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Identification of Saturation-type Nonlinear Feedback Control Systems

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Abstract

The authors have recently proposed a new method for identifying Volterra kernels of nonlinear control systems by use of M-sequence and correlation technique. A specially chosen M-sequence is added to the nonlinear system to be identified, and the crosscorrelation function between the input and output is calculated. Then every crosssection of Volterra kernels up to 3rd order appears at a specified delay time point in the crosscorrelation. This method is applied to a saturation-type nonlinear feedback control system of mechanical-electrical servo system having torque saturation nonlinearity. Simulation experiments show that we can obtain Volterra kernels of saturation-type nonlinear system, and a good agreement is observed between the observed output and the calculated one from the measured Volterra kernels.

Keywords Nonlinear systems, Identification, Saturation-type, M-sequence, Volterra kernel

1. INTRODUCTION

When we control or design a dynamical control system, we must know its dynamical characteristics. Therefore the study for identifying linear and nonlinear control system have been carried out by many researchers for a long time. However, up to now, only a few methods of identification of nonlinear systems have been proposed since the nonlinear systems are too complex to be identified.

The authors have recently proposed a new method for identifying a nonlinear system by use of correlation technique[2)~6)]. In this method, we can obtain not only the linear impulse response, but also Volterra kernels of the nonlinear system simultaneously.

In this paper, this method of nonlinear system identification is applied to a saturation type mechatronic servo nonlinear system.

2. PRINCIPLE OF THE METHOD

A nonlinear dynamical system is, in general, described as follows.

$$y(t) = \sum_{i=1}^{\infty} \int_0^{\infty} \int_0^{\infty} \cdots \int_0^{\infty} g_i(\tau_1, \tau_2, \cdots \tau_i) \times u(t-\tau_1)u(t-\tau_2)\cdots u(t-\tau_i) d\tau_1 d\tau_2 \cdots d\tau_i \quad (1)$$

where $u(t)$ is the input, and $y(t)$ is the output of the nonlinear system, and $g_i(\tau_1, \tau_2, ...)$ is called Volterra kernel of i-th order.

When we take the crosscorrelation function between the input $u(t)$ and the output $y(t)$, we have,

$$\phi_{uy}(\tau) = \overline{u(t-\tau)y(t)} = \sum_{i=1}^{\infty} \int_0^{\infty} \int_0^{\infty} \cdots \int_0^{\infty} g_i(\tau_1, \tau_2, \cdots \tau_i) \times \overline{u(t-\tau)u(t-\tau_1)\cdots u(t-\tau_i)} d\tau_1 d\tau_2 \cdots d\tau_i \quad (2)$$

where $\phi_{uy}(\tau)$ is the crosscorrelation function of $u(t)$ and $y(t)$ and $\overline{\qquad\qquad}$ denotes time average.

The difficulty of obtaining $g_i(\tau_1, \tau_2, \cdots \tau_i)$ from $\phi_{uy}(\tau)$ is , in general, due to the difficulty of getting $(i+1)$th moment of the input $u(t)$, because the n-th moment of the input signal $u(t)$ is usually very difficult to obtain for actual signals.

The authors have shown[3)] that when we use an M-sequence as an input to the system, the n-th moment of $u(t)$ can be easily obtained by use of so-called "shift and add property" of the M-sequence. So we can obtain the Volterra kernels $g_i(\tau_1, \tau_2, \cdots \tau_i)$ from simply measuring the crosscorrelation function between the input and output of the nonlinear system.

The $(i+1)$th moment of the input M-sequence $u(t)$ can be written as

$$\overline{u(t-\tau)u(t-\tau_1)u(t-\tau_2)\cdots u(t-\tau_i)}$$

$$= \begin{cases} 1 & \text{(for certain } \tau) \\ -1/N & \text{(otherwise)} \end{cases} \quad (3)$$

where N is the period of the M-sequence. When we use the M-sequence with the degree greater than 10, $1/N$ is smaller than 10^{-3}. So Eq.(3) can be approximated as a set of impulses which appear at certain τ's.

Eq.(3) is due to the so-called shift and add property of the M-sequence; that is, for any integer $k_{i1}, k_{i2}, \cdots k_{i,i-1}$ (suppose $k_{i1} < k_{i2} < \cdots, k_{ii}$), there exists a unique k_{ii} (mod N) such that

$$u(t)u(t+k_{i1})u(t+k_{i2})\cdots u(t+k_{i,i-1}) = u(t+k_{ii}) \quad (4)$$

Note that when $k_{ij}(j = 1, 2, ...i)$ satisfy Eq.(4), then $2^p k_{ij}$ also satisfy Eq.(4) for any integer p. Therefore Eq.(3) becomes unity when

$$\tau_1 = \tau - k_{i1}, \tau_2 = \tau - k_{i2}, \cdots \tau_i = \tau - k_{ii} \quad (5)$$

Therefore Eq.(2) becomes

$$\phi_{uy}(\tau) = \sum_{i=1}^{\infty} g_i(\tau - k_{i1}, \tau - k_{i2}, \cdots \tau - k_{ii}) \quad (6)$$

Since $g_i(\tau_1, \tau_2, \cdots \tau_i)$ is zero when any of τ_i is smaller than zero, each $g_i(\tau - k_{i1}, \tau - k_{i2}, \cdots \tau - k_{ii})$ in Eq.(6) appear in the crosscorrelation function $\phi_{uy}(\tau)$ when $\tau > k_{ii}$. If the k_{ii}'s of i-th Volterra kernel g_i are sufficiently apart from each other(say, more than $50\Delta t$, where Δt is the time increment of the measurement time), we can obtain each Volterra kernel $g_i(\tau - k_{i1}, \tau - k_{i2}, \cdots, \tau - k_{ii})$ from Eq.(6). Volterra kernels $g_i(\tau_1, \tau_2, \cdots \tau_i)$ are obtained as a set of crosssections along 45 degree lines in $(\tau_1, \tau_2, \cdots, \tau_i)$ space. In order for this to be realized, we have selected some suitable M-sequences. (About the selection of M-sequence suitable for obtaining Volterra kernels, see Table 1 and Table 2 of the reference 3).

3. APPLICATION TO MECHATRONIC SERVO SYSTEM

Recently, mechatronic servo systems are used in industrial robots and NC machines widely. The torque saturation characteristics exist in the industrial mechatronic servo systems, and the characteristic often causes deterioration of the contour control performance[7]. In this paper, the authors tried to identify the Volterra kernels of the torque saturation characteristic of the mechatronic servo systems.

The system being measured is shown in Fig.1, where u is the position input to this servo system, K_p is position loop gain, K_v is velocity loop gain, and the element A shows the torque saturation type nonlinearity. y is the position output of the servo system.

A specially chosen M-sequence is applied to the input to the system, and the output $y(t)$ is observed. Taking the crosscorrelation between the input and the output, we obtain Volterra kernels.

The characteristic polynomial used for generating the input M-sequence is $f(x) = 201345$. We measured up to 3rd order Volterra kernels, and some of them are shown in Fig.2 $\sim$ Fig.4.

Fig.2 shows 1st order Volterra kernel $g_1(\tau_1)$ for $0 < \tau_1 < 20\Delta t$.

Fig.3 shows 2nd order Volterra kernel $g_2(\tau_1, \tau_2)$. Since the torque saturation characteristic is symmetric as is seen in Fig.1, the 2nd order kernel is seen to be equal to zero in this case.

Fig.4 shows one crosssection of the 3rd order Volterra kernel $g_3(\tau_1, \tau_2, \tau_3)$ when $\tau_1 = 5\Delta t$.

By use of these measured Volterra kernels and Eq.(1), we can calculate the estimated output of the system.

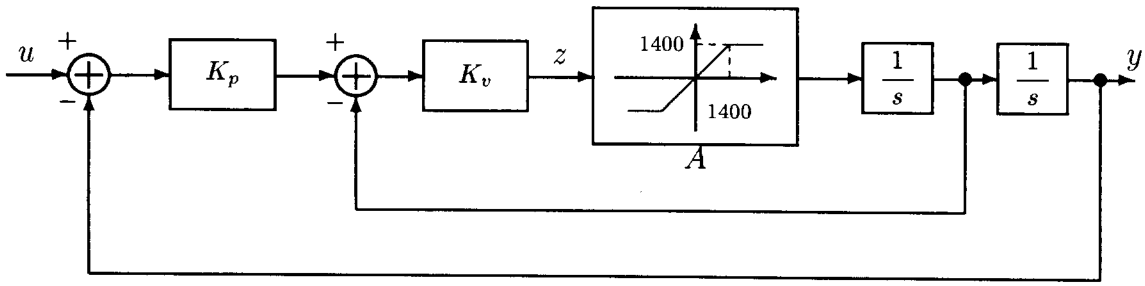

Fig.1 A saturation-type nonlinear feedback control system

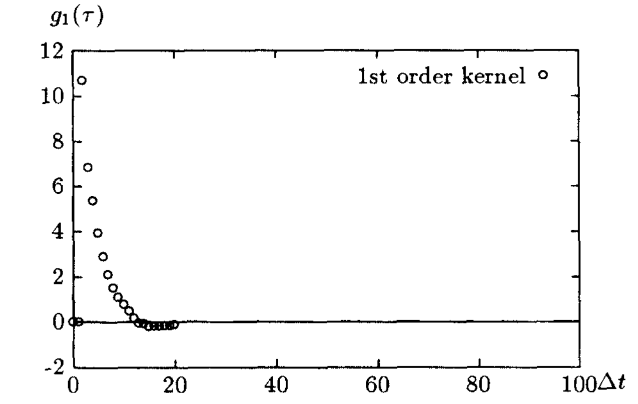

Fig.2 1st order kernel of the saturation-type nonlinear system

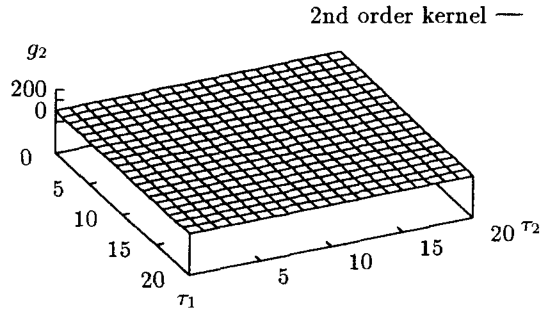

Fig.3 2nd order kernel of the saturation-type nonlinear system

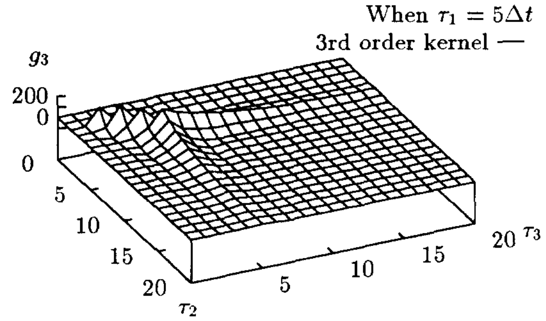

Fig.4 One of 3rd order kernel of the saturation-type nonlinear system

When the amplitude of an arbitrary input is within a certain range, the estimated output gives a good agreement with the actual output as is shown in Fig.5.

In general, the high order Volterra kernels of nonlinear system depend on the amplitude of M-sequence used for identifying the system. Therefore when the input of the system is arbitrary, the amplitude of the input must not exceed a certain level corresponding to

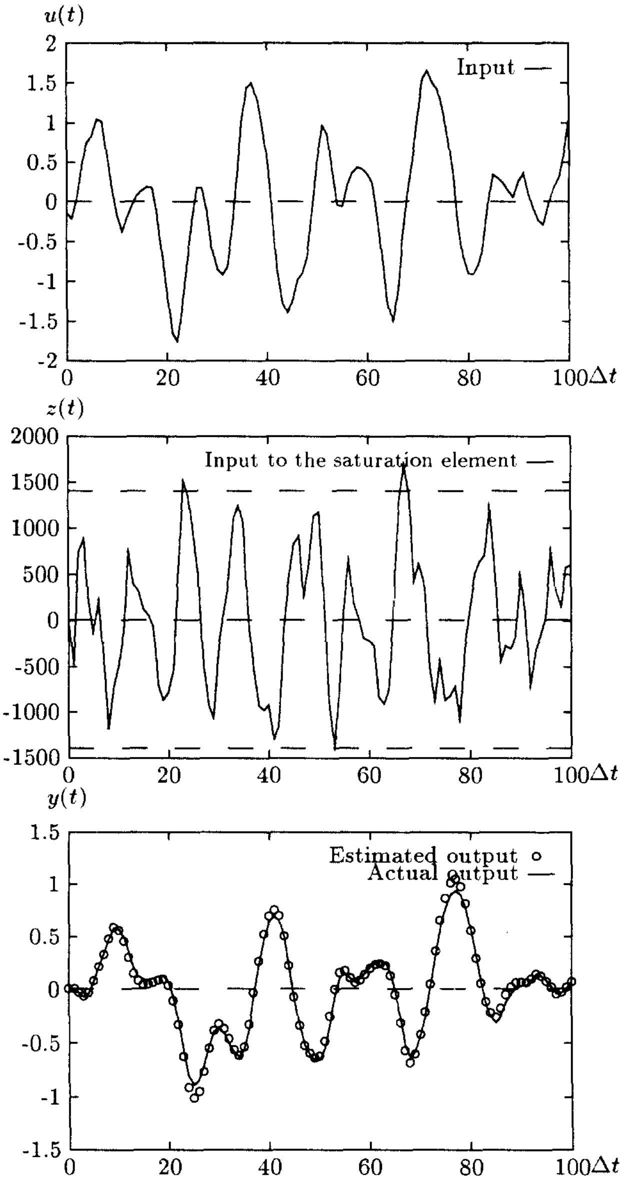

Fig.5 Comparison of the actual output with the estimated one for Fig.1

the amplitude of the M-sequence in order for the estimated output to be approximately equal to the actual output, since too big input may cause different Volterra kernels. But, if the input is a step signal, as in case of calculating the estimated output with Eq.(1), it is sufficient that the parts of the high order kernels should be multiplied by some constant coefficient. In this way, the amplitude of the step signal does not influence the measured Volterra kernels. Fig.6 and Fig.7 show the comparison of the actual output of nonlinear system (shown with solid line) and the calculated output (shown with circles) for different amplitude of the step signal. It is seen from there figures that the calculated output by use of measured Volterra kernels is in good agreement

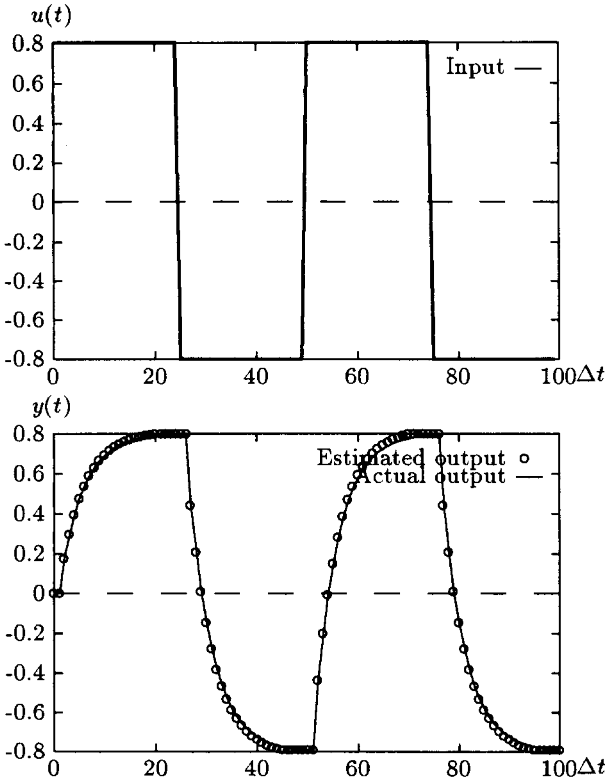

Fig.6 Comparison of the actual output with the estimated one for Fig.1 when the amplitude of the input is small

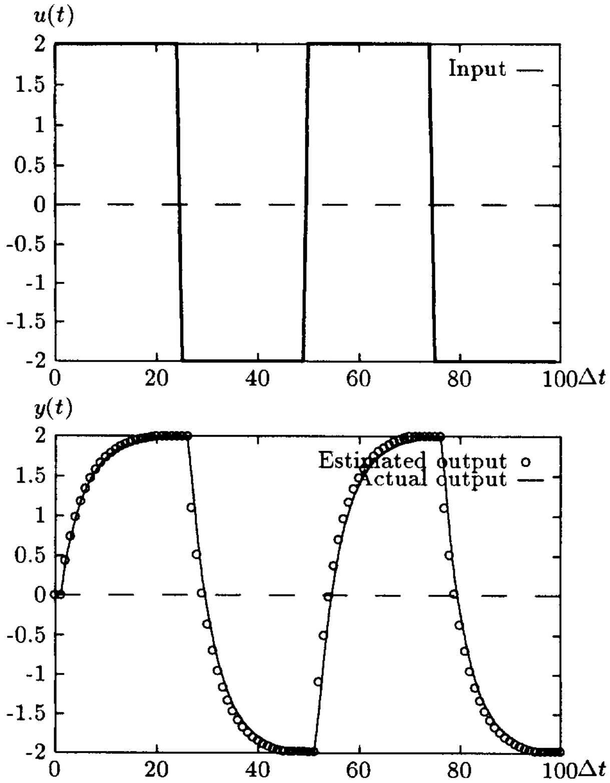

Fig.7 Comparison of the actual output with the estimated one for Fig.1 when the amplitude of the input is large

with the actual output, even when the amplitude of the step signal is different.

4. CONCLUSION

A method for obtaining Volterra kernels of nonlinear system by use of pseudorandom M-sequence is applied to a mechatronic servo system having a saturation type nonlinearity. The results show that the estimated output from the measured Volterra kernels are in good agreement with the actual output. Specially, when the input to the system is a step signal, the estimated output agrees well with the actual output regardless of the amplitude of the input step signal.

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