

# SOLUTION OF TIME-VARYING SINGULAR NONLINEAR SYSTEMS BY SINGLE-TERM WALSH SERIES

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A method for finding the solution of time-varying singular nonlinear systems by using single-term Walsh series is proposed. The properties of single-term Walsh series are given and are utilized to find the solution of time-varying singular nonlinear systems.

## 1. Introduction

Singular nonlinear systems has been of interest to some investigators [4, 12], however no closed-form solution was given in [4, 12]. In some analysis of neural networks, both singular systems [8] and bilinear systems [16] have been used. For singular bilinear systems, Lewis et al. [11] applied the Walsh function (WF) approach for time-invariant singular bilinear systems and Hsiao and Wang [9] used the Haar wavelets for the solution of time-varying singular nonlinear systems.

Walsh functions (WFs) have received considerable attention in dealing with various problems of dynamic systems. Chen and Hsiao [5, 6, 7] applied the WF technique to the analysis, optimal control, and synthesis of linear systems. WFs have also found wide applications in signal processing, communication, and pattern recognition [13]. Rao et al. [14] presented a method of extending computation beyond the limit of the initial normal interval in Walsh series analysis of dynamical systems. In [14] various time functions in the system were first expanded in terms of their truncated WF with unknown coefficients. Using the Kronecker product [10], the unknown coefficient of the rate variable was obtained by finding the inverse of a square matrix. It was shown that this method involve some numerical difficulties if the dimension of this matrix is large. To remove the inconveniences in WF technique, the single-term Walsh series (STWS) was introduced in [14], and Balachandran and Murugesan [1, 2, 3] applied STWS technique to the analysis of the linear and nonlinear singular systems. The STWS method provides block-pulse and discrete solutions to any length of time.

In the present paper, we use the STWS approach for the solution of time-varying singular nonlinear systems. As compared to [9], our method is simpler and consumes less computer time.

The paper is organized as follows: in [Section 2](#) we describe the basic properties of the WF and STWS required for our subsequent development. [Section 3](#) is devoted to the formulation of the time-varying singular nonlinear systems. In [Section 4](#) we apply the proposed numerical method to the time-varying singular nonlinear systems and in [Section 5](#), we report our numerical finding and demonstrate the accuracy of the proposed method.

## 2. Properties of WF and STWS

**2.1. Walsh functions.** A function  $f(t)$ , integrable in  $[0, 1)$ , may be approximated using WF as

$$f(t) = \sum_{i=0}^{\infty} f_i \phi_i(t), \quad (2.1)$$

where  $\phi_i(t)$  is the  $i$ th WF and  $f_i$  is the corresponding coefficient. In practice, only the first  $m$  terms are considered, where  $m$  is an integral power of 2. Then from (2.1), we get

$$f(t) = \sum_{i=0}^{m-1} f_i \phi_i(t) = F^T \Phi(t), \quad (2.2)$$

where

$$F = (f_0, f_1, \dots, f_{m-1})^T, \quad \Phi(t) = (\phi_0(t), \phi_1(t), \dots, \phi_{m-1}(t))^T. \quad (2.3)$$

The coefficients  $f_i$  are chosen to minimize the mean integral square error

$$\epsilon = \int_0^1 (f(t) - F^T \Phi(t))^2 dt, \quad (2.4)$$

and are given by

$$f_i = \int_0^1 f(t) \phi_i(t) dt. \quad (2.5)$$

The integration of the vector  $\Phi(t)$  defined in (2.3) can be approximated by

$$\int_0^t \Phi(t') dt' \simeq E \Phi(t), \quad (2.6)$$

where  $E$  is the  $m \times m$  operational matrix for integration with  $E_{1 \times 1} = 1/2$  and is given in [16].

**2.2. Single-term Walsh series.** With the STWS approach, in the first interval, the given function is expanded as STWS in the normalized interval  $\tau \in [0, 1)$ , which corresponds to  $t \in [0, 1/m)$  by defining  $\tau = mt$ ,  $m$  being any integer. In STWS, the matrix  $E$  in (2.6) becomes  $E = 1/2$ .

Let  $\dot{x}(\tau)$  and  $x(\tau)$  be expanded by STWS series in the first interval as

$$\dot{x}(\tau) = V^{(1)}\phi_0(\tau), \quad x(\tau) = X^{(1)}\phi_0(\tau), \quad (2.7)$$

and in the  $k$ th interval as

$$\dot{x}(\tau) = V^{(k)}\phi_0(\tau), \quad x(\tau) = X^{(k)}\phi_0(\tau). \quad (2.8)$$

Integrating (2.7) with  $E = 1/2$ , we get

$$X^{(1)} = \frac{1}{2}V^{(1)} + x(0), \quad (2.9)$$

where  $x(0)$  is the initial condition. According to Sannuti [15], we have

$$V^{(1)} = \int_0^1 \dot{x}(\tau)d\tau = x(1) - x(0). \quad (2.10)$$

In general, for any interval  $k$ ,  $k = 1, 2, \dots$ , we obtain

$$X^{(k)} = \frac{1}{2}V^{(k)} + x(k-1), \quad (2.11)$$

$$x(k) = V^{(k)} + x(k-1). \quad (2.12)$$

In (2.11) and (2.12),  $X^{(k)}$  and  $x(k)$  give the block-pulse and the discrete values of the state, respectively.

### 3. Problem statement

Consider a time-varying singular nonlinear system of the following form:

$$E(t)\dot{x}(t) = f(t, x(t), u(t)), \quad x(0) = x_0, \quad (3.1)$$

where the singular matrix  $E(t) \in \mathbb{R}^{n \times n}$ , the nonlinear function  $f \in \mathbb{R}^n$ , the state  $x(t) \in \mathbb{R}^n$ , and the control  $u(t) \in \mathbb{R}^q$ . The response  $x(t)$  is required to be found.

### 4. Solution of time-varying singular nonlinear systems via STWS

Normalizing (3.1) by defining  $\tau = mt$ , we get

$$mE(\tau)\dot{x}(\tau) = f(\tau, x(\tau), u(\tau)), \quad x(0) = x_0. \quad (4.1)$$

Let  $E(\tau)$  be expressed by STWS in the  $k$ th interval as

$$E(\tau) = E^{(k)}\phi_0(\tau), \quad (4.2)$$

where  $E^{(k)} \in \mathbb{R}^{n \times n}$ . By using (2.8) and (2.11), we get

$$x(\tau) = \left(\frac{1}{2}V^{(k)} + x(k-1)\right)\phi_0(\tau). \quad (4.3)$$

To solve (4.1), we first substitute (4.3) in  $f(\tau, x(\tau), u(\tau))$ ; we then express the resulting equation by STWS as

$$f\left(\tau, \left(\frac{1}{2}V^{(k)} + x(k-1)\right)\phi_0(\tau), u(\tau)\right) = F^{(k)}\phi_0(\tau). \quad (4.4)$$

Using (4.1), (4.2), (4.3), and (4.4), we get

$$mE^{(k)}V^{(k)} = F^{(k)}. \quad (4.5)$$

By solving (4.5), the components of  $V^{(k)}$  can be obtained. By substituting  $V^{(k)}$  in (2.11) and (2.12), we obtain block-pulse and discrete approximations of the state, respectively. Further, using (2.7), we get

$$x(\tau) = \int_0^\tau \dot{x}(\tau')d\tau' + x(0) = V^{(1)}\tau + x(0). \quad (4.6)$$

Thus, we can obtain a continuous approximation of the state as

$$x(\tau) = V^{(k)}\tau + x(k-1). \quad (4.7)$$

## 5. Numerical examples

Three examples are given in this section. These examples were considered by Hsiao and Wang [9] by using Haar wavelets. Our method differs from their approach and thus these examples could be used as a basis for comparison.

*Example 5.1.* Consider a time-varying nonlinear singular system of the following form [9]:

$$\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & t^2 \\ 0 & 0 & 0 \end{bmatrix} \dot{x}(t) = \begin{bmatrix} tx_1(t) + x_2(t) \\ \exp(t)x_1(t)x_2(t) \\ x_2(t)(x_1(t) + x_3(t)) \end{bmatrix} + \begin{bmatrix} 0 \\ 2t^2 \exp(-t) \\ 0 \end{bmatrix}, \quad x(0) = \begin{bmatrix} 2 \\ 0 \\ -2 \end{bmatrix}. \quad (5.1)$$

The exact solution is (see [9])

$$x(t) = \begin{bmatrix} 2\exp(-t)(1-2t) \\ t^2 \exp(-t) \\ -2\exp(-t)(1-2t) \end{bmatrix}. \quad (5.2)$$

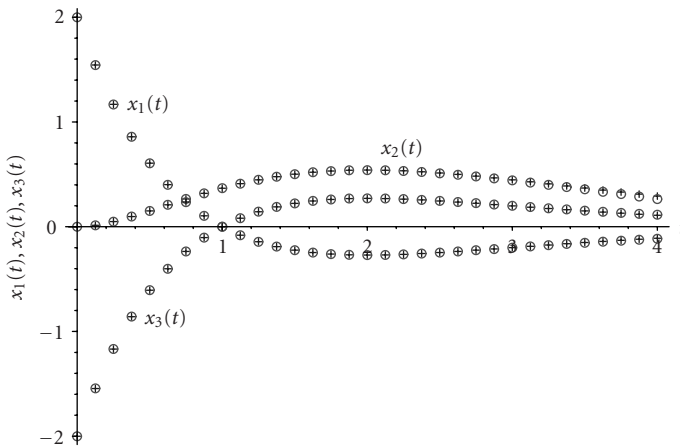


Figure 5.1. STWS with  $m = 32$  (circles) and exact solution: ++++ of Example 5.1.

To solve (5.1) by STWS, we first express  $t$ ,  $t^2$ ,  $\exp(t)$ , and  $2t^2 \exp(-t)$  by STWS, then we substitute these values together with  $V_i^{(k)} = \hat{x}_i(t)$  and  $x_i(t) = (1/2)V_i^{(k)} + x_i(k - 1)$ ,  $i = 1, 2, 3$ , in (5.1). By solving the resulting equation,  $V^{(k)} = [V_1^{(k)}, V_2^{(k)}, V_3^{(k)}]^T$  can be calculated. By using (2.11), (2.12), and (4.7), block-pulse, discrete, and continuous approximations of state  $x(t)$  are obtained.

The comparison between STWS solution with  $m = 32$  and the exact solution for  $t \in [0, 4)$  is shown in Figure 5.1.

Example 5.2. Consider the following time-invariant singular nonlinear system [9]:

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \dot{x}(t) + \begin{bmatrix} x_3(t) - x_5(t) \\ x_2(t) + x_3(t) - x_4(t) - x_5(t) \\ (x_1(t) + x_2(t) - 1)^2 - x_3(t) \\ -x_4(t) \\ x_2(t)(x_1(t) + x_2(t)) - x_5(t) \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad x(0) = \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}. \quad (5.3)$$

The results obtained by STWS with  $m = 16$  and  $m = 110$  together with those obtained by Haar wavelets with  $m = 512$  are presented in Tables 5.1, 5.2, and 5.3, respectively.

Example 5.3. Consider a time-invariant nonlinear singular system of the following form [9]:

$$\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \dot{x}(t) + \begin{bmatrix} 0 & 0 & 1 \\ 1 & 1 & 0 \\ 1 & 0 & -3 \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0 \\ x_3^3(t) \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}, \quad x(0) = \begin{bmatrix} 2 \\ -1 \\ -2 \end{bmatrix}. \quad (5.4)$$

The results obtained by STWS with  $m = 24$  and  $m = 32$  and those obtained by Haar wavelets with  $m = 32$  and  $m = 128$  are presented in Tables 5.4 and 5.5, respectively.

Table 5.1. Estimated values of  $x_1(t)$ ,  $x_2(t)$ ,  $x_3(t)$ ,  $x_4(t)$ , and  $x_5(t)$  by STWS with  $m = 16$ .

Time	$x_1(t)$	$x_2(t)$	$x_3(t)$	$x_4(t)$	$x_5(t)$
0.0	0.0000	0.0000	1.0000	0.0000	0.0000
0.5	-0.3297	0.5771	0.5671	0.0000	0.1443
1.0	-0.4776	0.8003	0.4596	0.0000	0.2599
1.5	-0.5486	0.9023	0.4186	0.0000	0.3209
2.0	-0.5835	0.9514	0.4004	0.0000	0.3516
2.5	-0.6008	0.9755	0.3919	0.0000	0.3674
3.0	-0.6094	0.9875	0.3877	0.0000	0.3752
3.5	-0.6137	0.9935	0.3856	0.0000	0.3791
4.0	-0.6159	0.9965	0.3846	0.0000	0.3811

Table 5.2. Estimated values of  $x_1(t)$ ,  $x_2(t)$ ,  $x_3(t)$ ,  $x_4(t)$ , and  $x_5(t)$  by STWS with  $m = 110$ .

Time	$x_1(t)$	$x_2(t)$	$x_3(t)$	$x_4(t)$	$x_5(t)$
0.0	0.0000	0.0000	1.0000	0.0000	0.0000
0.5	-0.3295	0.5774	0.5658	0.0000	0.1431
1.0	-0.4775	0.8006	0.4582	0.0000	0.2587
1.5	-0.5485	0.9027	0.4171	0.0000	0.3197
2.0	-0.5834	0.9518	0.3989	0.0000	0.3507
2.5	-0.6007	0.9760	0.3903	0.0000	0.3663
3.0	-0.6094	0.9880	0.3861	0.0000	0.3741
3.5	-0.6137	0.9940	0.3841	0.0000	0.3780
4.0	-0.6159	0.9970	0.3830	0.0000	0.3800

Table 5.3. Estimated values of  $x_1(t)$ ,  $x_2(t)$ ,  $x_3(t)$ ,  $x_4(t)$ , and  $x_5(t)$  by Haar wavelets with  $m = 512$ .

Time	$x_1(t)$	$x_2(t)$	$x_3(t)$	$x_4(t)$	$x_5(t)$
0.0	0.0000	0.0000	1.0000	0.0000	0.0000
0.5	-0.3295	0.5774	0.5658	0.0000	0.1431
1.0	-0.4775	0.8006	0.4582	0.0000	0.2587
1.5	-0.5485	0.9027	0.4171	0.0000	0.3197
2.0	-0.5834	0.9518	0.3989	0.0000	0.3507
2.5	-0.6007	0.9760	0.3903	0.0000	0.3663
3.0	-0.6094	0.9880	0.3861	0.0000	0.3741
3.5	-0.6137	0.9940	0.3841	0.0000	0.3780
4.0	-0.6159	0.9970	0.3830	0.0000	0.3800

Table 5.4. Estimated values of  $x_1(t)$ ,  $x_2(t)$ , and  $x_3(t)$  by STWS with  $m = 24$  and  $m = 32$ .

Time	STWS with $m = 24$			STWS with $m = 32$		
	$x_1(t)$	$x_2(t)$	$x_3(t)$	$x_1(t)$	$x_2(t)$	$x_3(t)$
0.0	2.00000	-1.00000	-2.00000	2.00000	-1.00000	-2.00000
0.125	1.75175	-0.75175	-1.97189	1.75175	-0.75175	-1.97189
0.25	1.50706	-0.50706	-1.94309	1.50706	-0.50706	-1.94309
0.375	1.26601	-0.26601	-1.91353	1.26601	-0.26601	-1.91353
0.5	1.02871	-0.02871	-1.88316	1.02871	-0.02871	-1.88316
0.625	0.79526	0.20474	-1.85187	0.79526	0.20474	-1.85187
0.75	0.56578	0.43422	-1.81960	0.56578	0.43422	-1.81960
0.875	0.34040	0.65960	-1.78622	0.34040	0.65960	-1.78622
1.0	0.11927	0.88073	-1.75160	0.11927	0.88073	-1.75160

Table 5.5. Estimated values of  $x_1(t)$ ,  $x_2(t)$ , and  $x_3(t)$  by Haar wavelets with  $m = 32$  and  $m = 128$ .

Time	Haar wavelets with $m = 32$			Haar wavelets with $m = 128$		
	$x_1(t)$	$x_2(t)$	$x_3(t)$	$x_1(t)$	$x_2(t)$	$x_3(t)$
0.0	2.0000	-1.0000	-2.0000	2.0000	-1.0000	-2.0000
0.125	1.7517	-0.7517	-1.9719	1.7517	-0.7517	-1.9719
0.25	1.5071	-0.5071	-1.9431	1.5071	-0.5071	-1.9431
0.375	1.2660	-0.2660	-1.9135	1.2660	-0.2660	-1.9135
0.5	1.0287	-0.0287	-1.8832	1.0287	-0.0287	-1.8832
0.625	0.7953	0.2047	-1.8519	0.7953	0.2047	-1.8519
0.75	0.5658	0.4342	-1.8196	0.5658	0.4342	-1.8196
0.875	0.3404	0.6596	-1.7862	0.34040	0.6596	-1.7862
1.0	0.1193	0.8807	-1.7516	0.1193	0.8807	-1.7516

### 6. Conclusion

The properties of STWS are used to solve the time-varying singular nonlinear systems. The key idea is to transform the time-varying functions into STWS. The method can be implemented using a digital computer. It occupies less memory space and consumes less computer time than the method in [9]. Illustrative examples were included to demonstrate the validity and applicability of the technique.

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