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Selected topics in analysis, identification and control of LTI MIMO systems

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Abstract

This paper presents a survey of new results of the authors in the area of analysis, modeling, simulation and identification of linear multivariable systems. Firstly, new characterization of multivariable systems is provided, in terms of the introduction of new types of zeros of possibly nonsquare systems. The so-called control zeros properly characterize the stabilizing potential of minimum variance control. Specifically, control zeros type 1 and type 2 are related with new classes of inverses of polynomial matrices, called T - and τ -inverses, respectively. Secondly, the value of modeling and identification of linear multivariable systems by means of orthonormal basis functions is demonstrated on a practical example from the electric power industry. The orthonormal basis function models are shown to outperform the familiar ARX ones in the problem of effective, control-oriented identification of a complex industrial multivariable plant, which is a boiler proper.

Keywords: control zeros, minimum variance control (MVC), minimum phase systems, identification, orthonormal basis functions (OBF), boiler proper.

Wybrane zagadnienia z analizy, identyfikacji i sterowania liniowymi stacjonarnymi układami wielowymiarowymi

Streszczenie

W artykule przedstawiono przegląd nowych rezultatów prac badawczych autorów w zakresie analizy, modelowania, symulacji i identyfikacji liniowych obiektów wielowymiarowych. Po pierwsze, zaproponowano nową charakteryzację obiektów wielowymiarowych, wprowadzając nowe typy zer obiektów niekwadratowych. Tak zwane zera sterownicze właściwie charakteryzują potencjał stabilizacyjny sterowania minimalnowariancyjnego. Zera sterownicze typu 1 i typu 2 są związane z nowymi klasami odwrotności macierzy wielomianowych, zwanych odpowiednio T - i τ -inwersjami. Po drugie, pokazano zalety modelowania i identyfikacji obiektów wielowymiarowych z wykorzystaniem funkcji bazy ortonormalnej na przykładzie obiektu energetycznego. Modele w postaci funkcji bazy ortonormalnej zapewniają lepszą jakość identyfikacji złożonego przemysłowego obiektu wielowymiarowego, jakim jest parownik kotła energetycznego, niż modele typu ARX.

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Słowa kluczowe: zera sterownicze, sterowanie minimalnowariancyjne, obiekty minimalnofazowe, identyfikacja, funkcje bazy ortonormalnej, parownik kotła energetycznego.

1. Introduction

In this paper, we firstly consider the elusive and ever-intriguing problem of zeros of LTI MIMO systems. In order to demonstrate the role of multivariable zeros in system characterization and control design we select an input-output approach, which was originally used to define zeros (and poles) for SISO systems. There have been some controversies when analyzing nonsquare systems, that is systems with different numbers of inputs and outputs, and synthesizing their multivariable controllers. A number of not necessarily equivalent definitions of zeros have been spread throughout the control literature, raising discussions, polemics and quarrels. The first goal of this paper is to present an original, control-oriented insight into the problem of zeros for LTI MIMO systems. Some intriguing properties of control zeros type 2 are indicated, with interesting implications to robust MVC design.

Secondly, the paper presents both ARX-based and new OBF-based (OBF-Orthonormal Basis Functions) methods for modeling and identification of MIMO systems. A number of various types of MIMO models have been analyzed. These include various versions of the familiar ARX model, in addition to new multivariable versions of OBF models and inverse OBF models. To compare identification performances for particular models we choose a boiler proper at the "Opole" Electric Power Station.

2. Control zeros type 1 and type 2

The minimum variance control (MVC) problem has originally been formulated and solved for LTI discrete-time systems, at first SISO and later square MIMO ones. The problem has not since been given extensive research interest, apparently due to the lack of robustness of MVC and its instability for nonminimum phase systems. Notwithstanding, an important inheritance of the original MVC research has been redefining of discrete-time minimum phase LTI SISO systems as those whose transfer function zeros lie strictly inside the unit disc, or those 'stably invertible', or in other words those systems for which MVC is asymptotically stable. This redefinition has soon been extended to the square MIMO case, involving the transmission zeros. This has later turned attention to the MVC problem for nonsquare LTI MIMO systems, giving rise to the introduction of new 'multivariable' zeros, i.e. the so-called 'control zeros' [6, 8].

Control zeros, being an extension of transmission zeros to nonsquare systems, have originally been introduced for discrete-time systems [6, 8]. The continuous-time MVC (CMVC) problem has only recently been effectively tackled [3, 7] in order to extend the definition of control zeros to continuous-time LTI MIMO systems.

It has been shown [7] that the concept of inverse systems, initially employed in the presentation of control zeros, can be essentially extended as compared to the notion exploited in Ref. [6], resulting in the introduction of two different types of control zeros and offering a number of degrees of freedom in the design of robust minimum variance control. Based on the so-called *T*- and *τ*-inverses [3-14], the new-defined type 1 and type 2 control zeros for possibly nonsquare MIMO systems adequately characterize the stabilizing potential of output-zeroing/perfect/minimum-variance control, in terms of its sensitivity to the new-redefined nonminimum phase behavior of a plant to be controlled. New, general types of inverses of polynomial matrices play an essential role here.

3. Minimum variance control

3.1. System representations

Consider an n_u-input n_y-output LTI discrete-time system governed by the input-output description

$$\underline{A}(q^{-1})y(t) = q^{-d}\underline{B}(q^{-1})u(t) + \underline{C}(q^{-1})v(t) \tag{1}$$

where $u(t)$ and $y(t)$ are the input and output vectors, respectively, $v(t)$ is the zero-mean uncorrelated disturbance vector, d is the time delay and $\underline{A}(q^{-1})$, $\underline{B}(q^{-1})$ and $\underline{C}(q^{-1})$ are the appropriate matrix polynomials (in the backward shift operator q^{-1}) of orders n, m and l, respectively. As usual, we assume that the leading coefficient of $\underline{A}(q^{-1})$ is equal to the identity matrix. Assume that $\underline{A}(q^{-1})$ and $\underline{B}(q^{-1})$ as well as $\underline{A}(q^{-1})$ and $\underline{C}(q^{-1})$ are left coprime, with $\underline{B}(q^{-1})$ and (stable) $\underline{C}(q^{-1})$ being of full normal rank n_y. Also we assume for clarity that time delays with respect to all inputs are equal. The case of different time delays in various inputs is considered in ref. [6].

3.2. Discrete-time minimum variance control (MVC)

<u>Theorem 1</u> (Minimum variance control) [5, 7, 11].

Let an LTI discrete-time system be described by the left coprime ARMAX model (1), with $\underline{B}(q^{-1})$ and $\underline{C}(q^{-1})$ being of full normal rank n_y. Then the general MVC law, minimizing $E\{\left\| y(t+d) - y_{ref}(t+d) \right\|^2\}$, is of form

$$u(t) = \underline{B}^{\mathrm{R}}(q^{-1})\widetilde{F}^{-1}(q^{-1})[\widetilde{\underline{C}}(q^{-1})y_{ref}(t+d) - \widetilde{H}(q^{-1})y(t)] \tag{2}$$

where $y_{ref}(t)$ is the reference, $\underline{B}^{\mathrm{R}}(q^{-1})$ is a right inverse of $\underline{B}(q^{-1})$ and the appropriate polynomial matrices $\widetilde{F}(q^{-1})$ and $\widetilde{H}(q^{-1})$ (both being of dimensions $n_y \times n_y$) are computed from the polynomial matrix identity

$$\widetilde{\underline{C}}(q^{-1}) = \widetilde{F}(q^{-1})\underline{A}(q^{-1}) + q^{-d}\widetilde{H}(q^{-1}) \tag{3}$$

with

$$\widetilde{\underline{C}}(q^{-1})F(q^{-1}) = \widetilde{F}(q^{-1})\underline{C}(q^{-1}) \tag{4}$$

and $\widetilde{F}(q^{-1}) = I + \widetilde{f}_1 q^{-1} + \ldots + \widetilde{f}_{d-1}q^{-d+1}$, $\widetilde{H}(q^{-1}) = \widetilde{h}_0 + \widetilde{h}_1 q^{-1} + \ldots + \widetilde{h}_{n-1}q^{-n+1}$.

<u>Theorem 2</u> (Stability of MVC) [7, 11].

Let an LTI discrete-time system be described by the left coprime ARMAX model (1), with $\underline{B}(q^{-1})$ and $\underline{C}(q^{-1})$ being of full normal rank n_y. Then the MVC law (2), where $\widetilde{F}(q^{-1})$ and $\widetilde{H}(q^{-1})$ are as above, is asymptotically stable iff $\underline{B}(q^{-1})$ is stably (right-) invertible.

<u>Remark</u>

Control zeros type 1 and type 2 have been defined as poles of the inverse polynomial matrix $\underline{B}^{\mathrm{R}}(q^{-1})$ [3-14]. There are an infinite number of sets of control zeros, from which we can always choose a set of stable control zeros so that the MVC system would be asymptotically stable.

3.3. Simulation examples

Consider a simple, nonsquare, two-input and one-output system described by the model (1), where $B(q^{-1}) = [2 + 3.5q^{-1} + 0.1q^{-2} \quad 3 - 2.5q^{-1} + 0.6q^{-2}]$, $A(q^{-1}) = 1 + 0.7q^{-1} + 0.1q^{-2}$, $C(q^{-1}) = 1 + 0.5q^{-1} + 0.2q^{-2}$, $d = 2$ and $\mathrm{var}\{v(t)\} = 1e-3$. Inspection of an unstable set of control zeros type 1 $\{-0.0132 \pm 1.3102i,\ 0.0517 \pm 0.1179i\}$, obtained on a basis of the T-inverse [3-14], reveals the unstable minimum variance control of the system. However, one set of stable control zeros type 2 ($0.0192 \pm 0.3918\mathrm{i}$), obtained on a basis of the τ-inverse [4, 5, 7, 10, 12, 13], suggests that the system as a whole is minimum phase, which is confirmed by the stable controls $u_1(t)$ and $u_2(t)$ (fig. 1). It is clear now that the properties of (some sets of) control zeros type 2 can be more attractive than those for control zeros type 1, with interesting implications related to the robustness of MVC for nonsquare MIMO systems [5, 7, 10, 12].

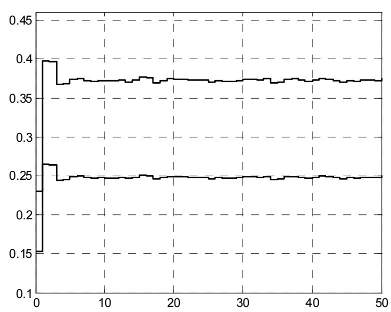

Fig. 1. Controls $u_1(t)$ and $u_2(t)$ according to (2)

Rys. 1. Sterowanie $u_1(t)$ i $u_2(t)$ dla równania (2)

4. ARX-based vs. OBF-based identification

We consider a linear MIMO system with *nu* inputs $u_i(t)$, i=1,2,…,*nu*,, *ny* outputs $y_i(t)$, i=1,2,…,*ny*, and *nz* measurable disturbances $z_i(t)$, i=1,2,…,*nz*. Additionally, the system is corrupted with unmeasurable disturbances $\varepsilon(t)$.

4.1. ARX-based identification

The system can be modeled by ARX

$$A(q^{-1})Y(t) = B(q^{-1})U(t-d_u) + C(q^{-1})Z(t-d_z) + \varepsilon(t) \quad (5)$$

where $A(q^{-1}) = I + A_1 q^{-1} + \ldots + A_{na} q^{-na}$, $B(q^{-1}) = B_0 + \ldots + B_{nb} q^{-nb}$, $C(q^{-1}) = C_0 + \ldots + C_{nc} q^{-nc}$ are the polynomial matrices, $U(t)$, $Y(t)$, $Z(t)$ are the input, output and measurable disturbance vectors in discrete time t, respectively, d_u and d_z are time delays in the input and measurable disturbance channels.

In the paper, three versions of the ARX model are analyzed: ARX in full polynomial form, in which the polynomial matrix $A(q^{-1})$ consists of matrices A_i, i=1,2…,na of rank ny, ARX in diagonal form, in which the polynomial matrix $A(q^{-1})$ consists of diagonal matrices A_i, i=1,2…,na of rank ny and ARX with common denominator, introduced in Ref. [20], in which elements of polynomial $A(q^{-1})$ are scalars.

4.2. OBF-based identification

It is well known that an open-loop stable linear discrete-time system described by the transfer function $G(z)$ can be represented with an arbitrary accuracy by the model $\hat{G}(z) = \sum_{i=1}^{M} c_i L_i(z)$, including a series of orthonormal transfer functions $L_i(z)$ and the weighting parameters c_i, i=1,...,M, characterizing the model dynamics [1, 2]. The system output can be presented in form [20, 21]

$$Y(t) = \sum_{i=1}^{M_u} C_i^u L_i(q^{-1}, p_u) U(t) + \sum_{i=1}^{M_z} C_i^z L_i(q^{-1}, p_z) Z(t) + \varepsilon(t) \quad (6)$$

where C_i^u and C_i^z are the parameter matrices to be estimated. Various OBF can be used in (6). Two commonly used sets of such functions are Laguerre and Kautz functions. These functions are characterized by the 'dominant' dynamics of a system, which is given by a real poles (p_u and p_z) or the pairs of complex ones (p_u, p_u* and p_z, p_z*). Although such a simple approximation of the real plant's pole spectrum may seem too rough, identification performances obtained can be surprisingly high, even for quite crude guesses of the pole(s). In case of discrete Laguerre models to be exploited hereinafter, the orthonormal transfer functions

$$L_i(z) = \frac{K_L}{z-p}\left[\frac{1-pz}{z-p}\right]^{i-1} \qquad i=1,...,M_u \text{ or } i=1,...,M_z \quad (7)$$

where $K_L=\sqrt{1-p^2}$, consist of a first-order low-pass factor and (i-1) th-order all-pass filters. The unknown parameter matrices C_i^u, C_i^z, with i=1,…,M_u (M_z), are easily estimated using e.g. Adaptive Least Squares (ALS) or Least Mean Squares (LMS) algorithms formalized in a linear regression fashion [19].

The main advantages of the OBF modeling approach result from 1) the output-error structure of the model (6) and 2) the specific structure of orthonormal, all-pass filters. These yield quite low values of the numbers M_u and M_z, in addition to high computational and numerical performances, including unbiasedness and low variance error of parameter estimates, low computational burden and improved numerical conditioning.

A concept of an inverse OBF modeling [7, 15, 17, 18] has lead to construction a new model, being a special case of the so-called AR-OBF model [16]. This model, called an 'inverse OBF model with integration', can be used in one of the alternative forms [20]

$$\Delta Y(t) = -\sum_{i=1}^{M_Y} C_i^y L_i(q^{-1}, p_y) Y(t) + \beta_0 U(t-d_u) + \sum_{i=1}^{M_Z} C_i^z L_i(q^{-1}, p_z) Z(t-d_z) + \varepsilon(t) \quad (8)$$

or

$$\Delta Y(t) = -\sum_{i=1}^{M_Y} C_i^y L_i(q^{-1}, p_y) Y(t) + \sum_{i=1}^{M_U} C_i^u L_i(q^{-1}, p_u) U(t-d_u) + \beta_0 Z(t-d_z) + \varepsilon(t) \quad (9)$$

where $\Delta Y(t)$=$Y(t)$-$Y(t$-1), d_u and d_z are time delays in the input and measurable disturbances, respectively, $L_i(q^{-1}, p)$, i=1,…,M, are the Laguerre filters for the output (M=M_y, p=p_y), input (M=M_u, p=p_u) and measurable disturbances (M=M_z, p=p_z), with p being the dominant Laguerre pole (being properly tuned).

The final selection of the model (8) or (9) depends on levels of disturbances affecting the input $U(t)$ and measurable disturbances $Z(t)$. When the input is more strongly contaminated with noise than the measurable disturbances, we select the model (8), thus avoiding the introduction of a number of strong noise-corrupted input entries into the regressor. Alternatively, in case the measurable disturbances are more noisy than the input, the choice is the model (9).

4.3. Application

To compare identification performances for particular models we have chosen a MIMO plant, which is a boiler proper at the "Opole" Electric Power Station. Boiler proper, being an important part of an electric power generation system, is a complex, open-loop unstable time-varying MIMO plant which creates a number of problems with its effective identification and control [19].

From the input-output point of view, the boiler proper can be considered as a classical multivariable system with two inputs: relative heat flux (q~), and mass flow of supply water (M_{zas}), two outputs: steam pressure in separator (P_{sep}) and water level in separator (H_{sep}) and three measurable disturbances: water mass flow to steam coolers (M_{sl}), enthalpy of supply water (h_{zas}) and mass flow of steam to steam turbine (M_{Psep}).

The boiler proper is a complex open-loop unstable time-varying system corrupted with strong measurable and unmeasurable disturbances.

The accuracy of identification of a model of the boiler proper is assessed by the following performance indices $I_{13} = \sum_{5000}^{10798} (y_i(t) - \hat{y}_i(t))^2$ for i=1,…,7. In our ALS and LMS estimation schemes, additional adaptive filters are employed to smooth the very noisy process variables taken from real-life identification experiments for the boiler proper. Tab. 1 presents the performance of system identification.

Tab. 1. Prediction error of particular models of the system

Models	Output	ALS		LMS
		λ=1	λ=0.995	
ARX in full poly. form	P_{sep}	2.934	1.764	2.435
	H_{sep}	4.424	3.139	5.556
ARX in diagonal form	P_{sep}	3.048	1.825	2.332
	H_{sep}	4.506	3.27	4.923
ARX with com. denominator	P_{sep}	7.403	5.533	6.937
	H_{sep}	4.106	3.311	4.527
Laguerre	P_{sep}	5.448	3.174	9.751
	H_{sep}	8.42	6.455	12.12
Inverse Laguerre(8)	P_{sep}	1.727	1.854	2.184
	H_{sep}	3.094	3.377	3.791
Inverse Laguerre(9)	P_{sep}	1.73	1.797	2.376
	H_{sep}	3.012	3.246	3.764

Fig. 2 presents excellent results of adaptive identification of the boiler proper as a MIMO plant. The highest identification accuracy, represented by the lowest output prediction error, is obtained using the inverse Laguerre model with integration.

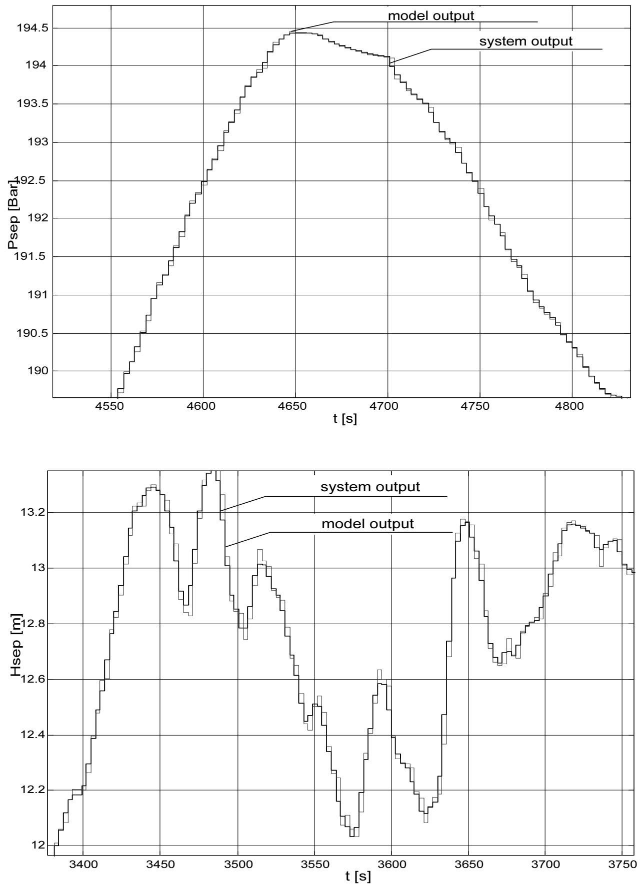

Fig. 2. Plots of the outputs of the boiler proper (as a MIMO system) vs. inverse Laguerre model outputs

Rys. 2. Przebiegi czasowe sygnałów wyjściowych parownika i odwrotnego modelu Laguerre'a

5. Conclusions

This paper has presented a new, inverse system-related solutions to the two leading, design and modeling problems behind the input-output approach: 1) zeros of LTI MIMO systems and their implications in analysis of robust MVC and 2) OBF-based vs. ARX-based modeling and identification of MIMO systems. The two, seemingly far distant problems have been bridged together under the common heading of inverse systems. Control zeros type 2 have been shown to possess nice, and intriguing properties. On the other hand, inverse OBF modeling has been proved effective in the task of identification of a complex MIMO system, that is a boiler proper at the "Opole" Electric Power Station.

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