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ADAPTIVE ROBUST CONTROL OF MULTIVARIABLE STATIC PLANTS WITH POSSIBLY SINGULAR TRANSFER MATRIX

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Abstract*. A new problem of the adaptive robust control of linear discrete-time multivariable static plants with the singular transfer matrices in the presence of bounded disturbances is stated and solved. The asymptotical properties of the adaptive robust feedback control systems designed via the proposed method are established.*

Keywords: multivariable static plant; discrete time; adaptive system; robust control; identification algorithm.

I. INTRODUCTION

The problem of controlling multivariable systems subjected to arbitrary unmeasurable disturbances stated several decades ago in the paper [1] remains actual up to now [2]. It is important problem from both theoretical and practical point of view.

Since the seventies, the so-called internal model method becomes popular among other methods dealing with an improvement of the control system by exploiting the different types of plant and disturbances models. A perspective modification of the internal model control principle is the model inverse approach [2]. The perfect output control performance is an important multivariable control problem closely related to inverse systems. The discrete-time multivariable process control systems containing the inverse model was proposed by one of the authors in the work [3].

Unfortunately, the inverse model approach is quite unacceptable if the systems to be controlled are square but singular because they become noninvertible. It turned out that the so-called generalized inverse (pseudoinverse) model approach can be exploited to cope with the nonivertibility of singular system [4].

The common feature of the works [1, 3] dealing with the control of multivariable plants is that their parameters are assumed to be known. Usually, the adaptive approach is used to cope with the parametric uncertainty [5], [6]. Namely, this approach was before utilized in the work [7] to controlling a multivariable static plant whose transfer matrix is unknown but nonsingular.

Recently, new adaptive methods have been advanced in literature [8] – [10]. However, they do not allow to avoid the crucial assumption with respect to the nonsingularity of the plant transfer matrix made before in the book [5, item 4.2.3°] and also in text book [6, item 5.2.3]. In other words, the problem of adaptive control applicable to controlling the singular multivariable plant remained, as yet unresolved.

This paper gives a new method for the adaptive robust control which allows to cope with the possible singularity of the transfer matrix above mentioned.

II. PROBLEM FORMULATION

Consider a linear multivariable static plant described by

$$y_n = Bu_n + v_n. \qquad (1)$$

where $y_n = [y_n^{(1)}, \ldots, y_n^{(N)}]^{\mathrm{T}}$ is the N-dimensional output vector to be measured at nth time instant $u_n = [u_n^{(1)}, \ldots, u_n^{(N)}]^{\mathrm{T}}$ is the N-dimensional vector of unmeasurable disturbances and

$$B = \begin{pmatrix} b_{11} & \ldots & b_{1N} \\ \ldots & \ldots & \ldots \\ b_{N1} & \ldots & b_{NN} \end{pmatrix} \qquad (2)$$

is an arbitrary transfer $N \times N$ matrix.

It is assumed that the elements of the matrix B in (2) are all unknown. However, there are some interval estimates

$$\underline{b}_{ik} \le b_{ik} \le \bar{b}_{ik}, \quad i, k = 1, \ldots, N \qquad (3)$$

with the known upper and lower bounds. This implies that B in (1) may be ill-conditioned or even singular, in general. Hence its rank satisfies

$$\operatorname{rank} B \le N.$$

Suppose $\{v_n^{(i)}\} \in \ell_\infty$, where ℓ_∞ denotes the space of all bounded scalar sequences $\{x_n\}$ having the norm $\|x\|_\infty = \sup_{0 \le n < \infty} |x_n| < \infty$. Thus,

$$|v_n^{(i)}| \le \varepsilon_i < \infty \quad \forall\, i = 1,\ldots,N, \qquad (4)$$

where ε_i s are constant. For simplicity of exposition, we assume that they are known.

Let $y^0 = [y^{0(1)},\ldots,y^{0(N)}]^{\mathrm{T}}$ denote the desired output vector whose components satisfy

$$|y^{0(1)}| + \ldots + |y^{0(N)}| \ne 0.$$

The problem is to design an adaptive controller of the form

$$u_{n+1} = U_n(u_n, y_n, y^0), \qquad (5)$$

to be able to guarantee the boundedness of all signals in the closed-loop system (1), (5), i.e.,

$$\lim_{n\to\infty}(\|u_n\| + \|y_n\|) \qquad (6)$$

provided that the assumptions (3) and (4) take place. In the expression (5), $U_n : R^N \times R^N \times R^N \to R^N$ represents a time-varying linear operator defined later.

III. BASIC IDEA

Basic idea is the transaction from the adaptive identification of the true plant having the singular transfer matrix $\widetilde{B}$ to the adaptive identification of a fictitious plant with the nonsingular transfer matrix of the form

$$\widetilde{B} = B + \delta_0 I, \qquad (7)$$

where I denotes the identity matrix and δ_0 is a fixed quantity.

Although $\widetilde{B}$ as well as B remain unknown, the requirement

$$\det \widetilde{B} \ne 0 \qquad (8)$$

can always be satisfied by the suitable choice of . δ_0 in (7). In fact, each ith eigenvalue $\lambda_i(B)$ of B lies in one of the N closed regions of the complex z-plane consisting of all the Gerŝgorin discs [11, p. 146]

$$|z - b_{ii}| \le \sum_{\substack{k=1\\k\ne i}}^{N} |b_{ik}|, \quad i = 1,\ldots,N. \qquad (9)$$

Since, at least, one of the eigenvalues $\lambda_i(B)$ is equal to zero (due to the singularity of B), by virtue of (8) there are the numbers

$$\underline{\beta}^{(i)} := b_{ii} - \sum_{\substack{k=1\\k\ne i}}^{N} |b_{ik}|, \quad \overline{\beta}^{(i)} := b_{ii} + \sum_{\substack{k=1\\k\ne i}}^{N} |b_{ik}|, \qquad (10)$$

such that if

$$|b_{i1}| + \ldots + |b_{iN}| \ne 0 \qquad (11)$$

then either $\underline{\beta}^{(i)} \le 0$ but $\overline{\beta}^{(i)} > 0$ or $\underline{\beta}^{(i)} < 0$ but $\overline{\beta}^{(i)} \ge 0$. These numbers define the intersection points of the ith Gerŝgorin disc with the real axis of the complex z-plane as show in Figs 1 and 2, respectively, left. In both cases, $\underline{\beta}^{(i)}\,\overline{\beta}^{(i)} \le 0$ if (11) is satisfied because $\underline{\beta}^{(i)}$ and $\overline{\beta}^{(i)}$ cannot have the same sign.

Denote

$$\underline{\beta} := \min\{\underline{\beta}^{(1)},\ldots,\underline{\beta}^{(N)}\}, \quad \overline{\beta} := \max\{\overline{\beta}^{(1)},\ldots,\overline{\beta}^{(N)}\} \qquad (12)$$

and consider the following cases: a) $|\underline{\beta}| < |\overline{\beta}|$; b) $|\underline{\beta}| > |\overline{\beta}|$ (The case when $|\underline{\beta}| = |\overline{\beta}|$ can be combined with any two cases.) In order to go to the transfer matrix $\widetilde{B}$ of the fictitious plant having the form (7) in the case a), it is sufficient to shift the Gerŝgorin disc (9) right taking

$$\delta_0 > |\underline{\beta}|, \qquad (13)$$

as shown in Fig. 1, right. In the case b), the discs (9) need to be shifted left according to

$$\delta_0 < -|\overline{\beta}|. \qquad (14)$$

See Fig. 2, right. In both cases, the nonsingularity of $\widetilde{B}$ is guaranteed. Nevertheless, the conditions (13) and (14) cannot be satisfied, as yet. In fact, the numbers $\underline{\beta}$ and $\overline{\beta}$ given by the expressions (12) depend of $\underline{\beta}^{(i)}$ and $\overline{\beta}^{(i)}$s defined by (10). But they are unknown because b_{ik}s are all unknown.

To choose a number δ_0 satisfying (8), we propose the following actions.

Define

$$\underline{\beta}^{(i)}_{\min} := \underline{b}_{ii} - \sum_{\substack{k=1\\k\ne i}}^{N} \max\{|\underline{b}_{ik}|, |\overline{b}_{ik}|\}, \qquad (15)$$

$$\overline{\beta}^{(i)}_{\max} := \overline{b}_{ii} + \sum_{\substack{k=1\\k\ne i}}^{N} \max\{|\underline{b}_{ik}|, |\overline{b}_{ik}|\}, \qquad (16)$$

minimizing and maximizing the right side of (10) for $\underline{\beta}^{(i)}$ and $\overline{\beta}^{(i)}$, respectively in $b_{ik} \in [\underline{b}_{ik}, \overline{b}_{ik}]$.

Now, introduce such quantities:

$$\underline{\beta}_{\min} := \min\{\underline{\beta}^{(1)}_{\min}, \ldots, \underline{\beta}^{(N)}_{\min}\},$$
$$\bar{\beta}_{\max} := \max\{\bar{\beta}^{(1)}_{\max}, \ldots, \bar{\beta}^{(N)}_{\max}\}. \quad (17)$$

Then δ_0 has to satisfy the conditions

$$\delta_0 > -\underline{\beta}_{\min} \text{ при } |\underline{\beta}_{\min}| < |\bar{\beta}_{\max}|,$$
$$\delta_0 < -\bar{\beta}_{\max} \text{ при } |\underline{\beta}_{\min}| > |\bar{\beta}_{\max}|. \quad (18)$$

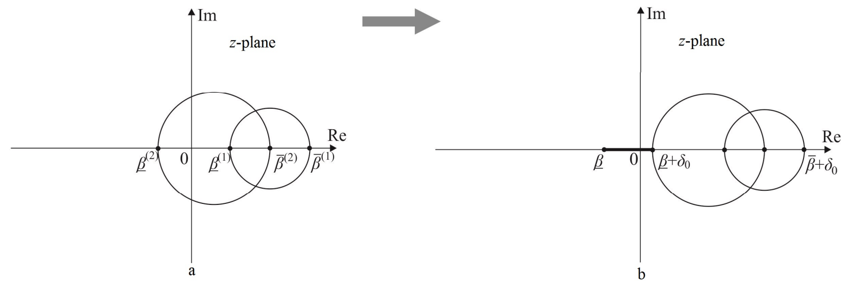

Fig. 1. The Gerŝgorin discs for $N = 2$ in the case $|\underline{\beta}^{(2)}| < |\bar{\beta}^{(1)}|$

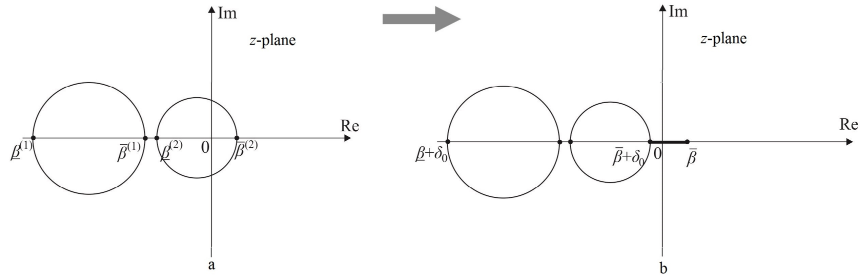

Fig. 2. The Gerŝgorin discs for $N = 2$ in the case $|\bar{\beta}^{(2)}| < |\underline{\beta}^{(1)}|$

It can be clarified that if (18) together with (15) – (17) will be satisfied then the condition (8) will without fail be ensured.

After determining the number (δ_0) we able to proceed to the consideration of the fictitious plant. Since the input variables $u_n^{(1)}, \ldots, u_n^{(N)}$ and the disturbances $v_n^{(1)}, \ldots, v_n^{(N)}$ of both true plant and fictitious plant are the same, this feature allows to describe our fictitious plant by the equation

$$\tilde{y}_n = \tilde{B} u_n + v_n, \quad (19)$$

similar to (1). In this equation, $\tilde{y}_n = [\tilde{y}_n^{(1)}, \ldots, \tilde{y}_n^{(N)}]^{\mathrm{T}}$ denotes the output vector of the fictitious plant.

It is interesting that the components of $\tilde{y}_n$ can be measured while the components of v_n in (19) remain unmeasurable. In fact, substituting (7) into (19) due to (1) we produce

$$\tilde{y}_n = y_n + \delta_0 u_n. \quad (20)$$

It is seen from (20) that $\tilde{y}_n$ can always be found indirectly having u_n and y_n to be measured.

Now, our problem reduces to the known problem of adaptive control applicable to the fictitious plant (19) with the unknown transfer matrix $\tilde{B}$ in the presence of arbitrary bounded disturbances $v_n^{(1)}, \ldots, v_n^{(1)}$.

IV. Adaptive controller design

As in [8, chapt. 7], the adaptive control law is designed in the from

$$u_{n+1} = u_n + \tilde{B}_n^{-1} \tilde{e}_n, \quad (21)$$

where instead of the current estimate B_n of $\tilde{B}$ is exploited where as the error vector

$$e_n = y^0 - y_n$$

is replaced by

$$\tilde{e}_n = y^0 - \tilde{y}_n. \quad (22)$$

with $\tilde{y}_n$ given by the expression (20).

The adaptive identification algorithm used to determine the estimates $\tilde{B}_n$ may be taken as

$$\tilde{b}_n^{(i)} = \tilde{b}_{n-1}^{(i)} + \gamma_n f(\tilde{e}_n^{*(i)}, \varepsilon_i, \varepsilon_i^0) \nabla u_n \|\nabla u_n\|^{-2},$$
$$i = 1, \ldots, N, \quad (23)$$

which is similar to that in [8, chapt. 7]. In this algorithm,

$$f(\tilde{e}_n^{*(i)}, \varepsilon_i, \varepsilon_i^0) = \begin{cases} 0, & \text{if } |\tilde{e}_n^{*(i)}| \le \varepsilon_i^0 \\ \tilde{e}_n^{*(i)} - 2\varepsilon_i \operatorname{sign} \tilde{e}_n^{*(i)} & \text{otherwise} \end{cases} \quad (24)$$

represents the dead-zone function depending on ε_i and on an

$$\varepsilon_i^0 > \varepsilon_i, \quad (25)$$

and on the identification error

$$\tilde{e}_n^{*(i)} = \nabla \tilde{y}_n^{(i)} - \tilde{b}_{n-1}^{(i)\mathrm{T}} \nabla u_n, \quad (26)$$

where

$$\nabla u_n := u_n - u_{n-1}, \quad (27)$$

$$\nabla \tilde{y}_n^{(i)} := \tilde{y}_n^{(i)} - \tilde{y}_{n-1}^{(i)}, \quad (28)$$

and the notation $\tilde{b}_n^{(i)} := [\tilde{b}_{i1}(n), \ldots, \tilde{b}_{iN}(n)]^{\mathrm{T}}$ is introduced. The coefficient γ_n is chosen as

$$0 < \gamma' \le \gamma_n \le \gamma'' < 2 \quad (29)$$

to ensure $\det \tilde{B}_n \ne 0$. The numbers $\varepsilon_i^0 (i = 1, \ldots, N)$ in (25) are chosen by the designer to be close to ε_is.

The feedback adaptive robust control system described in the equations (1), (20)–(29) is designed as depicted in Fig. 3. In this figure, ∇ denotes the operation

$$\nabla x_n := x_n - x_{n-1}$$

with any x_n.

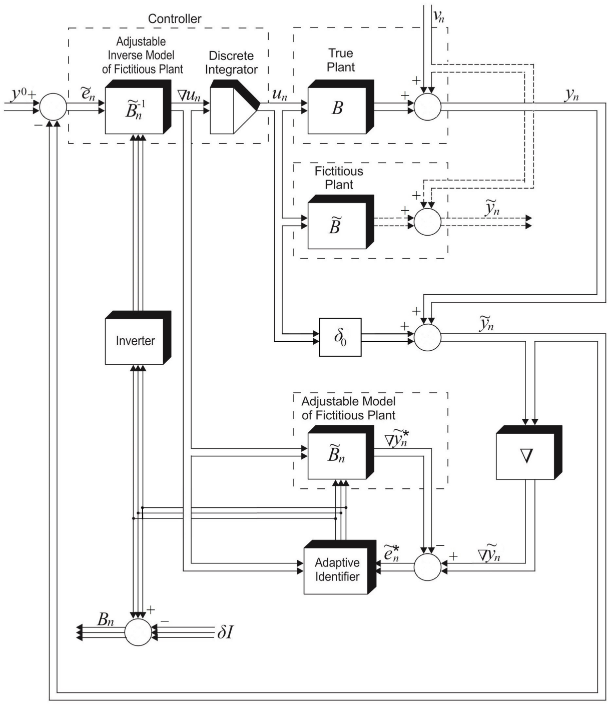

Fig. 3. Block diagram of adaptive control system

The asymptotical behavior of the adaptive control system is established in the following theorem.

Theorem. Determine δ_0 using the formulas (15) – (18) and choose an arbitrary initial $\tilde{B}_0 = B_0 + \delta_0 I$ with $B_0 = \{b_{ik}(0)\}$ whose elements satisfy

$$\underline{b}_{ik} \le b_{ik}(0) \le \bar{b}_{ik}.$$

Subject to the assumptions given in the inequalities (3), (4) with know $\underline{b}_{ik}$s, $\bar{b}_{ik}$s and ε_is the adaptive control algorithm described in the equation (21) – (29) when applied with to the plant (1) yields

i) the matrix sequence $\{\tilde{B}_n\} := \tilde{B}_1, \tilde{B}_2, \ldots,$ induced by the identification procedure converges in a finite number n_x of steps such that

$$\tilde{B}_\infty := \lim_{n \to \infty} \tilde{B}_n = \tilde{B}_{n^*};$$

ii) $\| \tilde{b}^{(i)} - \tilde{b}_n^{(i)} \| \le \| \tilde{b}^{(i)} - \tilde{b}_{n-1}^{(i)} \| \quad \forall i = 1, \ldots, N$ at each n, where $\tilde{b}^{(i)} = [\tilde{b}_{i1}, \ldots, \tilde{b}_{iN}]^{\mathrm{T}}$; denotes the ith row of $\tilde{B}$;

iii) the requirement (6) is satisfied.

The validity of i)–iii) follows directly from the results obtained in [5, item 4.2.3°] and applied the first-order multivariable plant

$$\tilde{y}_n = \tilde{y}_{n-1} + \tilde{B} u'_n + v'_n,$$

which is equivalent to (19), however, it has another control vector $u'_n := u_n - u_{n-1}$ and another disturbance vector $v'_n := v_n - v_{n-1}$, bounded in norm: $\| v'_n \| \le 2\varepsilon$ (due to (4)).

Corollary. Under the condition of the theorem given before the convergence $\{B_n\}$ to a B_∞ at the same number n^* of steps is guaranteed and $\| b^{(i)} - b_n^{(i)} \| \ (i = 1, \ldots, N)$ do not increase.

Remark. Since $B_{n^*} \ne \tilde{B}$, in general, there is no guarantee that the ultimate performance index which is achieved in the nonadaptive control system containing the generalized inverse model may here be guaranteed.

V. SIMULATION

To demonstrate some features and the efficiency of the proposed method, a simulation of the adaptive feedback control system (1), (20) – (27) for $N = 2$ with the elements $b_{11} = 4, b_{12} = 2, b_{21} = 2, \ b_{22} = 1$ of $B \ (\det B = 0)$. The estimates (3) were given as $1 \le b_{11} \le 5, 0 \le b_{12} \le 2, \ 0 \le b_{21} \le 2, \ 1 \le b_{22} \le 2.$ The sequences of $\{v_n^{(i)}\}$ $(i = 1, 2, \ldots)$ were generated as the sequences of the independent identically distributed (i.i.d) pseudorandom numbers belonging to $[-1, 1]$. It was fixed $y^0 = [1, 3]^{\mathrm{T}}$.

Using the formulas (10) – (12), the numbers $\underline{\beta}^{(1)}_{\min} = -1$, $\underline{\beta}^{(2)}_{\min} = -1$, $\overline{\beta}^{(1)}_{\max} = 7$, $\overline{\beta}^{(2)}_{\max} = 4$, $\underline{\beta}_{\min} = -1$, $\overline{\beta}_{\max} = 7$ were found. Since, it turned out, that $|\underline{\beta}_{\min}| < |\overline{\beta}_{\max}|$, we conclude that $\delta_0 > 1$ has to take place to satisfy (13). Hence, $\delta_0 = 1.1$ was taken. From the conditions $b_{11}(0) \in [1, 5]$, $b_{12}(0) \in [0, 2]$, $b_{21}(0) \in [0, 2]$, $b_{22}(0) \in [1, 2]$ the following initial estimates $b_{11}(0) = 1, b_{12}(0) = 1, b_{21}(0) = 0, b_{22}(0) = 1.9$ of B_0 were taken. The following initial estimates were taken $\tilde{b}_{11}(0) = 2.1$, $\tilde{b}_{12}(0) = 1$, $\tilde{b}_{21}(0) = 0$ and $\tilde{b}_{22}(0) = 3$.

Results of the simulation experiment are presented in Figs 4 and 5. They show that they are successful.

Furthermore, we observe from Fig. 4 that the current estimates $\tilde{b}_n^{(1)} := [\tilde{b}_{11}(n), \tilde{b}_{12}(n)]^{\mathrm{T}}$ and $\tilde{b}_n^{(2)} := [\tilde{b}_{21}(n), \tilde{b}_{22}(n)]^{\mathrm{T}}$ approach to the vectors $\tilde{b}^{(1)} := [\tilde{b}_{11}, \tilde{b}_{12}]^{\mathrm{T}}$ and $\tilde{b}^{(2)} := [\tilde{b}_{21}, \tilde{b}_{22}]^{\mathrm{T}}$, respectively, as n goes to infinity.

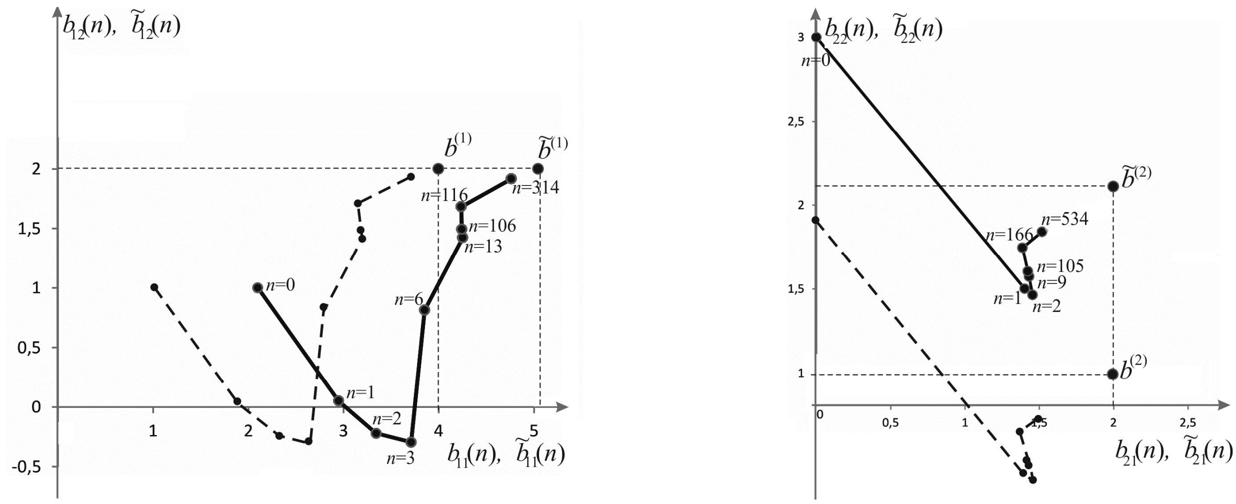

Fig. 4. The current estimates of the parameter vector of the fictions plant (solid line) and of the true plant (clashed line)

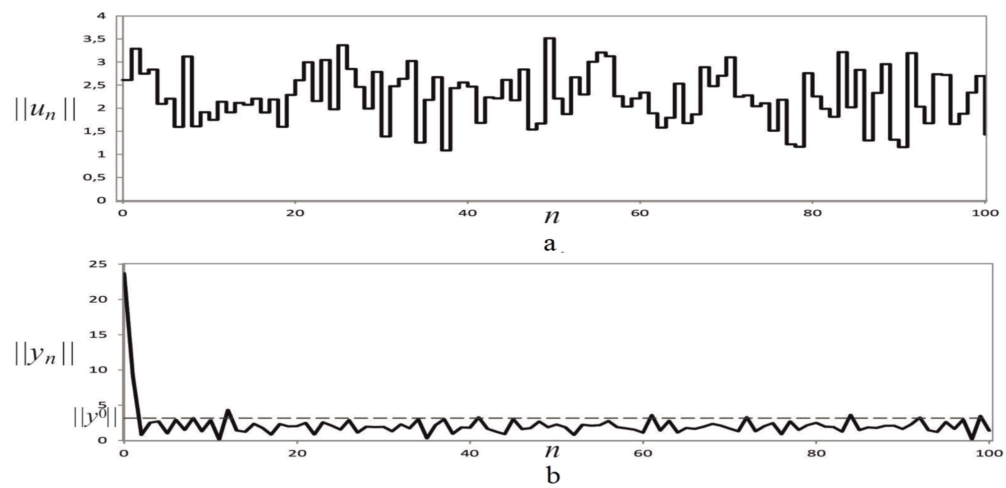

Fig. 5. The behavior the control system: a) = the norm of control vector; b) = the norm of output vector

VI. Conclusion

It is possible to design the adaptive robust controller which is capable to controlling the linear multivariable plant whose transfer is singular. Nevertheless, the problem of adaptive suboptimal control of this plant remains open, as yet.

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В. М. Азарсков, Л. С. Житецький, К. Ю. Соловчук. Адаптивне робастне керування багатовимірними статичними об'єктами з можливо виродженою передатною матрицею

Ставиться та вирішується нова задача адаптивного робастного керування лінійним дискретним багатовимірним статичним об'єктом з виродженою передатною матрицею за наявності обмежених збурень. Встановлено асимптотичні властивості адаптивної робастної системи керування зі зворотнім зв'язком, побудованої запропонованим методом.

Ключові слова: багатозв'язний статичний об'єкт; дискретний час; адаптивна система; робастне керування; алгоритм ідентифікації.

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В. Н. Азарсков, Л. С. Житецкий, К. Ю. Соловчук. Адаптивное робастное управление многомерным статическим объектом с возможно вырожденной передаточной матрицей

Ставится и решается новая задача адаптивного робастного управления линейным дискретным многомерным статическим объектом с вырожденной передаточной матрицей при наличии ограниченных возмущений. Установлены асимптотические свойства адаптивной робастной системы управления с обратной связью, построенной посредством предложенного метода.

Ключові слова: многомерный статический объект; дискретное время; адаптивная система; робастное управление; алгоритм идентификации.

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