PROCESS DESIGN AND CONTROL

Low-Order Modeling from Relay Feedback

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There have recently been considerable interests in extensions of PID relay autotuning to model-based controllers, and this necessitates transfer function modeling from relay feedback. The methods reported in the literature for this purpose require *two* tuning tests, and their results are approximate in nature. In this paper, exact expressions for the periods and amplitudes of limit cycles under relay feedback are derived for processes which may be modeled by first-order plus dead-time dynamics. This time-domain information is then combined with frequency response point estimation using Fourier series expansions of the limit cycles so that a first-order plus dead-time model can be identified with a *single* relay test. Furthermore, no approximation is made in our derivations and the resultant model will be precise if it matches the structure of the process. In the case of the mismatched structure, it is shown through extensive simulations that our procedure yields very accurate results in the sense that the identified model frequency response fits the actual process one well. Both unbiased and biased relays with or without hysteresis are considered.

1. Introduction

Relay autotuning of PID controllers has been successful in industrial process control application and led to a number of commercial autotuners (Astrom and Hagglund, 1988). Now the relay feedback is being extended to tune some other controllers, such as model-based controllers which need transfer function models (Hang *et al.*, 1995; Palmor *et al.*, 1994; Wang *et al.*, 1995). The transfer function models (or their equivalent step response models) also play an important role in the analysis of the multivariable process. Luyben (1987) proposes the following method for first-, second-, and third-order process modeling (called the ATV method): (1) The ultimate gain and ultimate frequency are obtained by using Astrom's autotuning method. (2) The dead time is read off from the initial response of the system to the autotuning test. (3) The steady-state gain is obtained from a steady-state model of the process or from use of the step response method (Luyben, 1990); (4) First-, second-, and third-order transfer functions are fitted to the data at zero and the ultimate frequencies. The procedure was later modified (Li *et al.*, 1991) to remove the condition that the gain should be known. The modified procedure uses two relay experiments. The first is a straightforward one; the second is run with a dead time added. Thus, the steady-state gain can be determined. However, accurate measurement of the dead time from the initial response is very difficult, and the ultimate gain and ultimate frequency derived from the describing function are approximate and may have significant errors in the case of processes with high-order dynamics and/or long dead times. Recently, an input-biased relay experiment is introduced (Shen *et al.*, 1996) to identify two points on the Nyquist curve from a single test based on the describing function analysis.

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The most commonly used dynamic model for the industrial process is the first-order plus dead-time model, which has three parameters. In this paper, exact expressions for the periods and amplitudes of limit cycles under relay feedback are derived for first-order plus dead-time processes. This time-domain information is combined with frequency response point estimation using Fourier series expansions of the limit cycles so that a first-order plus dead-time model can be identified with a single relay test. Our methods avoid the difficulty of measuring the dead time from the relay test. Furthermore, no approximation is made in our derivations, and the resultant model will be precise if it matches the structure of the process. In the case of the mismatched structure, it is shown through extensive simulations that our procedure is robust and yields very accurate results in the sense that the identified model frequency response fits the actual process one well. Both unbiased and biased relays with or without hysteresis are considered.

The paper is organized as follows. In section 2, modeling from a biased relay feedback is developed. In section 3, the unbiased relay feedback is considered. The conclusions are in section 4.

2. Biased Relay

Consider a first-order plus dead-time process

$$G(s) = \frac{Ke^{-Ls}}{Ts+1} \qquad (1)$$

A relay feedback system of Figure 1 is set up for the process. In the ATV method (Luyben, 1987), only the approximate critical point information of the process frequency response can be obtained from one relay test. In order to obtain the steady-state gain of the process from the same relay experiment, in addition to the critical point information, the biased relay as shown in the Figure 2 is introduced. The resulting oscillation

S0888-5885(96)00412-5 CCC: $14.00

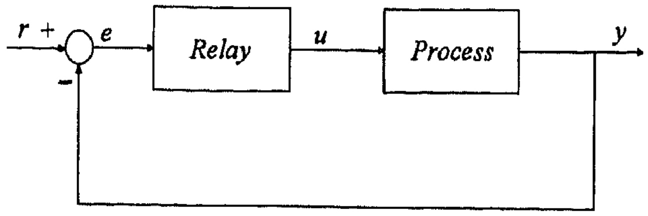

Figure 1. Relay feedback system.

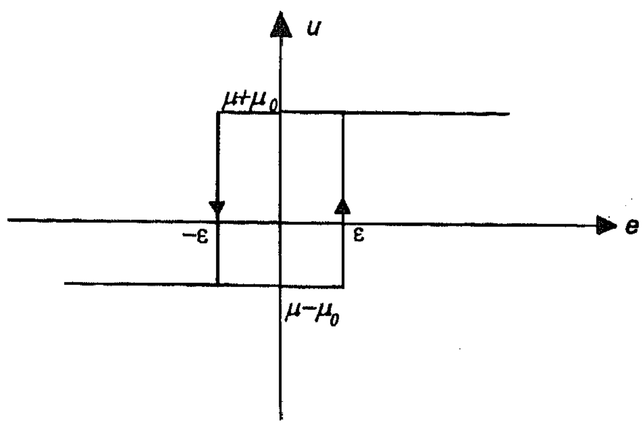

Figure 2. Biased relay.

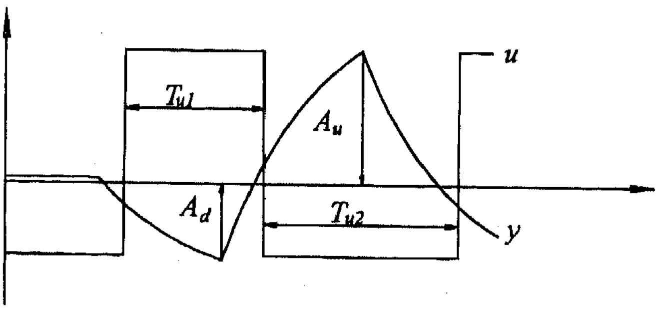

Figure 3. Oscillatory waveforms under a biased relay feedback.

waveform of the process is shown in Figure 3. The following theorem gives the properties of the oscillation.

Theorem 1: For the process of eq 1 under the relay feedback of Figure 2, the process output y converges to the stationery oscillation in one period $(T_{u1} + T_{u2})$, and the oscillation is characterized by

$$A_u = (\mu_0 + \mu)K(1 - e^{-L/T}) + \epsilon e^{-L/T} \tag{2}$$

$$A_d = (\mu_0 - \mu)K(1 - e^{-L/T}) - \epsilon e^{-L/T} \tag{3}$$

$$T_{u1} = T \ln \frac{2\mu K e^{L/T} + \mu_0 K - \mu K + \epsilon}{\mu K + \mu_0 K - \epsilon} \tag{4}$$

and

$$T_{u2} = T \ln \frac{2\mu K e^{L/T} - \mu K - \mu_0 K + \epsilon}{\mu K - \mu_0 K - \epsilon} \tag{5}$$

Proof: See the Appendix.

Equations 2–5 are the exact expressions of the period and the amplitude of limit cycle oscillation for the process (1). Some simulation examples are given in Table 1, where the outputs of biased relay are 1.3 and −0.7, respectively, and the hysteresis of relay is 0.1. The results show the accuracy of the formulas (2)–(5), and very small errors are caused by simulation computations.

The four equations (2)–(5) are sufficient to determine the three parameters of the process, but solving these equations is somehow tedious. To simplify the computations, we now look into frequency response information contained in the limit cycle. Theorem 1 indicates that the waveforms of the process input $u(t)$ and output $y(t)$ are periodic with the period $T_{u1} + T_{u2}$. They can be expanded into Fourier series. The direct-current components of these periodic waves are extracted, and the steady-state gain of the process can be computed (Ramirez, 1985) via the following formula:

$$K = G(0) = \frac{\int_0^{T_{u1}+T_{u2}} y(t)\, dt}{\int_0^{T_{u1}+T_{u2}} u(t)\, dt} \tag{6}$$

With K known, the normalized dead time of the process $\Theta = L/T$ is obtained from eq 2 or eq 3 as

$$\Theta = \ln \frac{(\mu_0 + \mu)K - \epsilon}{(\mu_0 + \mu)K - A_u} \tag{7}$$

or

$$\Theta = \ln \frac{(\mu - \mu_0)K - \epsilon}{(\mu - \mu_0)K + A_d} \tag{8}$$

It then follows from eq 4 or eq 5 that

$$T = T_{u1}\left(\ln \frac{2\mu K e^{\Theta} + \mu_0 K - \mu K + \epsilon}{\mu K + \mu_0 K - \epsilon}\right)^{-1} \tag{9}$$

or

$$T = T_{u1}\left(\ln \frac{2\mu K e^{\Theta} - \mu_0 K - \mu K + \epsilon}{\mu K - \mu_0 K - \epsilon}\right)^{-1} \tag{10}$$

The dead time is thus

$$L = T\Theta \tag{11}$$

The above development can be summarized as the following identification procedure.

Identification Procedure. The biased relay experiment is performed. The process input *u(t)* and output *y(t)* are recorded, and the periods and the amplitudes of the oscillation are measured.

Table 1. Limit Cycle under the Biased Relay Feedback

process			calculated result				measured result				percentage error, %			
K	T	L	T_{u1}	T_{u2}	A_u	A_d	T_{u1}	T_{u2}	A_u	A_d	T_{u1}	T_{u2}	A_u	A_d
1	2	1	1.620	2.503	0.5722	−0.3361	1.620	2.505	0.572	−0.336	0.000	0.080	0.035	0.030
1	2	2	2.788	3.909	0.8585	−0.4793	2.790	3.910	0.859	−0.479	0.072	0.026	0.058	0.063
1	2	5	5.972	7.307	1.2015	−0.6507	5.970	7.310	1.202	−0.651	0.034	0.041	0.042	0.046
1	1	2	2.469	3.119	1.1376	−0.6188	2.470	3.120	1.138	−0.619	0.041	0.032	0.035	0.032
1	5	2	3.432	5.447	0.4956	−0.2978	3.430	5.445	0.496	−0.298	0.058	0.037	0.081	0.067
0.5	2.	2	3.003	4.321	0.4477	−0.2580	3.005	4.320	0.448	−0.258	0.067	0.023	0.067	0.000
2	2	2	2.685	3.725	1.6803	−0.9218	2.685	3.725	1.680	−0.922	0.000	0.000	0.018	0.022

Table 2. Parameter Estimation from Biased Relay

	process			biased relay				new method			ATV method		
case	K	T	L	T_{u1}	T_{u2}	A_u	A_d	K	T	L	K	T	L
1	1	2	2	2.79	3.91	0.859	−0.480	1.000	1.999	2.002	1	1.658	2
2	1	1	3	3.50	4.18	1.241	−0.670	1.000	0.999	3.006	1	1.042	3
3	1	5	2	3.44	5.46	0.497	−0.299	0.999	4.990	2.009	1	4.068	2
4	1	5	1	2.15	3.65	0.318	−0.209	1.001	5.003	1.004	1	4.055	1

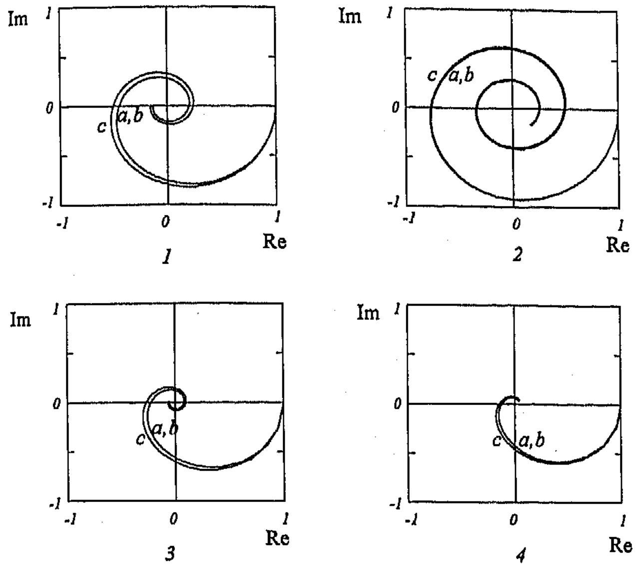

Figure 4. Nyquist curves of the processes and the models: (a) real process, (b) new method, (c) ATV method.

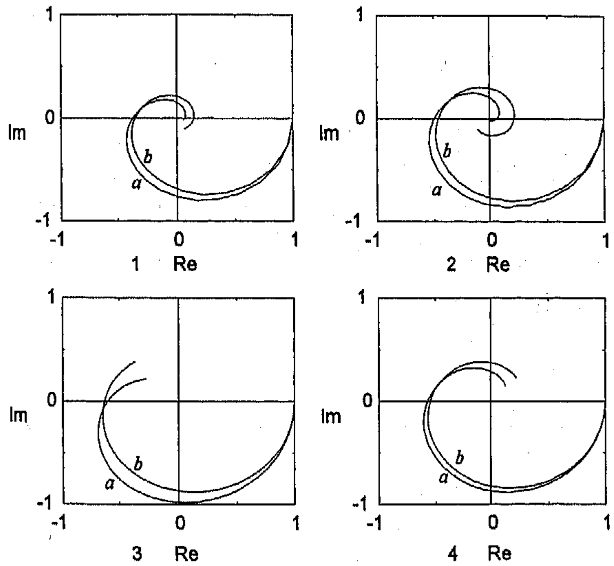

Figure 5. Nyquist curves of high-order processes and corresponding low-order models: (a) real process, (b) model.

Step 1: Compute K from eq 6.
Step 2: Compute Θ from eq 7 or eq 8.
Step 3: Compute T from eq 9 or eq 10.
Step 4: Compute L from eq 11.

Simulation is carried out for processes with different normalized dead time to illustrate the accuracy of the proposed method. The outputs of biased relay are 1.3 and −0.7, respectively, and the hysteresis of relay is 0.1. The resultant limit cycles and model parameters are presented in Table 2. For comparison, the parameters obtained by the ATV (Luyben, 1987) are also given in Table 2, where it is assumed that the steady-state gain is known and the dead time is read exactly. The Nyquist curves of the models and the corresponding real processes are shown in Figure 4. The results show that the proposed method can give nearly the exact identification of the process parameters.

Table 3. Models for the High-Order Processes

case	process	model
1	$\frac{1}{(2s+1)^2}e^{-2s}$	$\frac{1.00}{4.072s+1}e^{-2.93s}$
2	$\frac{1}{(2s+1)^5}e^{-2s}$	$\frac{1.00}{6.809s+1}e^{-7.26s}$
3	$\frac{1}{(s+1)(s^2+s+1)}e^{-0.5s}$	$\frac{1.00}{1.152s+1}e^{-2.1s}$
4	$\frac{-s+1}{(s+1)^5}e^{-s}$	$\frac{1.00}{2.99s+1}e^{-4.24s}$

In practice, many high-order processes can be well approximated by first-order plus dead-time models. The proposed method can also be used to model the high-order process. The results for some typical processes are listed in Table 3. The Nyquist curves of the real processes and the models are shown in Figure 5, and they are very close to each other over a phase range of 0 to π. Therefore, this low-order modeling will be accurate enough for control design in most cases.

If the relay has no hysteresis, i.e., $\epsilon = 0$, eqs 2−5 reduce to

$$A_u = (\mu_0 + \mu)K(1 - e^{-L/T}) \qquad (12)$$

$$A_d = (\mu_0 - \mu)K(1 - e^{-L/T}) \qquad (13)$$

$$T_{u1} = T \ln \frac{2\mu e^{L/T} + \mu_0 - \mu}{\mu + \mu_0} \qquad (14)$$

$$T_{u2} = T \ln \frac{2\mu e^{L/T} - \mu - \mu_0}{\mu - \mu_0} \qquad (15)$$

Remark 1. One sees from eqs 12−15 that the periods (T_{u1}, T_{u2}) and the amplitudes (A_u, A_d) of the limit cycle are proportional to the time constant T and the steady-state gain K of the process, respectively, provided that the normalized dead time $\Theta = L/T$ is constant.

Remark 2. It follows from eqs 12 and 13 that the ratio of the up-amplitude and the down-amplitude is independent of the process parameters, and it depends only on the bias of the relay amplitude. Equation 13 is thus redundant.

Noise Issue. In the real process, the measurement noise is unavoidable. Different identification methods are more or less sensitive to noise. As for the measurement noise in the relay test, Astrom *et al.* (1984) pointed out that a hysteresis in the relay is a simple way to reduce the influence of the measurement noise. The width of hysteresis should be bigger than the noise band (Astrom *et al.*, 1988) and is usually chosen as 2 times larger than the noise band (Hang *et al.*, 1993). In the context of system identification, noise-to-signal ratio (Haykin, 1989) is usually defined as

$$\text{noise-to-signal power spectrum ratio} = \frac{\text{mean power spectrum density of noise}}{\text{mean power of signal}}$$

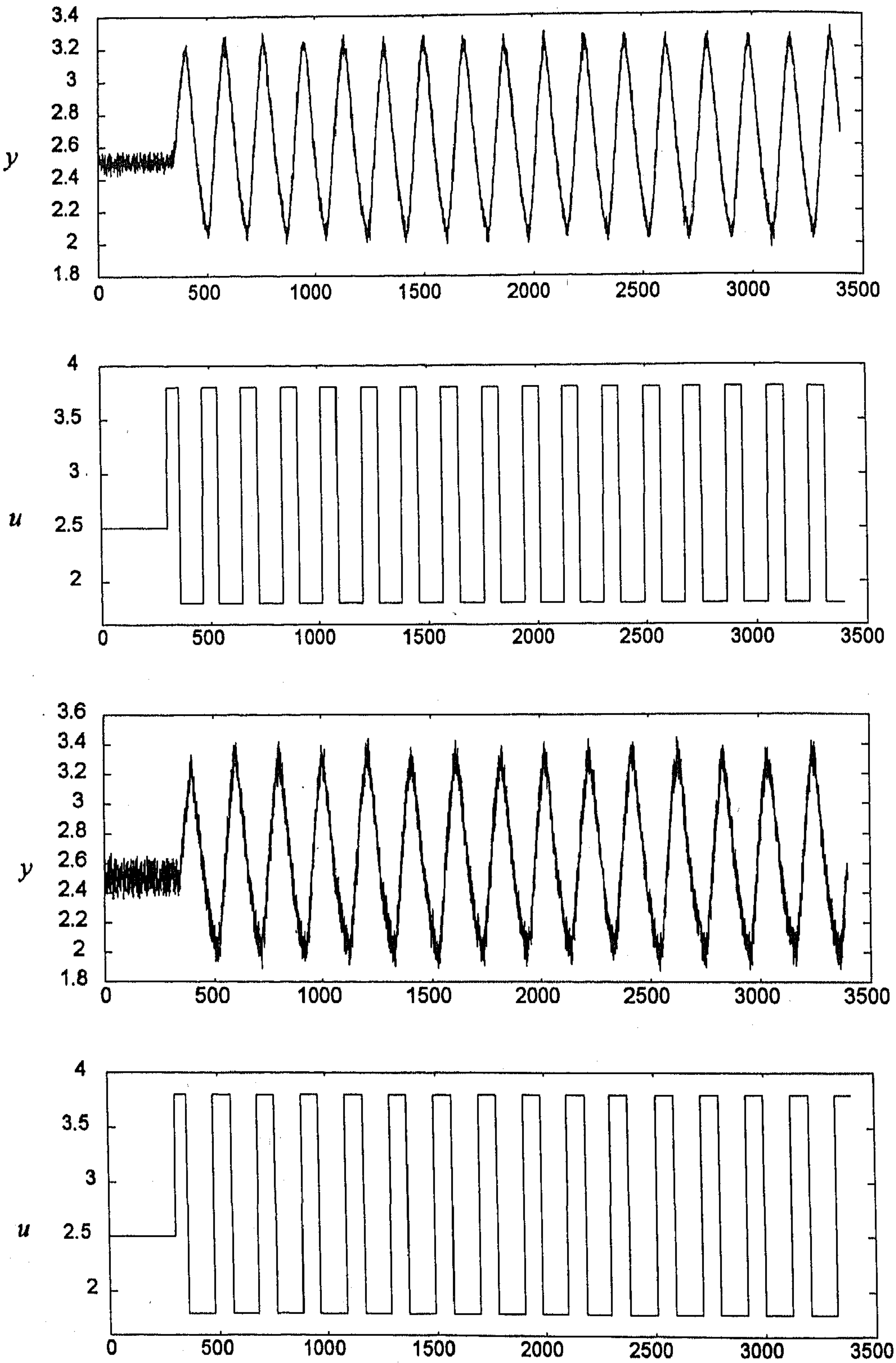

Figure 6. Input–output responses of biased relay experiments with noise-to-signal ratio N_2 of 0.08 and 0.190, respectively.

(denoted by N_1) or

$$\text{noise–signal mean ratio} = \frac{\text{mean(abs(noise))}}{\text{mean(abs(signal))}}$$

(denoted by N_2). In order to test our method in a realistic environment, real-time relay tests were performed using *Dual Process Simulator KI 100* from KentRidge Instruments (KentRidge, 1992). The simulator is an analog process simulator and can be configured to simulate a wide range of industrial processes with different kinds of dynamics and with different levels of noise. The simulator is connected to a PC computer via an A/D and D/A board. The window-based DT VEE 3.0 (DataTranslation, 1995) is used as the system control platform, on which the relay control code is written in C++. The fastest sampling time of the VEE system is 0.06 s. The following typical process is configured to illustrate the effect of process noises:

$$G(s) = \frac{1}{(2s+1)^2}e^{-2s} \tag{16}$$

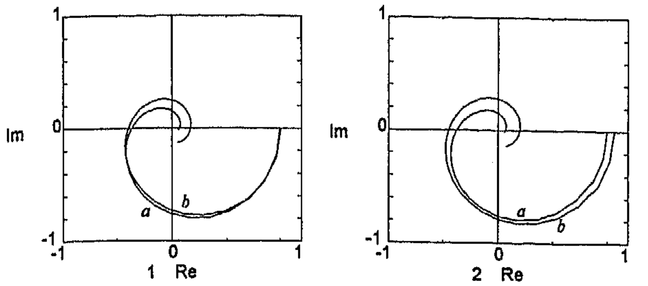

Figure 7. Nyquist curves of real processes and corresponding models: (1) for $N_2 = 0.08$, (2) for $N_2 = 0.190$, (a) real process, (b) model.

Figure 6 shows the input–output responses for the biased relay tests with noise-to-signal ratio N_2 of 0.08 and 0.190 (N_1 of 0.006 and 0.033), respectively. The models are identified as

$$\tilde{G}(s) = \frac{1.01}{3.53s + 1}e^{-3.03s} \qquad \text{for } N_2 = 0.08 \qquad (17)$$

and

$$\tilde{G}(s) = \frac{1.07}{3.28s + 1}e^{-2.99s} \qquad \text{for } N_2 = 0.190 \qquad (18)$$

It is noted that eight cycles of periodical stationary oscillations are used in the steady-state gain calculation (eq 6), and the up and down amplitudes are calculated as the mean value of those in the same data, respectively. The Nyquist curves of the real processes and the models are shown in Figure 7, and they are very close to each other over a phase range of 0 to π. In a conclusion, since only steady-state information is used to develop the model in our method, and more periodical stationary oscillation data can be employed to effectively reduce noise effect on estimation, our method is less sensitive to noise compared with most identification methods.

3. Unbiased Relay

The biased relay will cause the operating point to drift. It is thus a larger disturbance than an unbiased relay with the same amplitude. For this reason, a biased relay might sometimes be undesirable in practice. In this case, an unbiased relay has to be used and the process steady-state gain is no longer identifiable. We now have to employ the first harmonic information contained in limit cycles instead of DC component. This makes exact identification from a single unbiased relay test still possible but at the expense of a few more calculations.

Consider again the first-order plus dead-time process (1). An unbiased relay feedback system is set up for the process. The following corollary, which can be easily reached with $\mu_0 = 0$ in Theorem 1, gives the properties of the limit cycle oscillation.

Corollary 1. For the process of eq 1 under the relay feedback of Figure 8, the limit cycle oscillation is symmetric and is characterized by the period

$$T_u = 2T \ln \frac{2\mu K e^{L/T} - \mu K + \epsilon}{\mu K - \epsilon} \qquad (19)$$

and the amplitude

$$A = \mu K(1 - e^{-L/T}) + \epsilon e^{-L/T} \qquad (20)$$

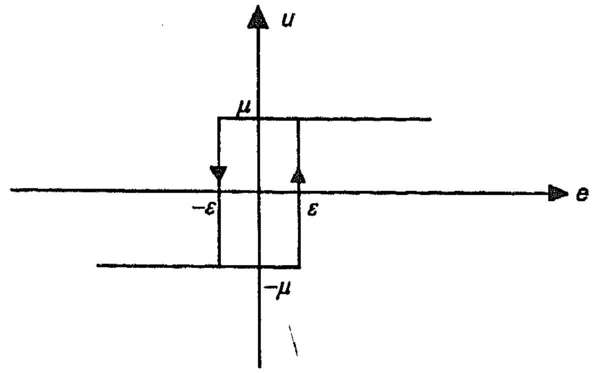

Figure 8. Unbiased relay.

If the process steady-state gain K is known, it follows from the corollary that the other two process parameters T and L are easily obtained as

$$T = \frac{1}{2}T_u\left(\ln \frac{\mu K + A}{\mu K - A}\right)^{-1} \qquad (21)$$

and

$$L = \frac{1}{2}T_u\left(\ln \frac{\mu K - \epsilon}{\mu K - A}\right)\left(\ln \frac{\mu K + A}{\mu K - A}\right)^{-1} \qquad (22)$$

Otherwise, if K is unknown, we need additional relations to determine the three parameters of the process in one relay test. Since the oscillation waveforms of the process input $u(t)$ and output $y(t)$ are periodic with the period T_u, they can be expended into Fourier series. The first harmonics are then extracted, and their coefficients give one point of process frequency response (Ramirez, 1985) via the formula

$$G(j\omega_0) = \frac{\int_0^{T_u} y(t)\, e^{-j\omega_0 t}\, dt}{\int_0^{T_u} u(t)\, e^{-j\omega_0 t}\, dt} = A_0 e^{j\phi_0} \qquad (23)$$

where

$$\omega_0 = 2\pi/T_u$$

is the oscillation frequency. Unlike the describing function method, formula (23) introduces no approximation and gives an accurate estimation of one frequency response point at $\omega = \omega_0$. Substituting eq 1 into eq 23 and taking amplitudes on both sides give

$$\frac{K}{\sqrt{(\omega_0 T)^2 + 1}} = A_0 \qquad (24)$$

Combining eq 24 with eq 21 yields

$$e^{T_u/2T} = \frac{\mu A_0\sqrt{(\omega_0 T)^2 + 1} + A}{\mu A_0\sqrt{(\omega_0 T)^2 + 1} - A} \qquad (25)$$

This equation contains only one unknown T, and it can be solved with a simple iterative method such as Newton interpolation. On the basis of eqs 22–25, the following identification procedure is proposed.

Identification Procedure. The unbiased relay experiment is performed. The process input *u(t)* and output *y(t)* are recorded, and the period and the amplitude of the oscillation are measured.

Step 1: Compute A_0 from eq 23.

Table 4. Parameter Estimation from Unbiased Relay

	process			limit cycle			new method			ATV method		
case	K	T	L	T_u	A	A_0	K	T	L	K	T	L
1	1	2	2	6.47	0.669	0.458	1.001	2.000	2.004	1	1.658	2
2	1	1	3	7.55	0.955	0.769	0.998	1.002	3.007	1	1.042	3
3	1	5	2	8.40	0.397	0.258	1.002	5.003	1.998	1	4.068	2
4	1	5	1	5.39	0.263	0.169	0.999	4.999	1.004	1	4.055	1

Step 2: Solve eq 25 with an iterative method to obtain T.

Step 3: Compute K from eq 24.

Step 4: Compute L from eq 22.

The same simulation examples as in section 2 are used to illustrate the accuracy of the proposed method, the estimated model parameters are given in Table 4, and the Nyquist curves of the processes and the corresponding models are almost the same and thus not shown. The results indicate that the proposed method can also give nearly the exact identification of the process parameters.

4. Conclusions

Systems identification from the relay feedback has recently attracted a lot of interest from the process control community. In this paper, the new methods have been presented for first-order plus dead-time modeling, and extensive simulations have shown that the proposed methods are both accurate and feasible.

Appendix: Proof of Theorem 1

Suppose without loss of generality that the initial output is $y(0) > 0$ and the relay switches to $\mu = \mu_0 - \mu$ at time $t = 0$, the following switches occur at $t = t_1, t_1 + t_2, t_1 + t_2 + t_3, ...$ After a delay L, the response to this switch is shown in Figure 3 and is described by

$$\begin{aligned} y(t) &= y(0)\,e^{-(t-L)/T} + (\mu_0 - \mu)K(1 - e^{-(t-L)/T}) \\ &= (y(0)\,e^{L/T} - \mu_0 K e^{L/T})e^{-t/T} + \mu_0 K - \mu K(1 - e^{-(t-L)/T}) \\ &= y'(0)\,e^{-t/T} + \mu_0 K - \mu K(1 - e^{-(t-L)/T}) \qquad L \le t < t_1 + L \end{aligned}$$

Also, at $t = t_1$, the relay switches from $\mu = \mu_0 - \mu$ to $\mu = \mu + \mu_0$; it follows that

$$y(t_1) = y'(0)\,e^{-t_1/T} - \mu K(1 - e^{-(t_1-L)/T}) + \mu_0 K = -\epsilon$$

$$\Leftrightarrow y'(0)\,e^{-t_1/T} + \mu K e^{-(t_1-L)/T} = \mu K - \mu_0 K - \epsilon \qquad (A1)$$

and

$$y(t) = y'(0)\,e^{-t/T} - \mu K(1 - e^{-(t-L)/T}) + \mu_0 K + 2\mu K(1 - e^{-(t-t_1-L)/T}) \qquad t_1 + L \le t < t_1 + t_2 + L$$

At $t = t_1 + t_2$, the relay switches from $\mu = \mu + \mu_0$ to $\mu = \mu_0 - \mu$; thus

$$y(t_1 + t_2) = y'(0)\,e^{-(t_1+t_2)/T} - \mu K(1 - e^{-(t_1+t_2-L)/T}) + \mu_0 K + 2\mu K(1 - e^{-(t_2-L)/T}) = \epsilon \qquad (A2)$$

$$\Leftrightarrow y'(0)\,e^{-(t_1+t_2)/T} + \mu K e^{-(t_1+t_2-L)/T} - 2\mu K e^{-(t_2-L)/T} = \epsilon - \mu K - \mu_0 K \qquad (A3)$$

Substituting eq A1 in eq A2, we have

$$(\mu K - \mu_0 K - \epsilon)e^{-t_2/T} + (\mu + \mu_0)K - 2\mu K e^{-(t_2-L)/T} = \epsilon$$

and it follows that

$$t_2 = T \ln \frac{2\mu K e^{L/T} + \mu_0 K - \mu K + \epsilon}{\mu K + \mu_0 K - \epsilon}$$

Also, it is clear that

$$y(t) = y'(0)\,e^{-t/T} - \mu K(1 - e^{-(t-L)/T}) + 2\mu K(1 - e^{-(t-t_1-L)/T}) - 2\mu K(1 - e^{-(t-t_1-t_2-L)/T}) + \mu_0 K \qquad t_1 + t_2 + L \le t < t_1 + t_2 + t_3 + L$$

At $t = t_1 + t_2 + t_3$, the relay switches from $\mu = \mu_0 - \mu$ to $\mu = \mu + \mu_0$; then

$$y(t_1{+}t_2{+}t_3) = y'(0)\,e^{-(t_1+t_2+t_3)/T} - \mu K(1 - e^{-(t_1+t_2+t_3-L)/T}) + 2\mu K(1 - e^{-(t_2+t_3-L)/T}) - 2\mu K(1 - e^{-(t_3-L)/T}) + \mu_0 K = -\epsilon$$

Using eq A3 yields

$$(\epsilon - \mu_0 K - \mu K)e^{-t_3/T} + (\mu_0 - \mu)K + 2\mu K e^{-(t_3-L)/T} = -\epsilon$$

and it follows that

$$t_3 = T \ln \frac{2\mu e^{L/T} K - \mu K - \mu_0 K + \epsilon}{\mu K - \mu_0 K - \epsilon}$$

Similarly, one can show that

$$t_2 = t_4 = t_6 = ... = T_{u1}$$

and

$$t_3 = t_5 = t_7 = ... = T_{u2}$$

The down-amplitude and the up-amplitude of the oscillation can be computed from the output $y(t)$ at $t = t_1 + L$ and $t = t_1 + t_2 + L$ respectively as

$$\begin{aligned} a_d &= y(t_1{+}L) \\ &= (\mu_0 - \mu)K(1 - e^{-L/T}) - \epsilon e^{-L/T} \end{aligned}$$

$$\begin{aligned} a_u &= y(t_1{+}t_2{+}L) \\ &= (\mu_0 + \mu)k(1 - e^{-L/T}) + \epsilon e^{-L/T} \end{aligned}$$

which completes the proof.

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Received for review July 17, 1996
Revised manuscript received November 2, 1996
Accepted November 4, 1996[⊗]

IE960412+

⊗ Abstract published in *Advance ACS Abstracts*, December 15, 1996.