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Parametric Identification of Input-delay Systems with Unknown Time Delay

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Abstract: In this paper, a method is presented for on-line identification of systems with unknown time delay. This method is based on two parametric models of system that one of them is defined for transfer function parameters estimation and the other one is defined for delay value estimation. Gradient algorithm is used for estimating transfer function parameters and a new algorithm is suggested for estimating delay value. The effectiveness of this method has been demonstrated through simulation. Also this method has been used for identifying laboratory CNC system parameters. The delay in this system is due to signal transmission between the CNC and the network.
Key Words: Identification, Time delay systems, Gradient algorithm.

1 INTOROUCTION

System identification has been an active area of automatic control for a few decades. A considerable number of identification methods have been reported in [1], and they are generally classified into parametric and non-parametric methods. Transfer function parameters estimation is one of the most popular parametric methods. However, most of the existing methods for transfer function identification do not consider the process delay or just assume knowledge of the delay [2].
Time delay is a common phenomenon in many industrial processes due to material and energy transportation lags, measurement delay, and so on [3]. In many industrial systems the time delay and other parameters of the system are unknown. Thus, there has been continuing interest in identification of delay processes with unknown delay. One method is based on determining delay value from the process reaction curve obtained by injecting a step signal to the system [4]. This approach is off-line and is not suitable for systems with time-varying parameters.
Three main approaches have been presented for on-line identification of systems with unknown time delay. The first one is based on approximating the time delay with a rational transfer function such as polynomial approximation [5], Padé approximation [6] and Laguerre expansion [7]. The second is rooted in identification of a lower order model of the unknown system. It is inspired by Astrom's method [8] where the closed-loop system is brought into limit cycle oscillations by switching the closed-loop to a relay excitation and extrapolating the critical gain and frequency. The third approach is based on recursive estimation of system parameters [9].
In this paper, a method is presented for on-line identification of input-delay systems. It is assumed that the value of time delay is unknown, but its upper bound is known. This method is based on two parametric models of system that one of them is defined for transfer function parameters estimation and the other one is defined for delay value estimation. Gradient algorithm is used for estimating transfer function parameters and a new algorithm is suggested for estimating delay value.
This paper is organized as follows: In section 2, a method for identification of systems with known time delay is described. A new method for identification of input-delay systems with unknown time delay is introduced in section 3. In sections 4 and 5, a simulation example and an application to a laboratory CNC system are presented, respectively and conclusions are drawn in section 6.

2 IDENTIFICATION OF INPUT−DELAY SYSTEMS

In this section, we first assume that the delay value is known and estimate the transfer function parameters. Then, we consider systems with unknown delay value and present a method for estimation of transfer function parameters and delay value.

2.1 KNOWN TIME DELAY

Consider a linear input-delay system described by

$$y(t) = G(s)\mathrm{e}^{-d_1 s}u(t) \tag{1}$$

$$G(s) = \frac{b_m s^m + b_{m-1}s^{m-1} + \cdots + b_0}{s^n + a_{n-1}s^{n-1} + \cdots + a_0} \qquad n \geqslant m$$

where $u(t)$ and $y(t)$ are input and output signals of the system, respectively. The time delay $d_1 \in \mathbf{R}^+$ is assumed to be known. It is also assumed that input-output measurements are available.
Our objective is to estimate the unknown parameters $a_0, a_1, ..., a_{n-1}, b_0, b_1, ..., b_m$ of the transfer function $G(s)$. Any on-line parameter estimation described in [11,12,10] can be used to estimate these parameters. Here, we use gradient algorithm.
The plant equation (1) can be expressed as an n-th order differential equation given by

$$y^{(n)}+a_{n-1}y^{(n-1)}+\cdots+a_0y=b_mu^{(m)}(t-d_1)+ b_{m-1}u^{(m-1)}(t-d_1)+\cdots+b_0u(t-d_1) \tag{2}$$

Because in most applications the only signals available for measurement are the input $u(t)$ and output $y(t)$ and the use of differentiations is not desirable, One way to avoid them is to filter each side of (2) with an n-th order stable filter $1/\Lambda(s)$ to obtain parametric model [10]

$$z=\theta^{\mathrm{T}}\times\phi \tag{3}$$

where

$$z=\frac{s^n}{\Lambda(s)}y(s)$$

$$\theta=\begin{bmatrix}b_m & b_{m-1} & \cdots & b_0 & a_{n-1} & \cdots & a_0\end{bmatrix}^{\mathrm{T}}$$

$$\phi=\frac{1}{\Lambda(s)}\begin{bmatrix}s^m e^{-d_1 s}u & s^{m-1}e^{-d_1 s}u & \cdots & e^{-d_1 s}u & -s^{n-1}y & -s^{n-2}y & \cdots & -y\end{bmatrix}^{\mathrm{T}}$$

and $\Lambda(s)=s^n+\lambda_1 s^{n-1},\dots,\lambda_n$ is a monic Hurwitz polynomial. It should be noted that because the delay value d_1 is known, the delayed term $e^{-d_1 s}$ can be used in the regression vector ϕ for estimating transfer function parameters.

The estimate $\hat{z}$ of z at each time t is generated as

$$\hat{z}=\hat{\theta}^{\mathrm{T}}\times\phi \tag{4}$$

where $\hat{\theta}(t)$ is the estimate of θ at time t for each time t. Thus, the identification error is denoted as

$$e=z-\hat{z} \tag{5}$$

and gradient law is described by

$$\dot{\hat{\theta}}=\Gamma e\phi \tag{6}$$

where, $\Gamma=\Gamma^{\mathrm{T}}>0$ is a constant positive definite symmetric matrix.

The convergence properties of $\hat{\theta}(t)$ to its real value θ depend on the properties of the input signal $u(t)$. If $u(t)$ belongs to the class sufficiently rich signals, i.e., it has enough frequencies to excite all of the modes of the plant, $\hat{\theta}(t)$ converges to θ exponentially [10].

2.2 UNKNOWN TIME DELAY

Consider a linear input-delay system described by

$$y(t)=G(s)\mathrm{e}^{-ds}u(t) \tag{7}$$

$$G(s)=\frac{b_m s^m+b_{m-1}s^{m-1}+\cdots+b_0}{s^n+a_{n-1}s^{n-1}+\cdots+a_0} \qquad n\geq m,$$

where $u(t)$ and $y(t)$ are input and output signals of the system, respectively. The time delay d is assumed to be unknown satisfying $0\leqslant d\leqslant D_r$, in which the upper bound D_r of the time delay is known. Our objective is to estimate the unknown parameters

$$\theta=\begin{bmatrix}b_m & b_{m-1} & \cdots & b_0 & a_{n-1} & \cdots & a_0\end{bmatrix}^{\mathrm{T}}$$

of the transfer function $G(s)$ and unknown delay value d based on input and output data measurements.

$$z=\theta^{\mathrm{T}}\times\phi=\frac{s^n}{\Lambda(s)}y(s)$$

In order to estimate parameter vector θ and delay value d, two estimates $\hat{z}_1$ and $\hat{z}_2$ of z at each time t are generated, respectively. As in previous section, the estimate $\hat{z}_1$ is defined with parametric model

$$\hat{z}_1=\hat{\theta}^{\mathrm{T}}\times\phi_1 \tag{8}$$

where

$$\phi_1=\frac{1}{\Lambda(s)}\begin{bmatrix}s^m\mathrm{e}^{-\hat{d}s}u & s^{m-1}\mathrm{e}^{-\hat{d}s}u & \cdots & \mathrm{e}^{-\hat{d}s}u & -s^{n-1}y & -s^{n-2}y & \cdots & -y\end{bmatrix}^{\mathrm{T}} \tag{9}$$

where $\hat{d}(t)$ is estimate of time delay d that is calculated via $\hat{z}_2$.

The identification error is denoted as $e_1=z-\hat{z}_1$ and $\hat{\theta}(t)$ is generated by Gradient adaptive law

$$\dot{\hat{\theta}}(t)=\Gamma e_1\phi_1$$

$\hat{d}(t)$ is obtained by defining estimate $\hat{z}_2$ with second parametric model

$$\hat{z}_2=\hat{\theta}^{\mathrm{T}}\times\phi_2 \tag{10}$$

where

$$\phi_2=\frac{1}{\Lambda(s)}\begin{bmatrix}s^m u & s^{m-1}u & \cdots & u & -s^{n-1}y_1 & -s^{n-2}y_1 & \cdots & -y_1\end{bmatrix}^{\mathrm{T}} \tag{11}$$

and

$$y_1=\hat{G}(s)u$$

$$\hat{G}(s)=\frac{\hat{b}_m s^m+\hat{b}_{m-1}s^{m-1}+\cdots+\hat{b}_0}{s^n+\hat{a}_{n-1}s^{n-1}+\cdots+\hat{a}_0}$$

In the above equation $\hat{G}(s)$ is the estimate of $G(s)$ with parameter vector $\hat{\theta}(t)$, and y_1 is the estimate of the output y at time $t+d$. Thus, ϕ_2 and $\hat{z}_2$ are the estimates of ϕ_1 and z at time $t+d$.

For generating the estimate of delay value $\hat{d}(t)$, we suggest the following algorithm

$$\hat{d}_{\mathrm{new}}=\frac{\hat{d}_{\mathrm{old}}+\gamma.d^{\min}}{1+\gamma} \tag{12}$$

where $\gamma>0$ is a positive constant, $\hat{d}_{\mathrm{old}}$ is the estimated delay value in the previous step. $d^{\min}$ is the estimate of the delay value between $\hat{z}_2$ and z at time t.

Since $\hat{z}_2$ is the estimate of z at time $t+d$, the value of $\left|z(t)-\hat{z}_2(t-d^{\mathrm{test}})\right|$ is minimum for $d^{\mathrm{test}}=d$.

Therefore for estimating $d^{\min}$, we suggest to chose $d^{\min}$ for the value of $0\leqslant d^{\mathrm{test}}\leqslant D_r$ such that $\left|z(t)-\hat{z}_2(t-d^{\mathrm{test}})\right|$ is minimum and also $\operatorname{sign}(\dot{z}(t))$

and $\operatorname{sign}(\dot{\hat{z}}_2(t-d^{\text{test}}))$ are equal:

$$d^{\min} = \{d^{\text{test}} : \left| z(t) - \hat{z}_2(t-d^{\text{test}}) \right| = \min \\ \& \operatorname{sign}(\dot{z}(t)) = \operatorname{sign}(\dot{\hat{z}}_2(t-d^{\text{test}}))\} \quad (13)$$

The equation (13) is illustrated in Fig.1:

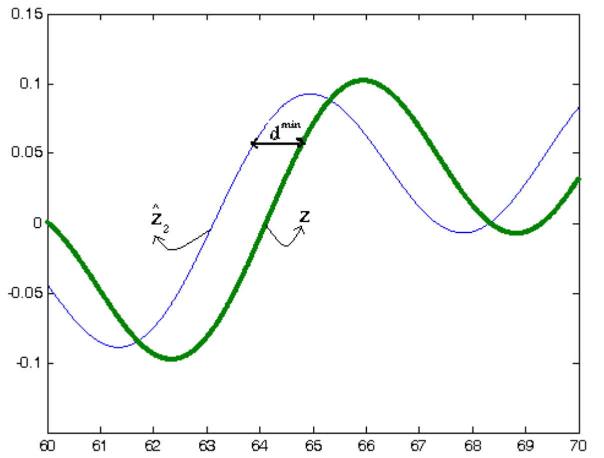

Fig.1 True estimating of delay for delay=1 and $F_u^{\max}$ =.16

For estimating $d^{\min}$ correctly, it is suggested that the maximum frequency of input signal u satisfies the assumption

$$f_u^{\max} \leqslant \frac{1}{D_r} \quad (14)$$

This assumption is illustrated in Fig.2.

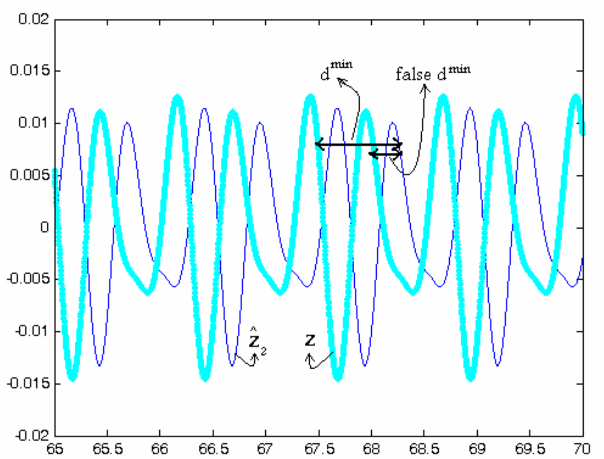

Fig.2 False estimating of delay for delay=1 and $F_u^{\max}$ =1.6

It should be considered to use this algorithm, $\hat{z}_2$ values should be saved up to D_r seconds. It means that, we need to have a vector:

$$\hat{Z}_2 = [\hat{z}_2(t-\Delta t_s) \quad \hat{z}_2(t-2\Delta t_s) \quad \hat{z}_2(t-3\Delta t_s) \quad \cdots \\ \hat{z}_2(t-D_r+\Delta t_s) \quad \hat{z}_2(t-D_r)]$$

at each time t, where Δt_s is the sampling time . Thus, $d^{\min}$ is calculated by:

$$d^{\min} = \{K.\Delta t_s : \left| z(t) - \hat{z}_2(t-K.\Delta t_s) \right| = \min \\ \& \operatorname{sign}(\dot{z}(t)) = \operatorname{sign}(\hat{z}_2(t-(K+1).\Delta t_s) - \hat{z}_2(t-K.\Delta t_s))\}$$

3 SIMULATION RESLTS

To illustrate the effectiveness of the proposed method, let us consider the second order plant described by

$$y = \frac{2}{s^2+4s+3} e^{-s} u \quad (15)$$

where $\theta = [2 \quad 4 \quad 3]^{\mathrm{T}}$, $d=1$ are system parameters to be estimated. By choosing

$$\Lambda(s) = (s+0.7)^2$$

$$\Gamma = \begin{bmatrix} 16 & 0 & 0 \\ 0 & 16 & 0 \\ 0 & 0 & 6 \end{bmatrix}$$

$\gamma = 0.001$ and $D_r = 3$ second.

Simulation results in Figs. 3, 4. Fig. 3 show the estimated parameters and Fig. 4 shows the estimation error $e(t)$. The initial values of transfer function parameters are chosen random integers and the initial value of the time delay is chosen to be zero. We note that the estimated parameters converge to their real value and the estimation error converges to zero as $t \to \infty$.

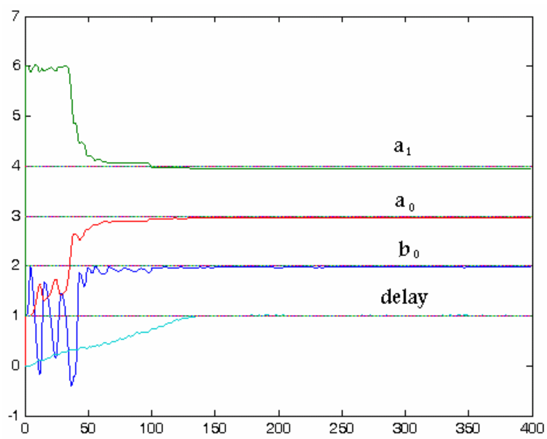

Fig .3 Estimated parameters of the plant (15)

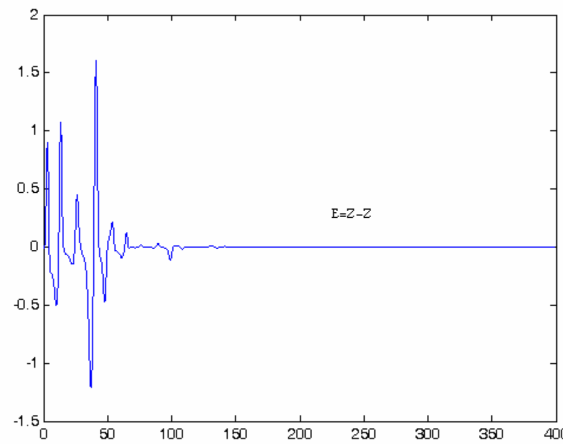

Fig. 4 Error between z and $\hat{z}_1$

By increasing γ, the rate of converge to real delay value increases but,it causes more variations. Therefore, it is suggested that γ is chosen about 0.1 of the sampling time value.

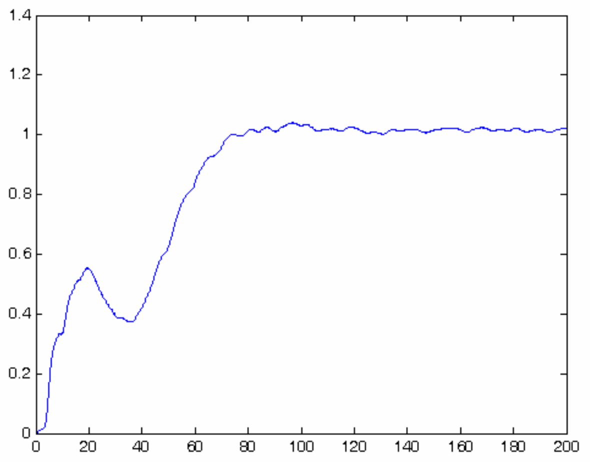

Fig.5 The effect of γ =.005 on estimating of delay

4 AN APPLICATION : PARAMETER IDENTIFICATION OF A LABORATORY CNC

In practice, this method is used for identification of a laboratory CNC that is manufactured in the digital control laboratory at Isfahan University of Technology (see Fig. 6).

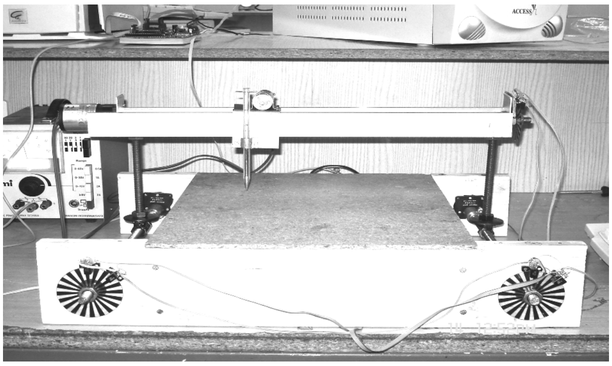

Fig.6 A picture of CNC

In this CNC, DC motor is used instead of Step motor which is usually used in CNCs. In order to control the speed of the motor we need to know CNC system parameters. Practical results are focused only on the identification of one axle of this CNC. The delay in this system is due to signal transmission between the CNC and the network. According to physical properties of the CNC system, the following model is suggested for the axle.

$$y = \frac{b_0}{s^2 + a_1 s \ + a_0} e^{-ds} u$$

where b_0, a_1, a_0 and d are unknown parameters to be estimated. Figs.7,8,9 were generated By choosing $\Lambda(s) = 0.5(s+0.1)^2$,

$$\Gamma = \begin{bmatrix} 0.033 & 0 & 0 \\ 0 & 0.333 & 0 \\ 0 & 0 & 0.005 \end{bmatrix} \times 10^{-3}$$

$\gamma = 0.001$ and $D_r = 1.2$ second.

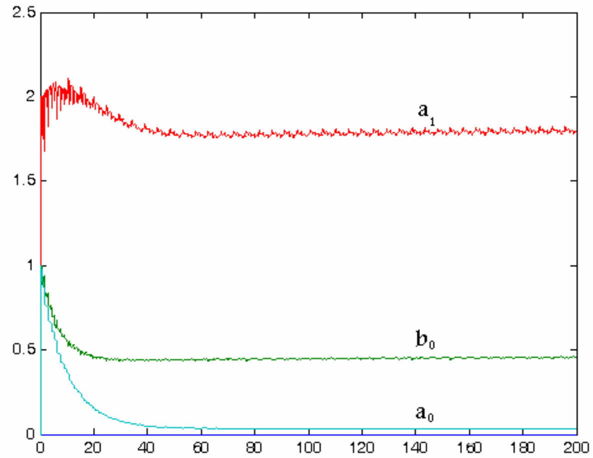

Fig 7 Estimated parameters of the CNC

Fig.7 shows the estimated transfer function parameters of the CNC. Fig. 8 shows the estimated value of the transport delay. The error between the output of the CNC and output of the estimated model is shown in Fig. 9. It is clear from this figure that the estimation error converges to zero as $t \to \infty$.

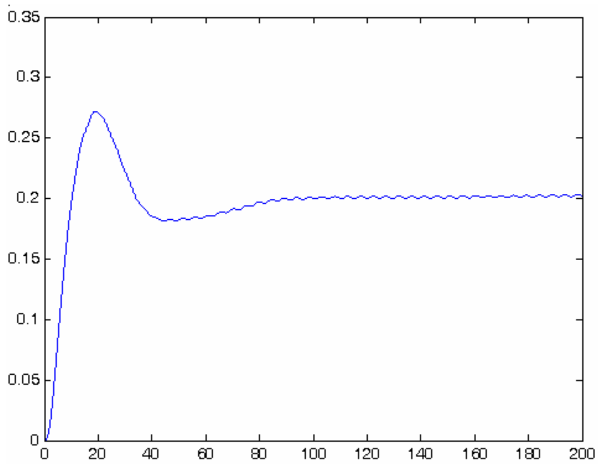

Fig.8 Estimated Delay

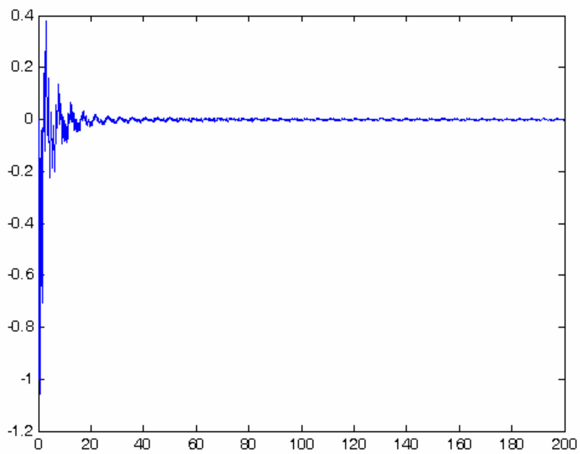

Fig .9 Error between z and $\hat{z}_1$

Through identification process, the transfer function is obtained for the axel.

$$Y(s) = \frac{0.4588}{s^2 + 1.7932s + 0.0342} e^{-0.2022s} u(s)$$

5 CONCLUSTION

This paper has presented a new method for on-line identification of systems with unknown time delay. We defined two separately parametric models of system for transfer function parameters estimation and delay value estimation. Gradient algorithm is used for estimating transfer function parameters and a new algorithm is suggested for estimating delay value. A simulation example is given to show the effectiveness of the proposed method.

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