alpha), p) A_c(\alpha) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}$$

if

$$L(M(\alpha), p) = \begin{bmatrix} M(\alpha) - I_n & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & M(\alpha) - I_n \end{bmatrix} =$$

$$[I_p \bigotimes M(\alpha) \quad 0_{pn,n}] + [0_{pn,n} \quad -I_p \bigotimes I_n] \in \in R^{pn \times (p+1)n}\,, \tag{18}$$

that is

$$\begin{bmatrix} G(M(\alpha), p) \\ G(M(\alpha), p) A_c(\alpha) \end{bmatrix} = \begin{bmatrix} A_c(\alpha) G_{n,p} & -G_{n,p} \\ L(M(\alpha), p) & 0 \\ 0 & L(M(\alpha), p) \end{bmatrix}^\perp . \tag{19}$$

Due to Lemma 2 the condition (16) can be rewritten, equivalently, in the following form

$$\begin{bmatrix} G_{n,p}(Q + C^\top F^\top RFC) G_{n,p}^\top + r_{11}\Pi_p(\alpha) & \Pi_p(\alpha) r_{12} \\ \Pi_p(\alpha) r_{12}^* & \Pi_o(\alpha) r_{22} \end{bmatrix} + He\left\{ Z \begin{bmatrix} A_c(\alpha) G_{n,p} & -G_{n,p} \\ L(M(\alpha), p) & 0 \\ 0 & L(M(\alpha), p) \end{bmatrix} \right\} < 0 \tag{20}$$

where $Z \in R^{2(p+1)n \times (2p+1)n}$ is any matrix which satisfies (20). The results in (16) clearly indicate that (11) is given in the form of first statement of Lemma 2. Because first statement of Lemma 2 is equivalent to third statement, the inequality (16) is equivalent to (20), which proves the following theorem.

THEOREM 1. *Consider the system* (8) *with control algorithm* (5). *The control algorithm* (5) *is guaranteed cost control law in* $D$*-region if there exist matrices* $F$, $Z$ *and* $M(\alpha)$ *such that for a given* $p \in R_+$ *and matrix* $M(\alpha)$ *the inequality* (20) *holds. For the closed-loop system* (6) *the PPDQS is guaranteed.*

Note that equations (11) and (20) are equivalent for any $P(\alpha)$ but for concrete $P(\alpha)$ they determined only a sufficient robust stability conditions and guaranteed cost in $D$-region.

## 4 ROBUST CONTROLLER DESIGN: CASE $p = 1$

In the preceding section we have derived PPDLM condition (20) by means of the Finslers' Lemma (Lemma 2). This strategy was introduced in Ebihara *et al* [4], to obtain numerically verifiable PPDQS condition for robust stability of polytopic uncertain LTI systems. In this section we present new procedure to design a static output feedback controller for continuous and discrete-time systems. The design procedure is based on (20). By solving the LMIs (20) we can compute the boundary of robust stability with respect to maximal value of uncertainty $\overline{\theta_i} = \underline{\theta_i} = \theta_m$, $i = 1, 2, \dots, s$. Results from Ebihara *et al* [4], that for $p_2 > p_1$ one obtain the maximal value of uncertainty $\theta_{m2} \geq \theta_{m1}$ that is increasing the degree of $G(M(\alpha)), p)$, $p$ the robust stability sufficient condition approaches to necessary one. For the case of $p = 1$, from (20) we obtain the following results. When the first term of (20) is in the form

$$\Pi_p(\alpha) = \begin{bmatrix} \sum_{i=1}^N P_{i,1,1}\alpha_i & \sum_{i=1}^N P_{i,1,2}\alpha_i \\ \sum_{i=1}^N P_{i,1,2}^\top \alpha_i & \sum_{i=1}^N P_{i,2,2}\alpha_i \end{bmatrix}$$

one obtain the following symmetric matrix:

$$Q_0 = \{qijk\}_{4\times 4} \quad i = 1, 2, \dots, N\,, \quad j, k = 1, 2, 3, 4$$

with $q_{ijk} = q_{ikj}$
where

$$q_{i11} = Q + C^\top F^\top RFC + r_{11} \sum_{i=1}^N P_{i,1,1}\alpha_i\,,$$

$$q_{i12} = r_{11} \sum_{i=1}^N P_{i,1,2}\alpha_i\,, \qquad q_{i13} = r_{12} \sum_{i=1}^N P_{i,1,1}\alpha_i\,,$$

$$q_{i14} = r_{12} \sum_{i=1}^N P_{i,1,2}\alpha_i\,, \qquad q_{i22} = r_{11} \sum_{i=1}^N P_{i,2,2}\alpha_i\,,$$

$$q_{i23} = r_{12} \sum_{i=1}^N P_{i,1,2}\alpha_i\,, \qquad q_{i24} = r_{12} \sum_{i=1}^N P_{i,2,2}\alpha_i\,,$$

$$q_{i33} = r_{22} \sum_{i=1}^N P_{i,11}\alpha_i\,, \qquad q_{i34} = r_{22} \sum_{i=1}^N P_{i,1,2}\alpha_i\,,$$

$$q_{i44} = r_{22} \sum_{i=1}^N P_{i,22}\alpha_i\,.$$

For $Z = \{Z_{jk}\}_{4n\times 3n}$ with $Z_{jk} \in R^{n\times n}$ and denoting $M(\alpha) = M, A_c(\alpha) = A_c$ for the last term of (20) one obtains:

$$He\{ZK\} = \{k_{jk}\}_{4n\times 4n}$$

where

$$\begin{aligned}
k_{11} &= Z_{11}A_c + Z_{12}M + M^\top Z_{12}^\top + A_c^\top Z_{11}^\top,\\
k_{12} &= -Z_{12} + A_cTZ_{21}^\top + M^\top Z_{22}^\top,\\
k_{13} &= -Z_{11} + Z_{13}M + A_c^\top Z_{31}^\top + M^\top Z_{32}^\top,\\
k_{14} &= -Z_{13} + A_c^\top Z_{41}^\top + M^\top Z_{42}^\top,\\
k_{22} &= -Z_{22} - Z_{22}^\top,\\
k_{23} &= -Z_{21} + Z_{23}M - Z_{32}^\top,\\
k_{24} &= -Z_{23} - Z_{24}^\top,\\
k_{33} &= -Z_{31} - Z_{31}^\top + Z_{33}M + M^\top Z_{33}^\top,\\
k_{34} &= -Z_{33} - Z_{41}^\top + M^\top Z_{43}^\top,\\
k_{44} &= -Z_{43} - Z_{43}^\top.
\end{aligned}$$

With above two auxiliary matrices inequality (20) can be rewritten in the LMI form

$$Q_0 + He\{ZK\} < 0 \tag{21}$$

Inequality (21) implies:

- for a given $M(\alpha)$ and robust output feedback controller design it is a bilinear matrix inequality,
- with respect to $\alpha_i, i = 1, 2, \dots, N$ (21) is linear, therefore it (21) can be rewritten for each vertex $i = 1, 2, \dots, N$ that is from (21) one obtains $N$ inequalities.
- for robust stability analysis ($A_{ci}, M_i$ are given) (21) represented $N$ LMI.

If one use the argument of Henrion *et al* [9] and substitute for $Z_{21} = Z_{31} = Z_{41} = I_n$ to (21) for robust controller design a bilinear matrix inequalities can be obtained where only $\{1, 1\}$ entry is non-convex. For this entry a linearization approach can be adopted and finally the inequality (21) for $i = 1, 2, \dots, N$ reduces to LMI. If there exists a feasible solution of (21) with respect to gain matrix $F$, matrices $P_{i,j,k}, Z_{11}$ and $Z_{ij}$, $i = 1, 2, 3, 4$, $j = 2, 3$ then the closed-loop system is PPDQS with guaranteed cost in $D$-region.

## 5 EXAMPLES

In this section we present the results of numerical calculations of two examples to design a static output feedback controller with a guaranteed cost. Design procedure based on LMI inequalities (21).

Example 1. The first example has been borrowed from Benton and Smith, [16]. It concerns the design of a robust controller with a guaranteed cost for stabilizing the lateral axis dynamics for an aircraft L-1011. Let matrices $(A(\theta), B(\theta), C)$ be defined as

$$A(\theta) = \begin{bmatrix} -2.98 & q_1(t) & 0 & -0.0340\\ -.9900 & -.2100 & 0.0350 & -0.0011\\ 0 & 0 & 0 & 1\\ .3900 & -5.555 & 0 & -1.890 \end{bmatrix},$$

$$B(\theta) = [\,-.0320 \quad 0 \quad 0 \quad -1.600\,], \quad C = \begin{bmatrix} 0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

with parameter bound $-0.5700 \le q_1(t) \le 2.4300$ for all time. The above model has been recalculated for the case of $-1 \le \theta \le 1$ and $A_0 = A(\theta)$ with of $A_0(1,2) = .930$ and $A_1 = 0$ with $A_1(1,2) = 1.50$. Input matrices are $B_0 = B(\theta)$ and $B_1 = 0$. Two vertices are calculated. The results of calculations are summarized in Table 1.
$r_0 = 150, r = 1, q = 0.0001$

**Table 1.** The results of calculation for example 1.

| Method | $\theta_m$ | maxEig |
|---|---|---|
| PPDLM | 1.16 | $-.0541$ |
| PDLM | 1.3 | $-.2203$ |

The gain matrices $F$ for the first and second approaches and $|\theta| = 1$ are:

PPDLM: $F = [0.8868 \quad 14.7492]\,,$

PDLM: $F = [1.4075 \quad 2.6673]\,.$

In Table 1 and the next table $\theta_m$ is the absolute value of the maximum uncertainty level while maintaining closed-loop stability and maxEig is the maximum closed-loop eigenvalue when $|\theta_1| = |\theta_2| = |\theta| = 1$. Design procedure PDLM is calculated for Ljapunov matrix given by (11), the obtain result valid only with necessarily stability conditions.

Example 2. The second linear discrete time example has been borrowed from [15]. Consider uncertain system (1) with matrices

$$A_0 = \begin{bmatrix} .7118 & .0736 & .1262\\ .7200 & .6462 & 2.3432\\ 0 & 0 & .6388 \end{bmatrix}, \; B_0 = \begin{bmatrix} .0122 & .0412\\ .3548 & .1230\\ .2015 & .2301 \end{bmatrix},$$

$$C = C_0 = \begin{bmatrix} 0 & 1 & 0\\ 0 & 0 & 1 \end{bmatrix}, \quad A_1 = \begin{bmatrix} .08 & .006 & .01\\ .07 & .03 & .1\\ 0 & 0 & .03 \end{bmatrix},$$

$$B_1 = \begin{bmatrix} 0 & .001\\ .012 & 0\\ .007 & .2301 \end{bmatrix}, \quad A_2 = \begin{bmatrix} 0 & .004 & 0\\ .1 & 0.0 & .12\\ 0 & 0 & 0 \end{bmatrix},$$

$$B_2^\top = \begin{bmatrix} 0 & 0.02 & .014\\ 0.0 & 0 & .02 \end{bmatrix}$$

with $-1 \le \theta_i \le 1, i = 1, 2$. The results of the robust output feedback controller design are summarized in Table 2
$r_0 = 150, r = 1, q = 0.0001$

**Table 2.** The results of calculation for Example 2.

| Method | $\theta_m$ | maxEig |
|---|---|---|
| PPDLM | 4.2 | .8312 |

The gain matrix $F$ for the PPDLM approach and $|\theta| = 1$ is:

$$\text{PPDLM:} \qquad F = \begin{bmatrix} -3.0244 & -7.1593 \\ 1.3248 & 2.498 \end{bmatrix}.$$

## 6 CONCLUSION

In this paper, we have proposed a new procedure for the robust output feedback controller design for a polytopic uncertain system with a polynomially parameter dependent Lyapunov function. The feasible solutions of the output feedback controller design provide sufficient conditions guaranteeing PPDQS with a guaranteed cost in $D$-region. It should be noted that the above proposed procedure is under research and there are many questions rather open than closed. The examples show the effectiveness of the proposed method.

### Acknowledgement

The work has been supported by grant 1/3841/06 of the Slovak Grant Agency.

## References

[1] APKARIAN, P.—FERON, E.—GAHINET, P.: Parameter-Dependent Lyapunov Functions for Robust Control of Systems with Real Parametric Uncertainty, In: Proceedings of 3rd EEC, Rome, Italy, 1995, pp. 2275–2280.

[2] BACHELIER, O.—BERNUSSOU, J.—de OLIVEIRA, M. C.—GEROMEL, J. C.: Parameter Dependent Lyapunov Control Design: Numerical Evaluation, In: Proceedings of the 38th Conference on D.C, Phoenix, Arizona, USA, 1999, pp. 293–297.

[3] BOYD, S.—El GHAOUI, L.—FERON, E.—BALAKRISHNAN, V.: Linear Matrix Inequalities in System and Control Theory, SIAM, 115, Philadelphia, 1994.

[4] EBIHARA, Y.—PEAUCELLE, D.—ARZELIER, D.—HAGIVARA, T.: Robust $H_2$ Performance Analysis of Uncertain LTI Systems via Polynomially Parameter Dependent Lyapunov functions, In: Preprint of the 5th IFAC Symposium on Robust Control Design, ROCOND 06, Toulouse, France, July 5-7, 2006, CD-ROM.

[5] GAHINET, P.—APKARIAN, P.—CHILALI, M.: Affine Parameter Dependent Lyapunov Functions and Real Parametric Uncertainty, IEEE Trans. on AC **41** No. 3 (1996), 436–442.

[6] CHILALI, M.—GAHINET, P.—APKARIAN, P.: Robust Pole Placement in LMI Region, IEEE Transaction on AC **44** No. 12 (1999), 2257–2267.

[7] DETTORI, M.—SCHERER, W. C.: New Robust Stability and Performance Conditions Based on Parameter Dependent Multiplier, In: 39th IEEE Conference on DC, Sydney, Australia, 2000.

[8] GAHINET, P.—APKARIAN, P.—CHILALI, M.: Affine Parameter-Dependent Lyapunov Functions and Real Parametric Uncertainty, IEEE Trans. Circuits and Systems **41** No. 3 (1996), 436–442.

[9] HENRION, D.—ALZELIER, D.—PEAUCELLE, D. Positive Polynomial Matrices and Improved Robustness Conditions: In: 15th Triennial World Congres, Barcelona, CD-ROM, 2002.

[10] CHESI, G.—GARULLI, A.—TESI, A.—VICIHO, A.: Robust Stability of Polytopic Systems via Polynomially Parameter Dependent Lyapunov Functions, Procedings of the 42nd IEEE Conf. on Decision and Control, Maui, HI,USA, 2003, pp. 4670–4675.

[11] de OLIVEIRA, M. C.—BERNUSSOU, J.—GEROMEL, J. C.: Systems and Control Letters **37** (1999), 261–265.

[12] de OLIVEIRA, M. C.—CAMINO, J. F.—SKELTON, R. E.: A Convexifying Algorithm for the Design of Structured Linear Controllers, In: Proceedings of the 39th IEEE Conference on DC, Sydney, Australia, 2000, pp. 2781–2786.

[13] OLIVEIRA, R. C. L. F.—PERES, P. L. D.: LMI Conditions For Robust Stability Analysis Based On Polynomially Parameter Dependent Lyapunov Functions, Systems and Control Letters **55** No. 1 (Jan 2006), 52–61.

[14] PEAUCELLE, D.—ARZELIER, D.—BACHELIER, O.—BERNUSSOU, J.: A New Robust D-stability Condition for Real Convex Polytopic Uncertainty, Systems and Control Letters **40** (2000), 21–30.

[15] ROSINOVÁ, D.—VESELÝ, V.: Robust Output Feedback Design of Linear Discrete-Time Systems: LMI Approach, In: 4th IFAC Symposium on Robust Control Design, Milano, June 2003, CD-ROM, 2003.

[16] SKELTON, R. E.—IWASAKI, T.—GRIGORIADIS, K.: A Unified Algebraic Approach to Linear Control Design, Taylor and Francis, 1998.

[16] BENTON, R. E. Jr.—SMITH, D.: A Non Iterative LMI Based Algorithm For Robust Static Output Feedback Stabilization, Int. J. Control **72** No. 14 (1999), 1322–1330.

Received 5 April 2007

**Vojtech Veselý** (Prof, Ing, DrSc) was born in 1940. Since 1964 he has worked at the Department of Automatic Control Systems at the Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava, where he has supervised 18 PhD students. Since 1986 he has been Full Professor. His research interests include the areas of power system control, decentralized control of large-scale systems, process control and optimization. He is author and coauthor of more than 250 scientific papers.