Positive minimal realizations of continuous-discrete linear systems with transfer function with separable denominator or numerator

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Abstract: The positive minimal realization problem for continuous-discrete linear single-input, single-output (SISO) systems is formulated. Two special case of the continuous-discrete systems are analyzed. Method based on the state variable diagram for finding positive minimal realizations of given proper transfer functions is proposed. Sufficient conditions for the existence of positive minimal realizations of given proper transfer functions with separable numerator or transfer functions with separable denominator are established. Two procedures for computation of positive minimal realizations are proposed and illustrated by numerical examples.

Keywords: continuous-discrete, minimal, positive, realization, existence, computation

In positive systems inputs, state variables and outputs take only non-negative values. Examples of positive systems are: industrial processes involving chemical reactors, heat exchangers and distillation columns, storage systems, compartmental systems, water and atmospheric pollution models. A variety of models having positive linear systems behavior can be found in engineering, management science, economics, social sciences, biology and medicine, etc. Positive linear systems are defined on cones and not on linear spaces. Therefore, the theory of positive systems is more complicated and less advanced. An overview of state of the art in positive systems theory is given in the monographs [1, 2]. The realization problem for positive discrete-time and continuous-time systems without and with delays was considered in [3–7].

Continuous-discrete 2D linear system is a dynamic system that incorporates both continuous-time and discrete-time dynamics. It means that state, input and output vectors of 2D system depend on continuous and discrete variables. Examples of continuous-discrete systems include systems with relays, switches, and hysteresis, transmissions, and other motion controllers, constrained robotic systems, automated highway systems, flight control and management systems, analog/digital circuit. Wide variety of not only 2D system examples can be found e.g. in book [8]. The positive continuous-discrete 2D linear systems have been introduced in [9], positive hybrid linear systems in [10] and the positive fractional 2D hybrid systems in [11]. Different methods of solvability of 2D hybrid linear systems have been discussed in [12] and the solution to singular 2D hybrids linear systems has been derived in [13]. The realization problem for positive 2D hybrid systems have been addressed in [2, 14–16] and the minimal realization problem for the transfer function with separable denominators and the transfer function with separable numerators of 2D systems has been addressed in [17, 18].

Positive minimal realization problem for 1D systems is well-known [2]. The same problem for 2D continuous-discrete systems is much more complicated and there is only a few publications concerning positive minimal realizations. The presented paper is focused on extending the state diagram method [2, 17], previously used to solve positive realization problem (non-minimal) [13, 19], on minimal realizations. In this paper it will be shown that the state variable diagram method can be used to compute the positive minimal realizations for special case of 2D transfer function – proper transfer functions with separable denominators or separable numerators. Also, the sufficient conditions for the existence of positive minimal realizations of the given proper transfer functions will be established, and procedures for computation of positive minimal realizations for the two cases of transfer functions will be proposed.

The paper is divided in 3 sections. In section 1 some preliminaries concerning the positive continuous-discrete 2D linear systems and minimal realization are recalled and the positive minimal realization problem is formulated. Two special cases of continuous-discrete systems are analyzed in section 2. In the same section the solution to the positive minimal realization problem for two cases of transfer functions are presented and the sufficient conditions for existence of positive minimal realization are established. Concluding remarks are given in section 3.

In the paper the following notation will be used: the set of \( n \times m \) real matrices will be denoted by \( \mathbb{R}^{n \times m} \) and \( \mathbb{R}^n = \mathbb{R}^{n \times 1} \). The set of \( n \times m \) real matrices with nonnegative entries will be denoted by \( \mathbb{R}_+^{n \times m} \) and \( \mathbb{R}_+^n = \mathbb{R}_+^{n \times 1} \). \( M_n \) be the set of \( n \times m \) Metzler matrices (real matrices with nonnegative off-diagonal entries). The \( n \times n \) identity matrix will be denoted by \( I_n \) and the transpose will be denoted by \( T \).
1. Preliminaries and problem formulation

Consider a continuous-discrete linear system described by the equations [2]:

\[ x_1(t,i) = A_{11} x_1(t,i) + A_{12} x_2(t,i) + B_1 u(t,i) , \]  
\[ x_2(t,i+1) = A_{21} x_1(t,i) + A_{22} x_2(t,i) + B_2 u(t,i) , \]  
\[ y(t,i) = C_1 x_1(t,i) + C_2 x_2(t,i) + D u(t,i) , \]

where \( t \in \mathbb{R}_+ = [0, +\infty) \), \( i \in \mathbb{Z}_+ \), \( \dot{x}_i(t,i) = \frac{\partial x_i(t,i)}{\partial t} \), \( x_1(t,i) \in \mathbb{R}^{n_1} \), \( x_2(t,i) \in \mathbb{R}^{n_2} \), \( y(t,i) \in \mathbb{R}^m \), \( y(t,i) \in \mathbb{R}^p \) and \( A_{11} \in \mathbb{R}^{n_1 \times n_1} \), \( A_{12} \in \mathbb{R}^{n_1 \times n_2} \), \( A_{21} \in \mathbb{R}^{n_2 \times n_1} \), \( A_{22} \in \mathbb{R}^{n_2 \times n_2} \), \( B_1 \in \mathbb{R}^{n_1 \times m} \), \( B_2 \in \mathbb{R}^{n_2 \times m} \), \( C_1 \in \mathbb{R}^{p \times n_1} \), \( C_2 \in \mathbb{R}^{p \times n_2} \), \( D \in \mathbb{R}^{p \times m} \) are real matrices.

Boundary conditions for (1a) and (1b) have the form:

\[ x_1(0,i) = x_1(i) , \quad i \in \mathbb{Z}_+ \]  
\[ x_2(t,0) = x_2(t) , \quad t \in \mathbb{R}_+ . \]

Note that the continuous-discrete linear system (1) has a similar structure as the Roesser model [10, 20].

Definition 1. The continuous-discrete linear system (1) is called internally positive if \( x_1(t,i) \in \mathbb{R}^{n_1}_+ \), \( x_2(t,i) \in \mathbb{R}^{n_2}_+ \), \( y(t,i) \in \mathbb{R}^p_+ \), \( u(t,i) \in \mathbb{R}_+^m \), \( A_{11} \in \mathbb{R}^{n_1 \times n_1}_+ \), \( A_{12} \in \mathbb{R}^{n_1 \times n_2}_+ \), \( A_{21} \in \mathbb{R}^{n_2 \times n_1}_+ \), \( A_{22} \in \mathbb{R}^{n_2 \times n_2}_+ \), \( B_1 \in \mathbb{R}^{n_1 \times m}_+ \), \( B_2 \in \mathbb{R}^{n_2 \times m}_+ \), \( C_1 \in \mathbb{R}^{p \times n_1}_+ \), \( C_2 \in \mathbb{R}^{p \times n_2}_+ \), \( D \in \mathbb{R}^{p \times m}_+ \) and all inputs \( u(t,i) \in \mathbb{R}^m_+ \), \( t \in \mathbb{R}_+ \) and all initial conditions \( x_1(i) \in \mathbb{R}^{n_1}_+ \), \( i \in \mathbb{Z}_+ \), \( x_2(t) \in \mathbb{R}^{n_2}_+ \), \( t \in \mathbb{R}_+ \) and all initial inputs \( u(t) \in \mathbb{R}^m_+ \), \( t \in \mathbb{R}_+ \), \( i \in \mathbb{Z}_+ \).

Theorem 1. [2, 10] The continuous-discrete linear system (1) is internally positive if and only if:

\[ A_{11} \in M_{n_1}, A_{12} \in \mathbb{R}^{n_1 \times n_2}_+, A_{21} \in \mathbb{R}^{n_2 \times n_1}_+, A_{22} \in \mathbb{R}^{n_2 \times n_2}_+, B_1 \in \mathbb{R}^{n_1 \times m}_+, B_2 \in \mathbb{R}^{n_2 \times m}_+, C_1 \in \mathbb{R}^{p \times n_1}_+, C_2 \in \mathbb{R}^{p \times n_2}_+, D \in \mathbb{R}^{p \times m}_+ . \]

The transfer matrix of the system (1) is given by the formula:

\[ T(s,z) = \begin{bmatrix} C_1 & C_2 \end{bmatrix} \begin{bmatrix} I_n s - A_{11} & -A_{12} \\ -A_{21} & I_n s - A_{22} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} + D \in \mathbb{R}^{p \times m}(s,z) \]

where \( \mathbb{R}^{p \times m}(s,z) \) is the set of \( p \times m \) real matrices in \( s \) and \( z \) with real coefficient. For the \( m \)-inputs and \( p \)-outputs continuous-discrete linear system (1), the proper transfer matrix has the following form:

\[ T(s,z) = \begin{bmatrix} T_{11}(s,z) & \cdots & T_{1m}(s,z) \\ \vdots & \ddots & \vdots \\ T_{p1}(s,z) & \cdots & T_{pm}(s,z) \end{bmatrix} \in \mathbb{R}^{p \times m}(s,z) \]

where:

\[ T_{kl}(s,z) = \frac{\sum_{i=0}^{n_{1,l}} \sum_{j=0}^{n_{2,l}} a_{i,j}^{kl} s^i z^j}{z^m + \sum_{i=0}^{n_{1,l}} \sum_{j=0}^{n_{2,l}} b_{i,j}^{kl} s^i z^j} \]

for \( k = 1,2,\ldots; l = 1,2,\ldots,m \) where \( U(s,z) = z \{ \mathcal{L}[u(t,i)] \} \), \( Y(s,z) = z \{ \mathcal{L}[y(t,i)] \} \) and \( z \) and \( \mathcal{L} \) are the Z-transform and Laplace operators.

Multiplying the numerator and denominator of transfer matrix (5b) by \( s^{-n_1} z^{-n_2} \) we obtain the transfer matrix in the state space form, eq. form which is desired to draw the state space diagram [9, 15, 20]:

\[ T_{kl}(s^{-1}, z^{-1}) = \left[ 1 - \sum_{i=0}^{n_{1,l}} \sum_{j=0}^{n_{2,l}} a_{i,j}^{kl} s^{-i} z^{-j} \right] \left( \mathcal{L}^{-1} \left[ \sum_{i=0}^{n_{1,l}} \sum_{j=0}^{n_{2,l}} b_{i,j}^{kl} s^{-i} z^{-j} \right] \right) \]

for \( k = 1,2,\ldots; l = 1,2,\ldots,m \).

Definition 2. The matrices (3) are called the positive realization of the transfer matrix \( T(s,z) \) if they satisfy the equality (4). The realization is minimal if the matrix

\[ A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \]

has the lowest possible dimension among all realizations. The positive minimal realization problem can be stated as follows: given a proper rational matrix \( T(s,z) \in \mathbb{R}^{p \times m}(s,z) \), find its positive and minimal realization (3).

Remark 1. For 1D systems the minimal realization is the one with the matrix \( A \) of dimension \( n \times n \) where \( n \) is the degree of the characteristic polynomial of the system [9]. This was implicated by controllability and observability of the 1D system. For 2D system in general case this relationship is not true [19] and the observability and controllability of the 2D system does not implicate the minimality of its realization.

Remark 2. The minimal realization for 2D system is the one with the matrix \( A \) of dimension \( (n_1 + n_2) \times (n_1 + n_2) \) where \( n_1 \) and \( n_2 \) are the degrees of the characteristic polynomial in \( s \) and \( z \) of the system [19].

2. Problem solution for SISO systems

The solution to the minimal positive realization problem will be presented on two special cases of the 2D transfer functions. Proposed method will be based on the state variable diagram [2, 17, 15].

Two cases of the transfer functions of continuous-discrete linear system will be considered.

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Case 1. The transfer function with separable denominators:

\[
T(s^{-1}, z^{-1}) = \frac{\sum_{i=0}^{n_i} \sum_{j=0}^{n_j} b_{ij} s^{-i} z^{-j}}{1 - \sum_{k=0}^{n_k} \beta_k s^{-k}} = \frac{Y(s^{-1}, z^{-1})}{U(s^{-1}, z^{-1})} \quad (7)
\]

Case 2. The transfer function with separable numerators:

\[
T(s^{-1}, z^{-1}) = \frac{\sum_{i=0}^{n_i} \beta_i z^{-i}}{1 - \sum_{k=0}^{n_k} \sum_{l=0}^{n_l} a_{kl} s^{-i} z^{-j}} = \frac{Y(s^{-1}, z^{-1})}{U(s^{-1}, z^{-1})} \quad (8)
\]

2.1. Case 1

Defining:

\[
E(s^{-1}, z^{-1}) = \frac{U(s^{-1}, z^{-1})}{1 - \beta_1 s^{-1} - \beta_2 s^{-2} - \ldots - \beta_{n_0} s^{-n_0}},
\]

\[
Y(s^{-1}, z^{-1}) = \frac{(b_{00} + b_{01} z^{-1} + b_{10} s^{-1} + \ldots + b_{n_0, n_0} s^{-n_0} z^{-n_0}) E(s^{-1}, z^{-1})}{1 - A_1 s^{-1} - A_2 s^{-2} - \ldots - A_{n_0} s^{-n_0}} \quad (9)
\]

from (9) and (7) we obtain:

\[
E(s^{-1}, z^{-1}) = U(s^{-1}, z^{-1}) + (\beta_1 s^{-1} + \beta_2 s^{-2} + \ldots + \beta_{n_0} s^{-n_0}) E(s^{-1}, z^{-1}),
\]

\[
Y(s^{-1}, z^{-1}) = (b_{00} + b_{01} z^{-1} + b_{10} s^{-1} + \ldots + b_{n_0, n_0} s^{-n_0} z^{-n_0}) E(s^{-1}, z^{-1}) + (A_1 s^{-1} + A_2 s^{-2} + \ldots + A_{n_0} s^{-n_0}) Y(s^{-1}, z^{-1}) \quad (10)
\]

Using (10) we may draw the state variable diagram shown in fig. 1.

Fig. 1. State variable diagram for transfer function (7) with separable denominators

Rys. 1. Schemat zmiennych stanu dla transmitancji (7) z separowanym mianownikiem

As state variables we choose the outputs of integrators \((x_{11}(t, i), x_{12}(t, i), \ldots, x_{1, n_1}(t, i))\) and of delay elements \((x_{21}(t, i), x_{22}(t, i), \ldots, x_{2, n_2}(t, i))\). Using the state variable diagram (fig. 1) we can write the following differential and difference equations:

\[
\begin{align*}
\dot{x}_{11}(t, i) &= e(t, i), \\
\dot{x}_{12}(t, i) &= x_{11}(t, i), \\
&\vdots \\
\dot{x}_{1, n_1}(t, i) &= x_{1, n_1}(t, i), \quad (11a)
\end{align*}
\]

\[
\begin{align*}
x_{21}(t, i + 1) &= b_{01} e(t, i) + b_{11} x_{11}(t, i) + b_{21} x_{12}(t, i) + \ldots + b_{n_1, n_1} x_{1, n_1}(t, i) + x_{22}(t, i) + A_1 y(t, i), \\
&\vdots \\
x_{2, n_2}(t, i + 1) &= b_{0, n_2} e(t, i) + b_{1, n_2} x_{11}(t, i) + b_{2, n_2} x_{12}(t, i) + \ldots + b_{n_2, n_2} x_{1, n_2}(t, i) + A_y y(t, i),
\end{align*}
\]

where:

\[
y(t, i) = b_{00} e(t, i) + b_{01} x_{11}(t, i) + b_{02} x_{12}(t, i) + \ldots + b_{n_0, n_0} x_{1, n_0}(t, i) + u(t, i) \quad (11b)
\]

Substituting (11b) into (11a) we obtain:

\[
\begin{align*}
\dot{x}_{11}(t, i) &= b_1 x_{11}(t, i) + b_2 x_{12}(t, i) + \ldots + b_{n_1} x_{1, n_1}(t, i) + u(t, i), \\
\dot{x}_{12}(t, i) &= x_{11}(t, i), \\
&\vdots \\
\dot{x}_{1, n_1}(t, i) &= x_{1, n_1}(t, i), \\
\end{align*}
\]

\[
\begin{align*}
x_{21}(t, i + 1) &= b_{01} e(t, i) + b_{11} x_{11}(t, i) + b_{21} x_{12}(t, i) + \ldots + b_{n_1, n_1} x_{1, n_1}(t, i) + x_{22}(t, i) + A_1 y(t, i), \\
&\vdots \\
x_{2, n_2}(t, i + 1) &= b_{0, n_2} e(t, i) + b_{1, n_2} x_{11}(t, i) + b_{2, n_2} x_{12}(t, i) + \ldots + b_{n_2, n_2} x_{1, n_2}(t, i) + A_y y(t, i),
\end{align*}
\]

where:

\[
b_{k,l} = b_{k,l} + b_{k,l} + A_{k,l} b_{k,l} + b_{k,l} A_{k,l} y(t, i) \quad (12a)
\]

for \(k = 1, 2, \ldots, n_1; l = 1, 2, \ldots, n_2\).

Defining state vectors in the form:

\[
\begin{align*}
\mathbf{x}_1(t, i) &= \begin{bmatrix} x_{11}(t, i) \\
&\vdots \\
&x_{1, n_1}(t, i) \end{bmatrix}, \\
\mathbf{x}_2(t, i) &= \begin{bmatrix} x_{21}(t, i) \\
&\vdots \\
&x_{2, n_2}(t, i) \end{bmatrix}
\end{align*}
\]
we can write the equations (12) in the form:

\[
\begin{bmatrix}
    x_1(t, i) \\
    x_2(t, i + 1)
\end{bmatrix} =
\begin{bmatrix}
    A_{11} & A_{12} \\
    A_{21} & A_{22}
\end{bmatrix}
\begin{bmatrix}
    x_1(t, i) \\
    x_2(t, i)
\end{bmatrix} +
\begin{bmatrix}
    B_1 \\
    B_2
\end{bmatrix} u(t, i),
\]

(14)

where:

\[
A_1 = \begin{bmatrix}
    \beta_1 & \beta_2 & \cdots & \beta_{n_2 - 1} & \beta_{n_2} \\
    1 & 0 & \cdots & 0 & 0 \\
    \vdots & \vdots & \ddots & \vdots & \vdots \\
    0 & 0 & \cdots & 1 & 0
\end{bmatrix},
A_2 = \begin{bmatrix}
    \lambda_1 & 0 & \cdots & 0 \\
    0 & \lambda_2 & \cdots & 0 \\
    \vdots & \vdots & \ddots & \vdots \\
    0 & 0 & \cdots & \lambda_{n_2}
\end{bmatrix},
B_1 = \begin{bmatrix}
    1 \\
    0
\end{bmatrix},
B_2 = \begin{bmatrix}
    b_{10} + \lambda b_{10} \\
    \vdots \\
    b_{n_2} + \lambda b_{n_2}
\end{bmatrix},
C_1 = [b_{10} + \beta b_{10}, \ldots, b_{n_2} + \beta b_{n_2}],
C_2 = [1, 0, \ldots, 0],
D = [b_{10}] = [b_{i0}].
\]

(15)

Therefore, the consequent theorem has been proved.

**Theorem 2.** There exists positive realization of dimension \((n_1 + n_2) \times (n_1 + n_2)\) of transfer function (7) if it has separable denominator with nonnegative coefficients \(A_k, \beta_j\) for \(k = 1, 2, \ldots, n_1; \ l = 1, 2, \ldots, n_2\) and arbitrary nonnegative numerator coefficients \(b_{i,j}\) for \(i = 0, 1, \ldots, n_1; \ j = 0, 1, \ldots, n_2\).

If the assumptions of Theorem 2 are satisfied, then positive realization (3) of (7) can be found by the use of the following procedure:

**Procedure 1.**

Step 1. Using the transfer function (7) write (10).
Step 2. Using (10) draw the state variable diagram shown in Fig.1.
Step 3. Choose as the state variables the outputs of integrators and of delay elements and write equations (12).
Step 4. Using (12) find the desired realization (15).

**Example 1.** Find positive realization (3) of the continuous-discrete system with proper transfer function:

\[
T(s^{-1}, z^{-1}) = \frac{0.6 + 0.5s^{-1} + 0.4s^{-2} + 0.3s^{-3} + 0.2s^{-4} + 0.1s^{-5}}{1 - 4s^{-1} - 2s^{-2} + 8s^{-3} - 3s^{-4} - 12s^{-5}}
\]

(16a)

In this case \(n_1 = 2, \ n_2 = 1\) and transfer function has separable denominator, since:

\[
d(s^{-1}, z^{-1}) = 1 - 4s^{-1} - 2s^{-2} + 8s^{-3} - 3s^{-4} - 12s^{-5}
\]

(16b)

Using Procedure 1 we obtain the following:

Step 1. Using transfer function (16a) we can write:

\[
E = U + (2s^{-1} + 3s^{-2})e;
Y = (0.6 + 0.5s^{-1} + 0.4s^{-2} + 0.3s^{-3} + 0.2s^{-4} + 0.1s^{-5})E + (4s^{-1})y.
\]

(17)

Step 2. State variable diagram has the form shown in fig.2.

**Fig. 2.** State space diagram for transfer function (16) for: \(A_1 = 4\), \(B_1 = 2\), \(\beta_2 = 3\), \(b_{00} = 0.6\), \(b_{01} = 0.5\), \(b_{10} = 0.4\), \(b_{11} = 0.3\), \(b_{20} = 0.2\), \(b_{21} = 0.1\).

Rys. 2. Schemat zmienności stanu dla transmitancji (16), przy czym: \(A_1 = 4\), \(B_1 = 2\), \(\beta_2 = 3\), \(b_{00} = 0.6\), \(b_{01} = 0.5\), \(b_{10} = 0.4\), \(b_{11} = 0.3\), \(b_{20} = 0.2\), \(b_{21} = 0.1\).

Step 3. Using state variable diagram we can write the following equations:

\[
\begin{align*}
\dot{x}_{11}(t, i) &= \epsilon(t, i), \\
\dot{x}_{12}(t, i) &= x_{11}(t, i), \\
x_{21}(t, i + 1) &= 0.5(t, i) + 0.3\epsilon_{11}(t, i) \\
&\quad + 0.1x_{12}(t, i) + 4\epsilon(t, i)
\end{align*}
\]

(18a)

and

\[
\begin{align*}
y(t, i) &= 0.6(t, i) + 0.4\epsilon_{11}(t, i) \\
&\quad + 0.2x_{12}(t, i) + x_{21}(t, i), \\
\epsilon(t, i) &= 2x_{11}(t, i) + 3x_{12}(t, i) + u(t, i).
\end{align*}
\]

(18b)

Substituting (18b) into (18a) we have:

\[
\begin{align*}
\dot{x}_{11}(t, i) &= 2x_{11}(t, i) + 3x_{12}(t, i) + u(t, i), \\
\dot{x}_{12}(t, i) &= x_{11}(t, i), \\
x_{21}(t, i + 1) &= 7.7x_{11}(t, i) + 9.6x_{12}(t, i) + 4x_{21}(t, i) + 2.9u(t, i), \\
y(t, i) &= 1.6x_{11}(t, i) + 2x_{12}(t, i) + x_{21}(t, i) + 0.6u(t, i)
\end{align*}
\]

(19)

Step 4. The desired realization of (16) has the form:

\[
A_{11} = \begin{bmatrix} 2 & 3 \\ 1 & 0 \end{bmatrix}, \quad A_{12} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \quad A_{21} = \begin{bmatrix} 7.7 & 9.6 \end{bmatrix}, \quad A_{22} = [4],
B_1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad B_2 = [2.9], \quad C_1 = [1.6, 2], \quad C_2 = [1], \quad D = [0.6].
\]

(20)
Obtained realization has only nonnegative entries and its dimension is minimal.

2.2. Case 2

Defining:

$$E(s^{-1}, z^{-1}) = \frac{(\lambda_0 + \lambda_2 z^{-1} + \lambda_2 z^{-2} + \ldots + \lambda_{n_2} z^{-n_2})U(s^{-1}, z^{-1})}{1 - a_{01} z^{-1} - a_{10} s^{-1} - \ldots - a_{n_1 n_2} s^{-n_1} z^{-n_2}}$$  \hspace{1cm} (21)

from (8) and (21) we obtain:

$$E(s^{-1}, z^{-1}) = (\lambda_0 + \lambda_2 z^{-1} + \lambda_2 z^{-2} + \ldots + \lambda_{n_2} z^{-n_2})U(s^{-1}, z^{-1})$$

$$Y(s^{-1}, z^{-1}) = (\beta_0 + \beta_2 z^{-1} + \beta_2 z^{-2} + \ldots + \beta_{n_1} z^{-n_1})E(s^{-1}, z^{-1}).$$  \hspace{1cm} (22)

Using (22) we may draw the state variable diagram shown in Fig. 3.

Fig. 3. State space diagram for transfer function (8) with separable numerators

Defining state vectors in the form (13) we can write the following equations (24) in the matrix form (14) where:

$$c(t, i) = a_{10} x_{11}(t, i) + a_{20} x_{12}(t, i) + \ldots + a_{n_1, 0} x_{1, n_1}(t, i) + x_{2,1}(t, i) + \lambda_0 u(t, i).$$  \hspace{1cm} (23a)

Substituting (23b) into (23a) we obtain:

$$x_{11}(t, i) = a_{10} x_{11}(t, i) + a_{20} x_{12}(t, i) + \ldots + a_{n_1, 0} x_{1, n_1}(t, i) + x_{2,1}(t, i) + \lambda_0 u(t, i).$$  \hspace{1cm} (23b)

Similarly as in section 2.1 as state variables we choose the outputs of integrators ($x_{11}(t, i)$, ..., $x_{1, n_1}(t, i)$) and of delay elements ($x_{2,1}(t, i)$, ..., $x_{2, n_2}(t, i)$). Using state variable diagram (fig. 3) we can write the following differential and difference equations:

$$\dot{x}_{11}(t, i) = c(t, i),$$

$$\dot{x}_{12}(t, i) = x_{11}(t, i),$$

$$\vdots$$

$$\dot{x}_{1, n_1}(t, i) = x_{1, n_1-1}(t, i),$$

$$x_{21}(t, i + 1) = a_{10} c(t, i) + a_{11} x_{11}(t, i) + a_{21} x_{1, 2}(t, i)$$

$$+ \ldots + a_{n_1, 1} x_{1, n_1}(t, i) + x_{2,1}(t, i) + \lambda_0 u(t, i)$$

$$\vdots$$

$$x_{2, n_2-1}(t, i + 1) = a_{0, n_2-1} c(t, i) + a_{1, n_2-1} x_{1, n_2-1}(t, i) + a_{2, n_2-1} x_{2, n_2-1}(t, i)$$

$$+ \ldots + a_{n_2, n_2-1} x_{1, n_2}(t, i) + x_{2, n_2}(t, i) + \lambda_{n_2-1} u(t, i),$$

$$x_{2, n_2}(t, i + 1) = a_{0, n_2} c(t, i) + a_{1, n_2} x_{1, n_2}(t, i) + a_{2, n_2} x_{2, n_2}(t, i)$$

$$+ \ldots + a_{n_1, n_2} x_{1, n_1}(t, i) + x_{2, n_2}(t, i) + \lambda_{n_2} u(t, i),$$

$$y(t, i) = \beta_0 c(t, i) + \beta_1 x_{11}(t, i) + \beta_2 x_{1, 2}(t, i) + \ldots + \beta_{n_1} x_{1, n_1}(t, i)$$

where:

$$c(t, i) = a_{10} x_{11}(t, i) + a_{20} x_{12}(t, i) + \ldots + a_{n_1, 0} x_{1, n_1}(t, i) + x_{2,1}(t, i) + \lambda_0 u(t, i).$$  \hspace{1cm} (23b)

Defining state vectors in the form (13) we can write the equations (24) in the matrix form (14) where:

$$A_{11} = \begin{bmatrix} a_{10} & a_{20} & \ldots & a_{n_1, 1, 0} & a_{n_1, 0} \\ 1 & 0 & \ldots & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & \ldots & 1 & 0 \end{bmatrix} \in \mathbb{R}^{n_1 \times n_1},$$

$$A_{12} = \begin{bmatrix} 1 & 0 & \ldots & 0 \\ 0 & 0 & \ldots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & 0 \end{bmatrix} \in \mathbb{R}^{n_1 \times n_2},$$

$$A_{21} = \begin{bmatrix} a_{11} + a_{10} a_{01} & \ldots & a_{n_1, 1, 1} + a_{n_1, 0} a_{01} \\ a_{11, 0} + a_{10} a_{01} & \ldots & a_{n_1, n_2, 1} + a_{n_1, 0} a_{01, n_2} \\ \vdots & \vdots & \ddots & \vdots \\ a_{0, n_2} + a_{0, n_2, 1} & \ldots & a_{0, n_2, n_2} \end{bmatrix} \in \mathbb{R}^{n_2 \times n_1},$$

$$B_1 = \begin{bmatrix} \lambda_0 \\ 0 \\ \vdots \end{bmatrix} \in \mathbb{R}^{n_1 \times 1}, \quad B_2 = \begin{bmatrix} \lambda_1 + a_{10} \lambda_0 \\ \lambda_2 + a_{10} \lambda_1 \\ \vdots \end{bmatrix} \in \mathbb{R}^{n_1 \times 1},$$

$$C_1 = \begin{bmatrix} \beta_1 + a_{10} \beta_0 & \ldots & \beta_{n_1} + a_{10} \beta_{n_1} \end{bmatrix} \in \mathbb{R}^{1 \times n_1},$$

$$C_2 = \begin{bmatrix} \beta_0 & 0 & \ldots & 0 \end{bmatrix} \in \mathbb{R}^{1 \times n_2},$$

$$D = \begin{bmatrix} \lambda_0, \lambda_1, \ldots, \lambda_{n_2} \end{bmatrix} \in \mathbb{R}^{1 \times 1}.$
Therefore, the consequent theorem has been proved.

**Theorem 3.** There exists a positive realization of dimension \((n_1 + n_2) \times (n_1 + n_2)\) of transfer function (8) if it has separable numerator with nonnegative coefficients \(A_i\), \(B_j\) for \(i = 0,1,...,n_1\), \(j = 0,1,...,n_2\) and arbitrary nonnegative denominator coefficients \(a_{k,l}\) for \(k = 0,1,...,n_1\), \(l = 0,1,...,n_2\) and \(k + l \neq 0\).

If the assumptions of Theorem 3 are satisfied, then positive realization (3) of (8) can be found by the use of the following procedure:

**Procedure 2.**

Step 1. Using the transfer function (8) write (22).

Step 2. Using (22) draw the state variable diagram shown in fig. 3.

Step 3. Choose as the state variables the outputs of integrators and of delay elements and write equations (24).

Step 4. Using (24) find the desired realization (25).

**Example 2.** Find positive realization (3) of the continuous-discrete system with proper transfer function:

\[
T(s^{-1},z^{-1}) = \frac{3 + 4z^{-1} + 6s^{-1} + 8s^{-1}z^{-1} + 5z^{-2} + 10s^{-1}z^{-2}}{1 - 0.5s^{-1} - 0.4s^{-2} - 0.3s^{-1}z^{-1} - 0.2s^{-2} - 0.1s^{-1}z^{-2}} \tag{26a}
\]

In this case \(n_1 = 1\), \(n_2 = 2\) and transfer function has separable numerator, since:

\[
n(s^{-1},z^{-1}) = 3 + 4z^{-1} + 6s^{-1} + 8s^{-1}z^{-1} + 5z^{-2} + 10s^{-1}z^{-2} = (1 + 2s^{-1})(3 + 4z^{-1} + 5z^{-2}) \tag{26b}
\]

Using Procedure 2 we obtain the following:

Step 1. Using the transfer function (26) we can write:

\[
E = (3 + 4z^{-1} + 5z^{-2})U + (0.5s^{-1} + 0.4z^{-1} + 0.3s^{-1}z^{-1} + 0.2s^{-2} + 0.1s^{-1}z^{-1})E, \tag{27}
\]

\[
Y = (1 + 2s^{-1})E. \tag{28}
\]

Step 2. State variable diagram has the form shown in fig. 4.

**Fig. 4.** State space diagram for transfer function (26) for \(\lambda_0 = 0.1\), \(\lambda_1 = 4\), \(\lambda_2 = 5\), \(\beta_0 = 1\), \(\beta_1 = 2\), \(a_{00} = 0.5\), \(a_{10} = 0.4\), \(a_{11} = 0.3\), \(a_{02} = 0.2\), \(a_{12} = 0.1\).

Rys. 4. Schemat zmiennych stanu dla transmitancji (26), przy czym: \(\lambda_0 = 0.3\), \(\lambda_1 = 4\), \(\lambda_2 = 5\), \(\beta_0 = 1\), \(\beta_1 = 2\), \(a_{00} = 0.5\), \(a_{10} = 0.4\), \(a_{11} = 0.3\), \(a_{02} = 0.2\), \(a_{12} = 0.1\).

Step 3. Using state variable diagram we can write the following equations:

\[
\dot{x}_{11}(t,i) = e(t,i),
\]

\[
x_{21}(t,i + 1) = 0.5x_{11}(t,i) + 0.3x_{21}(t,i) + x_{22}(t,i) + 4u(t,i), \tag{28a}
\]

\[
x_{21}(t,i + 1) = 0.2e(t,i) + 0.1x_{11}(t,i) + 4u(t,i)
\]

and

\[
y(t,i) = e(t,i) + 2x_{11}(t,i),
\]

\[
e(t,i) = 0.4x_{11}(t,i) + x_{21}(t,i) + 3u(t,i). \tag{28b}
\]

Substituting (28b) into (28a) we have:

\[
\dot{x}_{11}(t,i) = 0.4x_{11}(t,i) + x_{21}(t,i) + 3u(t,i),
\]

\[
x_{21}(t,i + 1) = 0.5x_{11}(t,i) + 0.5x_{21}(t,i) + x_{22}(t,i) + 5.5u(t,i),
\]

\[
x_{22}(t,i + 1) = 0.18x_{11}(t,i) + 0.2x_{21}(t,i) + 5.6u(t,i),
\]

\[
y(t,i) = 2.4x_{11}(t,i) + x_{21}(t,i) + 3u(t,i).
\]

Step 4. The desired realization of (26) has the form:

\[
A_{11} = [0.4], \quad A_{12} = [1\ 0], \quad A_{21} = \begin{bmatrix} 0.5 \\ 0.18 \end{bmatrix}, \quad A_{22} = \begin{bmatrix} 0.5 & 1 \\ 0.2 & 0 \end{bmatrix}, \quad B_1 = [3], \quad B_2 = \begin{bmatrix} 5.5 \\ 5.6 \end{bmatrix}, \quad C_1 = [2.4], \quad C_2 = [1\ 0], \quad D = [3]. \quad \tag{30}
\]

Obtained realization has only nonnegative entries and its dimension is minimal.

Presented approach can be used for transfer matrices (5a) of multi-input and multi-output systems. In MIMO case the transfer matrix (5a) should have the form:

\[
T(s,z) = D^{-1}(s,z)N(s,z) \quad \text{or} \quad T(s,z) = N(s,z)D^{-1}(s,z) \tag{31}
\]

where \(D(s,z)\) is diagonal matrix of common denominators for each row (column) of transfer matrix \(T(s,z)[4]\).

**3. Concluding remarks**

A method for computation of positive minimal realizations of given proper transfer functions with separable numerator and with separable denominator of continuous-discrete linear systems has been proposed. Sufficient conditions for the existence of positive minimal realizations of given proper transfer function have been established. Two procedures for computation of positive minimal realizations have been proposed. The effectiveness of the procedures have been illustrated by numerical examples. Extension of these considerations for 2D continuous-discrete linear systems described by second Fornasini-Marchesini model [15] is possible.

An open problem is formulation of the necessary and sufficient conditions for the existence of solution of the positive minimal realization problem for 2D continuous-discrete linear systems in the general form [21].
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References


Wyznaczanie dodatkowych realizacji minimalnych układów ciągło-dyskretnych o transmisyjności z separowanym licznikiem lub mianownikiem


Słowa kluczowe: ciągło-dyskretne, dodatni, minimalna, realizacja, wyznaczanie

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