A Simple Method for On-Line Identification and Controller Tuning

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The three-mode (PID) controller is still widely used in chemical industries because it is robust and is easy to operate. Many tuning guidelines have been recommended for the PID controllers. These include the Ziegler-Nichols closed-loop cycling method (Zeigler and Nichols, 1942), the Cohen-Coon open-loop reaction curve method (Cohen and Coon, 1952), and many other model-based minimum error integral methods (Lopez et al., 1967). The Ziegler-Nichols continuous cycling procedure is usually criticized for requiring the controlled process to be forced to the level of marginal stability. On the other hand, the advantage of the Ziegler-Nichols tuning formulae is that it need not characterize the process by parametric models, the results of which are known to depend on testing conditions. Many algorithms have been presented to obtain the critical data (ultimate gain and period) under acceptable conditions (e.g., Krishnaswamy et al., 1987).

Recently, Yuwana and Seborg (1982) proposed a simple online algorithm which used the closed-loop response and the Pade approximation of the dead-time element to evaluate the parameters of a first-order process model, then the critical data of the model are used for subsequent controller tuning by Ziegler-Nichols rules. Lee (1989) modified the identification algorithms by matching the dominate poles of the closed-loop model to the poles of observed process transfer function. This modification enables the method to be used for processes with large dead times such as were not comprehended in the original paper. However, the applicability of Lee's modification to underdamped processes has not been demonstrated.

Instead of using a low-order parametric model in process characterization, this article proposes determining the process critical data directly from the closed-loop response during step set-point change under *P* control mode. The modified method is expected to have two advantages over the algorithms of Yuwana-Seborg and Lee:

1) It can provide more robust process critical data under many different testing conditions.

2) It is applicable to underdamped processes and processes with dominant dead times.

Simulation examples are supplied to demonstrate the robustness and applicability of this identification method.

The Method

Consider a single-input/single-output (SISO) feedback control system as shown in Figure 1. With *P* mode controller, it is assumed that the closed-loop system is underdamped if a feedback gain large enough is chosen. The typical response to step set-point change is shown in Figure 2. The response approximates that of an underdamped second-order system with some element of dead time, as in Eq. 1,

$$G_{cl}(s) = \frac{C(s)}{R(s)} = \frac{K\, e^{-ds}}{\tau^2 s^2 + 2\zeta\tau s + 1} \tag{1}$$

Here,

$$K = \frac{c_\infty}{A} \tag{2}$$

$$\zeta = \frac{-\ln(H)}{\sqrt{\pi^2 + \ln^2(H)}} \tag{3}$$

$$\tau = \frac{(t_{m1} - t_{p1})\sqrt{1-\zeta^2}}{\pi} \tag{4}$$

$$d = 2\, t_{p1} - t_{m1} \tag{5}$$

$$c_\infty = \frac{c_{p1}c_{p2} - c_{m1}^2}{c_{p1} + c_{p2} - 2\, c_{m1}} \tag{6}$$

$$H = \frac{1}{3}\left[\frac{c_{p1} - c_\infty}{c_\infty} + \frac{c_\infty - c_{m1}}{c_{p1} - c_\infty} + \frac{c_{p2} - c_\infty}{c_\infty - c_{m1}}\right] \tag{7}$$

In these equations, *A* is the magnitude of input disturbance in set point, and *H* is the overshoot. Note that the new steady state

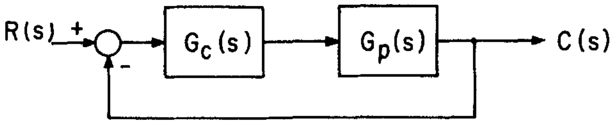

Figure 1. Conventional feedback control system.

(c_∞) after step change in set point can be inferred from the transient response data (Yuwana and Seborg, 1982). The testing period can thus be reduced dramatically.

Instead of estimating an open-loop parametric model from the closed-loop transfer function, the ultimate gain and frequency of the open-loop system, which are critical for subsequent controller settings, are determined directly. The phase cross-over frequency (ω_u) of the closed-loop transfer function can be easily obtained by solving the following nonlinear equation,

$$- d\omega_u - \tan^{-1}\left(\frac{2\zeta\tau\omega_u}{\sqrt{1-\tau^2\omega_u^2}}\right) = -\pi \qquad (8)$$

The corresponding magnitude at this frequency is,

$$|G_{cl}(i\omega_u)| = \frac{K}{\sqrt{(1-\tau^2\omega_u^2)^2 + (2\zeta\tau\omega_u)^2}} \qquad (9)$$

Note that ω_u is also the ultimate frequency of the loop transfer function $G_c(s)G_p(s)$. Thus, the ultimate gain of the open-loop system is,

$$|G_c(i\omega_u)G_p(i\omega_u)| = \frac{|G_{cl}(i\omega_u)|}{\sqrt{1 + 2|G_{cl}(i\omega_u)| + |G_{cl}(i\omega_u)|^2}} \qquad (10)$$

Equation (10) is the reciprocal of gain margin (GM) of the system with proportional controller gain K_c. Thus, the ultimate feedback controller gain can be obtained as,

$$K_{cu} = K_c\, GM \qquad (11)$$

The resulting ultimate frequency and feedback controller gain can then be used directly to determine controller settings according to Ziegler-Nichols rules (Ziegler and Nichols, 1942). For those tuning relations based on some form of parametric process model, such as Cohen and Coon rules and Minimum Error Integral tuning rules, the ultimate data can also be used to determine an equivalent approximation. For a first-order model this is,

$$G_m(s) = \frac{K_m e^{-d_m s}}{\tau_m s + 1} \qquad (12)$$

The parameters of the first-order model which give the resulting ultimate data can be obtained from the following relations,

$$\tau_m = \frac{1}{\omega_u}\sqrt{K_{cu}^2 K_m^2 - 1} \qquad (13)$$

$$d_m = \frac{1}{\omega_u}[\pi - \tan^{-1}(\tau_m\omega_u)] \qquad (14)$$

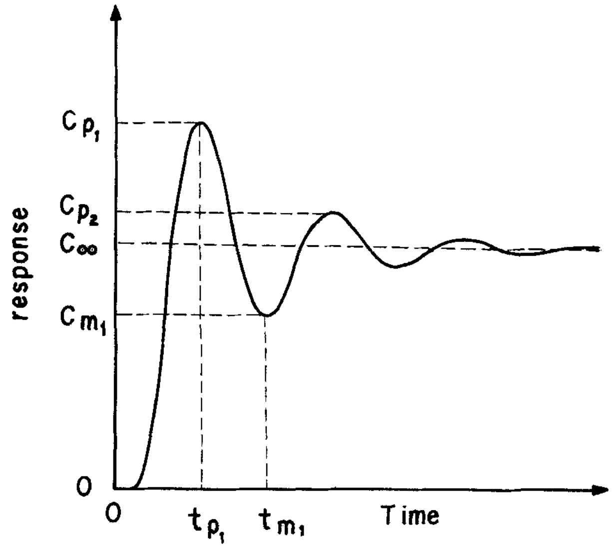

Figure 2. Typical underdamped closed-loop response to a step-setpoint change.

Here, the process gain, K_m, can be determined from the above-mentioned simple closed-loop test (Yuwana and Seborg, 1982),

$$K_m = \frac{c_\infty}{K_c\,(A - c_\infty)} \qquad (15)$$

Simulated Examples

Three simulated examples are supplied to illustrate the proposed identification and controller tuning algorithm. For comparison, the examples are the same as those used by Yuwana and Seborg (YS, 1982) and Lee (1989). The first example uses first-order with dead-time processes which give no inherent structural error according to methods of YS and Lee. The second example illustrates the applicability of the method when used in a process with high-order dynamics and large dead time for which the YS method is inadequate. The third example demonstrates the adequacy of the method when applied to underdamped process.

Example 1

This example considers a first-order process (Lee, 1989)

$$G_p(s) = \frac{e^{-d_p s}}{s+1} \qquad (16)$$

Table 1. Estimates of Model Parameters for Example 1

Process			Yuwana-Seborg				Lee			Proposed		
K_p	τ_p	d_p	K_c	K_m	τ_m	d_m	K_m	τ_m	d_m	K_m	τ_m	d_m
1	1	0.5	1.5	1	1.02	0.507	1	1.01	0.516	1	1.08	0.480
			2.0	1	1.03	0.554	1	0.98	0.520	1	1.05	0.490
		1	1.0	1	1.15	0.988	1	0.99	1.01	1	1.10	0.971
			1.5	1	1.27	1.14	1	1.03	1.05	1	1.04	0.993
		2	0.5	1	1.46	1.67	1	0.98	2.07	1	1.13	1.922
			1.0	1	1.59	2.09	1	1.04	2.03	1	0.99	1.991

Table 2. Estimates of Model Parameters for Example 2

Method	K_c	Model			Ultimate Data	
		K_m	τ_m	d_m	P_u	K_{cu}
Yuwana-Seborg	1.0	1	3.92	4.69	14.1	2.01
	0.25	1	3.57	3.19	10.1	2.44
Lee	1.0	1	2.78	4.74	13.4	1.64
	0.25	1	2.60	4.87	13.5	1.57
Proposed	1.0	1	3.01	4.44	12.9	1.77
	0.25	1	2.95	4.48	12.9	1.74
Ziegler-Nichols		1	2.89*	4.49*	12.9	1.73

*Calculated from ultimate data

Table 1 gives estimates for tests of two feedback gains and three different dead times. The results show that the proposed method can provide consistent estimates subject even to various degrees of process lag and testing condition.

Example 2

The considered process dynamics is (Yuwana and Seborg, 1982; Lee, 1989),

$$G_p(s) = \frac{e^{-3s}}{(s+1)^2(2s+1)} \tag{17}$$

Table 2 reveals testing conditions and the estimates obtained, including results based on methods of YS and Lee. These results also show that the present method can provide critical data and PID settings which are more consistent with the Ziegler-Nichols closed-loop cycling method.

Example 3

The underdamped process of Yuwana and Seborg (1982) is considered,

$$G_p(s) = \frac{e^{-s}}{9s^2 + 2.4s + 1} \tag{18}$$

The comparison of results of YS, Lee and present methods, Table 3, demonstrates the robustness of proposed process characterization method.

Table 3. Estimates of Model Parameters for Example 3

Method	K_c	Model			Ultimate Data	
		K_m	τ_m	d_m	P_u	K_{cu}
Yuwana-Seborg	2	1	4.69	4.20	13.2	2.45
	1	1	3.89	4.90	14.6	1.95
Lee	2	1	3.65	3.62	11.2	2.24
	1	1	2.67	4.82	13.5	1.57
Proposed	2	1	3.96	3.35	10.7	2.51
	1	1	4.21	3.27	10.5	2.66
Ziegler-Nichols		1	3.98*	3.36*	10.7	2.54

*Calculated from ultimate data

Notation

A = magnitude of set-point change
$c, C(s)$ = controlled variable and its Laplace transform
c_{m1}, c_{p1}, c_{p2} = first minimum, first and second peaks of c
c_∞ = steady state of c
d, d_m, d_p = dead times of closed-loop response, model and process
$G_c(s), G_{cl}(s)$ = controller and closed-loop transfer functions
$G_m(s), G_p(s)$ = model and process transfer functions
GM = gain margin
H = overshoot
K, K_c, K_{cu}, K_m = closed-loop gain, controller gain, ultimate controller gain and model gain
P_u = ultimate period
$R(s)$ = Laplace transform of set point
t_{m1}, t_{p1} = time of first minimum and first peak of closed-loop response
ζ = damping factor
τ, τ_m = process and model time constants
ω_u = ultimate frequency

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