Tuning PID Controllers for Processes with Large Time Delay

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Abstract

A calculation method of PID controller tunings for the large time delay process is presented in this study. Optimum PID controller tuning data based on the first-order-plus-time-delay process models and minimum IAE criteria were obtained via the MATLAB and the SIMULINK software tools. These data were then drawn into charts and correlated into sample equations by a nonlinear least-squares method. Thus, PID controller tunings based on the models can easily be obtained by the charts or by the correlated equations. Simulation results have demonstrated that the proposed tuning method can provide better performance and robustness for processes with large time delay.

1. Introduction

Although there are many complicated control theories have been proposed for process control in the recent years. But the PID controller is still used in most processes. The major reason behind it is its robustness and economic reasons. In the process industries like papermaking procedure, fiber pushes and reels procedure, plug-flow reactor etc., the occurrence of large "time delay" or "transportation lag" is quite common. The difficulties caused by time delay in control systems have been recognized for a long time. But there are only few papers discussing about the PID controller that used in large time delay systems. Papers like Smith（1972）, Hang, et al.,（1980）proposed that PID controller is not suitable for the large time delay systems. For the sake of this reason, this paper discusses the PID controller tuning techniques for the processes with large time delay. It also discusses how to get the optimum controller tunings by simple calculations.

Based on most of the papers discussing about PID control, the controller tuning procedure is classified as follows：

(1) to get the process mathematic model.
(2) to decide the controller tunings according to the model's parameters.

But most of the real models are very complicated and cannot be precisely described. So an approximate model was proposed for control. In a chemical process, we usually use a first-order-plus-time-delay model (FOPTD) to approximate the process.

For studying PID controller tuning used in a large time delay system, we used a closed loop control system based on FOPTD model, and the integral of the absolute error (IAE) is used as control performance criteria in set-point step change and disturbance step change to search the optimum PID controller tunings. After that, these tuning data are curve fitted by nonlinear least-square method (LSQ) to get the PID controller tuning equations. With the process FOPTD model parameters and the proposed tuning equations, we can get the optimized PID controller tunings for future use. The corresponding control performance of the Smith Predictor （Smith, 1957）, IMC_PID（Morari and Zafiriou, 1989）and Zhong-Li（2002） tuning methods are used as references for comparison. It is shown that the method we proposed yields improved control performance and robustness over the other methods being used for processes with large time delay.

2. Research Method

In this study we use the reset-feedback PID (RF_PID) controller based on FOPTD process model and MATLAB and SIMULINK computer software tools are used to perform the controller tuning and system simulation. We use MATLAB Optimization tool and the IAE criteria as the control performance index to search the optimized controller tunings in two different conditions – set-point step change and disturbance step change. Usually the integral item of PID control algorithm will be saturated by long time integration error. So we use RF_PID to prevent this saturation (or called "reset windup") phenomenon. And the high and low limits of the RF_PID output are used to match the real industrial controller action. There are some papers that discussed RF_PID optimized controller tuning - Huang, et al.（1996）, Huang, et al.（1997）and Huang et al.（1999）.

In order to describe the process model and controller, we normalize the process model and controller transfer function as follows：

The original process model of FOPTD is

$$G_p(s) = \frac{K_p e^{-\theta s}}{\tau s + 1} \qquad (1)$$

We define a dimensionless Laplace Transform variable $\hat{s} = s\tau$ ，then the process model will be revised as：

$$G_p(\hat{s}) = \frac{K_p e^{-\hat{\theta}\hat{s}}}{\hat{s} + 1} \qquad (2)$$

Among them, $\hat{\theta} = \theta / \tau$ is the dimensionless delay time of the process. The control algorithm used in this study is the RF_PID. Fig. 1 shows the dimensionless block diagram of the RF_PID control system.

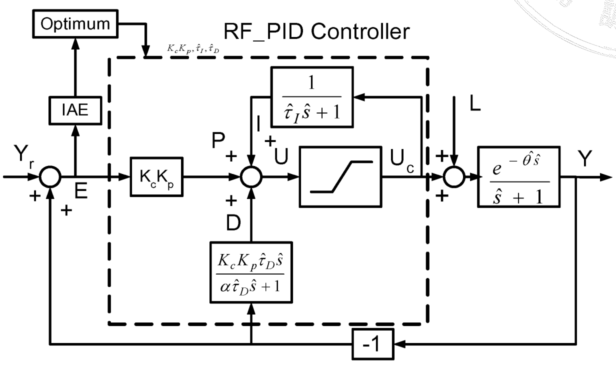

Fig 1. Dimensionless block diagram of the RF_PID control system

Among them,

$\hat{\tau}_I = \tau_I / \tau$ ， $\hat{\tau}_D = \tau_D / \tau$

τ_I is the integral time of the controller

$\hat{\tau}_I$ is the dimensionless integral time

τ_D is the derivative time of the controller

$\hat{\tau}_D$ is the dimensionless derivative time

τ is the time constant of the process

Because the process gain（ K_p ）will directly influence the controller proportional gain （ K_c ）, we combine the K_c and K_p to an overall gain K_cK_p for controller tuning.

The optimized controller tuning is done using MATLAB and SIMULINK software tools. RF_PID model and FOPTD process model are set in the SIMULINK and the control performance index

$$IAE = \int_0^t \left| E(t) \right| dt \qquad (3)$$

is used for optimized controller parameter tuning. Use random searching and MATLAB's Preconditioned Conjugate Gradients (PCG) searching method to find the optimized K_cK_p 、 τ_I / τ and τ_D / τ to get the minimum IAE. Then we change the different θ / τ (0.5 ～100) step by step and do the same searching procedure to get the optimized controller tunings and then regress to two different equations as follows：

$$y = b_0 + b_1 x^{-1} + b_2 x^{-2} \qquad (4)$$

$$y = b_0 + b_1 x + b_2 x^2 \qquad (5)$$

Among them , equation （4） is used for K_cK_p and equation （5）is used for τ_I / τ and τ_D / τ .

Fig. 2- Fig. 4 show the relationships of K_cK_p 、 τ_I / τ and τ_D / τ to the θ / τ for the set-point change, respectively. Fig. 5 to Fig. 7 shows the relationships of K_cK_p 、 τ_I / τ and τ_D / τ to the θ / τ for the disturbance step change, respectively.

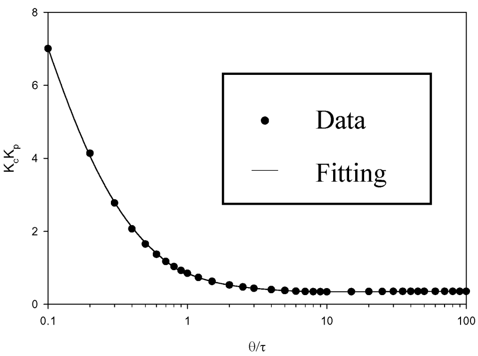

Fig 2. K_cK_p v.s. θ / τ relationship for set-point step change

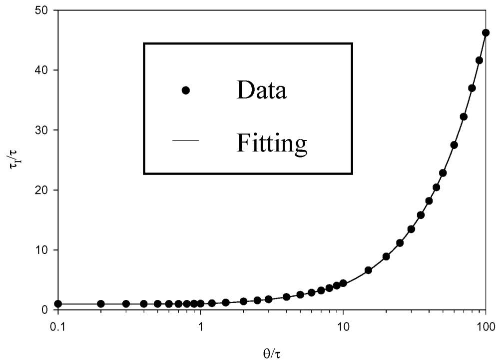

Fig 3. τ_I / τ *v.s.* θ / τ *relationship for set-point step change*

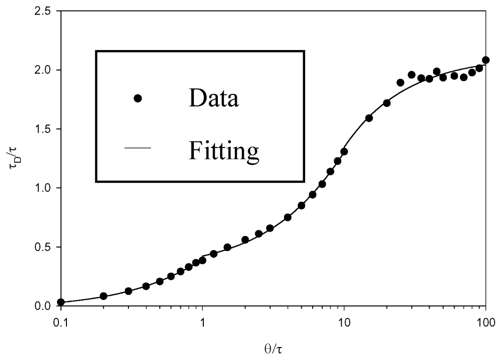

Fig 4. τ_D / τ *v.s.* θ / τ *relationship for set-point step change*

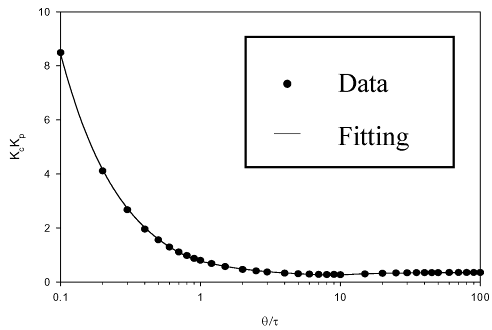

Fig 5. $K_c K_p$ *v.s.* θ / τ *relationship for disturbance step change*

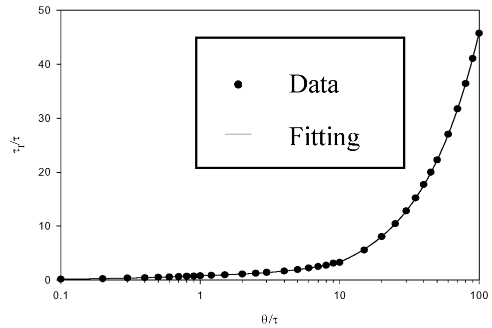

Fig 6. τ_I / τ *v.s.* θ / τ *relationship for disturbance step change*

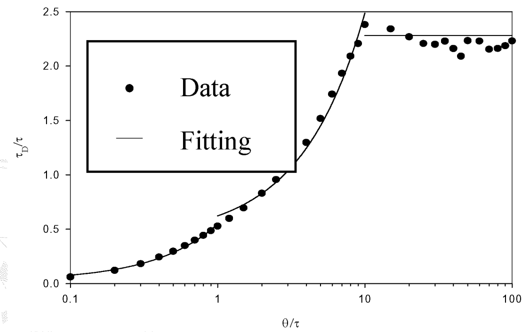

Fig 7. τ_D / τ *v.s.* θ / τ *relationship for disturbance step change*

3. Conclusions

In order to verify the benefit of the PID controller tuning in this study, we compared with the other tuning methods such as Ziegler and Nichols method (Ziegler and Nichols,1942, abbreviated as ZN) , Ciancone-Marlin method（Marlin, 1995, abbreviate as CM）and IMC_PID method(Morari and Zafiriou, 1989, abbreviated as IMC). Based on the same FOPTD system model, four different PID controller tunings were used by computer simulation in set-point step change and disturbance step change to assess the control performance and the robustness separately. The RF_PID controller shown in Fig 1 was used in this paper and ZN method. Parallel PID controller shown in equation (6) was used for CM method.

$$G_c(s) = K_c(1 + \frac{1}{\tau_I s} + \frac{\tau_D s}{\alpha \tau_D s + 1}) \qquad (6)$$

And equation (7) shows the control algorithm for IMC_PID method.

$$G_c(s) = K_c(1 + \frac{1}{\tau_I s} + \tau_D s)(\frac{1}{\tau_F s + 1}) \quad (7)$$

Table 1 shows 4 sets of controller tunings and the control performance for 0.2 set-point step change in different θ/τ. From the IAE values shown in table 1 we can see that the method proposed in this study turns out to be a little bit worse in the region $\theta/\tau \leq 1$, but it is the best for the other region. The ZN method starts to oscillate when $\theta/\tau \geq 5$, and diverge in $\theta/\tau \geq 10$, so those data are omitted in the table. For the CM method, it can only be used for $\theta/\tau \leq 10$, although the performance is good but it is a little bit worse than the method that we proposed. Similarly Table 2 shows the controller tunings and the control performance for 0.2 disturbance step change in different θ/τ. It shows the ZN method has the minimum M_p% for $\theta/\tau \leq 1$, and for the other conditions the control performance looks like the set-point step change response.

The Process Model Error was used for the robustness study of the controllers. The FOPTD process model was used and the model parameters θ/τ was changed by a fixed percent of errors (+20%、+30% and +40%) and used the original controller tunings to see the control performance. And the IAE value was still used for the controller robustness check. Table 3 shows the IAE values for 0.2 disturbance step change in different θ/τ with model error. From the table we can see that CM method has the better robustness in $\theta/\tau \leq 10$. But it cannot be used in $\theta/\tau \geq 10$. And the way we proposed has the better robustness in $\theta/\tau \geq 5$ for the disturbance step change.

Next we focused on the control performance and the robustness of large time delay process. From this study we know that both of the methods that this study proposed and the IMC method had better control performance and robustness for large time delay processes. So we used these two methods to compare with the Smith Predictor (Smith, 1957) and the Zhong-Li (2002) method that were proved in other papers which were suitable for large time delay systems. Based on FOPTD process model, 0.2 disturbance step change and three different θ/τ (50、80 and 100) were used for the control performance simulation. Table 4 shows the control performance data. From that table, we know that both of the Smith Predictor method and Zhong-Li method had the best IAE values. And the method we proposed is better than IMC method. Table 5 shows the robustness of those four methods is expressed in terms of three different process model errors. It shows that the Smith Predictor method and Zhong-Li method had the best IAE values in +5% model error. But both of them were diverged in +10% model error, and uncontrollable in +20% model error.

Fig. 8 shows a comparison of 0.2 disturbance step change response with Zhong-Li, IMC_PID and the method we proposed for the process which has θ/τ = 80 and +5% model error. From that we can see the overshoot of Zhong-Li is too big.

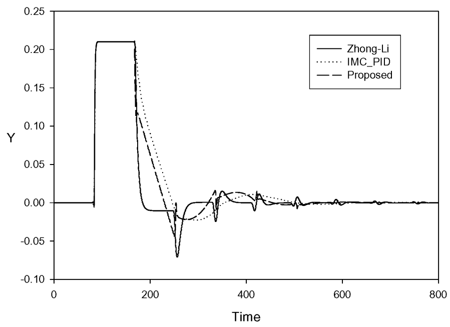

Fig 8. 0.2 disturbance step change response of Zhong-Li, IMC_PID and the method we proposed used in the process which has θ/τ = 80 and +5% model error

In this study, the optimized PID controller tunings can be obtained by simple calculations. The tuning method we proposed can get better control performance and robustness than ZN, CM and IMC_PID method in the small delay time FOPTD process. Although Smith Predictor and Zhong-Li methods can get the best control performance in large time delay processes, from table 5 we can see that the robustness of Smith Predictor is only good for model error less than +5%. And it is +10% for Zhong-Li method. But the method proposed in this study can get the best robustness in the large time delay process.

References

[1] Hang, C. C.; Tan, C. H.; Chan, W. P. A performance study of control systems with dead time. *IEEE Tran. Ind. Electron. Contr. Instrum*. **1980**, *27* (3), 234-241.

[2] Huang, C.-T.; Chou, C.-J.; Wang, J.-L. Tuning of PID controllers based on the second-order model by calculation. *J. Chin. Inst. Chem. Eng.* **1996**, *27*, 107-120.

[3] Huang, C.-T.; Chou, C.-J.; Chen, L.-Z. An Automatic PID controller tuning method by frequency response techniques. *Can. J. Chem. Eng.* **1997**, *75*, 596-604.

[4] Huang, C.-T.; Lin, M.-Y.; Huang, M.-C. Tuning PID controllers for processes with inverse response using artificial neural networks. *J. Chin. Inst. Chem. Eng.* **1999**, *30*, 223-232.

[5] Luyben, W. L. Effect of derivative algorithm and tuning selection on the PID control of dead-time processes. *Ind. Eng. Chem. Res.* **2001**, *40*, 3605-3611.

[6] Marlin, T. E. *Process Control: Designing Processes and Control Systems for Dynamic Performance*; McGraw-Hill, Inc., 1995; pp 299-309.

[7] Matlab, *MATLAB: The Language of Technical Computing*, Version 6.0, The MathWorks, Inc., 2001.

[8] Meyer, C.; Seborg, D. E.; Wood, R. K. A comparison of the Smith predictor and conventional feedback control. *Chem. Eng. Sci.* **1976**, *31*, 775-778.

[9] Morari, M.; Zafiriou, E. *Robust Process Control*;

Prentice Hall: New York, 1989.

[10] Shinskey, F. G. *Feedback Controllers for the Process Industries*; McGraw-Hill Inc., 1994; pp 114-116.

[11] Simulink, *SIMULINK: The Language of Technical Computing*, Version 3.0, The MathWorks, Inc., 2001.

[12] Smith, C. L. *Digital Computer Process Control*; Intext Educational Publishers; Scranton, Pa. 1972.

[13] Smith, O. Closer control of loops with dead time, *Chem. Eng. Prog.* **1957**, *53* （5）, 217-219.

[14] Zhong, Q.-C.; Li, H.-X. 2 Degree of freedom proportional integral derivative type controller incorporating the Smith principle for process with dead time. *Ind. Eng. Chem. Res.* **2002**, *41*, 2448-2454.

[15] Zhuang, M.; Atherton, D. P. Automatic tuning of optimum PID controllers. *IEE Proceedings-D.* **1993**, *140*, 216-224.

[16] Ziegler, J. G.; Nichols, N. B. Optimum setting for automatic controllers. *Trans. ASEM* **1942**, *64*, 759-768.

Table 1. PID controller tunings and the control performance for 0.2 set-point step change in different θ/τ

θ/τ	Method	Kc	τI	τD	IAE	Mp%
0.5	Ziegler-Nichol	2.2394	0.8553	0.2138	0.217	34.9%
	Ciancone-Marlin	1.0000	1.2750	0.0600	0.255	0.0%
	IMC(τF=0.0714)	1.7857	1.2500	0.2000	0.154	7.92%
	Proposed	1.6600	0.9825	0.2000	0.170	7.1%
1	Ziegler-Nichol	1.3305	1.5486	0.3871	0.44	22.3%
	Ciancone-Marlin	0.8000	1.3400	0.1900	0.335	0.0%
	IMC(τF=0.1)	1.2000	1.5000	0.3333	0.310	15.1%
	Proposed	0.9600	1.0300	0.4000	0.352	14.6%
5	Ziegler-Nichol	0.6659	5.9194	1.4798	2.702	17.9%
	Ciancone-Marlin	0.4000	2.8800	1.5000	1.513	4.6%
	IMC(τF=0.5)	0.5600	3.5000	0.7100	1.554	15.2%
	Proposed	0.3820	2.5400	0.8400	1.536	3.14%
10	Ciancone-Marlin	0.3200	5.5000	3.3000	4.108	20.6%
	IMC(τF=1.0)	0.4800	6.0000	0.8300	3.104	15.2%
	Proposed	0.3441	4.2500	1.3420	2.926	7.59%
25	IMC(τF=2.5)	0.4320	13.500	0.9259	7.758	15.1%
	Proposed	0.3527	11.300	1.8088	6.994	10.2%
50	IMC(τF=5.0)	0.4160	26.000	0.9615	15.51	15.1%
	Proposed	0.3526	23.050	1.9644	13.82	11.3%
75	IMC(τF=7.5)	0.4107	38.500	0.9740	23.28	15.1%
	Proposed	0.3574	34.800	2.0163	20.64	11.7%
100	IMC(τF=10.0)	0.4080	51.000	0.9804	31.02	15.1%
	Proposed	0.3580	46.550	2.0422	27.46	11.9%

Table 2. PID controller tunings and the control performance for 0.2 disturbance step change in different θ/τ

θ/τ	Method	Kc	τI	τD	IAE	Mp%
0.5	Ziegler-Nichol	2.2400	0.8550	0.2140	0.080	40.6%
	Ciancone-Marlin	1.5000	1.0000	0.1500	0.134	44.3%
	IMC(τF=0.0714)	1.7857	1.2500	0.2000	0.140	44.6%
	Proposed	1.5900	0.5025	0.2800	0.071	41.1%
1	Ziegler-Nichol	1.3305	1.5486	0.3871	0.252	63.8%
	Ciancone-Marlin	0.9000	1.3000	0.1600	0.289	66.1%
	IMC(τF=0.1)	1.2000	1.5000	0.3333	0.250	65.3%
	Proposed	0.7300	0.7600	0.5400	0.212	64.3%
5	Ziegler-Nichol	0.6600	5.9000	1.4800	2.620	100%
	Ciancone-Marlin	0.4000	3.0000	1.2000	1.505	100%
	IMC(τF=0.5)	0.5600	3.5000	0.7100	1.507	100%
	Proposed	0.3060	1.9400	1.4600	1.322	100%
10	Ciancone-Marlin	0.3000	5.0000	2.7000	3.384	100%
	IMC(τF=1.0)	0.4800	6.0000	0.8300	3.080	100%
	Proposed	0.2640	3.3100	2.2800	2.610	100%
25	IMC(τF=2.5)	0.4320	13.500	0.9259	7.748	100%
	Proposed	0.3324	10.360	2.2800	6.674	100%
50	IMC(τF=5.0)	0.4160	26.000	0.9615	15.51	100%
	Proposed	0.3480	22.110	2.2800	13.51	100%
75	IMC(τF=7.5)	0.4107	38.500	0.9740	23.26	100%
	Proposed	0.3524	33.860	2.2800	20.34	100%
100	IMC(τF=10.0)	0.4080	51.000	0.9804	31.02	100%
	Proposed	0.3545	45.610	2.2800	27.16	100%

Table 3 shows the IAE values for 0.2 disturbance step change in different θ/τ with model error

Model error	method \ θ/τ	0.5	1	5	10	25	50	75	100
+20%	ZN	0.167	0.560	5.786	divg	divg	divg	divg	divg
	CM	0.140	0.406	2.040	4.068	na	na	na	na
	IMC_PID	0.140	0.353	3.378	6.950	17.26	34.30	51.34	68.36
	Proposed	0.153	0.367	2.598	5.022	12.90	25.88	38.84	51.80
+30%	ZN	0.298	0.991	9.866	divg	divg	divg	divg	divg
	CM	0.159	0.547	2.786	5.064	na	na	na	na
	IMC_PID	0.148	0.502	6.074	12.60	30.96	61.18	91.36	121.5
	Proposed	0.276	0.573	4.272	8.150	21.04	41.66	62.22	82.80
+40%	ZN	0.558	1.844	17.46	divg	divg	divg	divg	divg
	CM	0.192	0.778	4.084	6.660	na	na	na	na
	IMC_PID	0.181	0.768	12.38	26.30	64.98	128.0	190.8	253.4
	Proposed	0.539	0.987	8.154	15.43	40.02	77.68	115.0	152.5

Table 4. Controller tunings and the control performance for 0.2 disturbance step change in different θ/τ

θ/τ	Method	K_c	τ_I	τ_D	IAE	Mp%
50	Proposed	0.3480	22.110	2.2800	13.51	100%
	IMC(τ_F=5)	0.4160	26.000	0.9615	15.51	100%
	Smith predictor	1.0019	5.0000	----	11.00	100%
	Zhong-Li	λ=0.3	α=5	----	11.00	100%
80	Proposed	0.3529	36.210	2.2800	21.70	100%
	IMC(τ_F=8)	0.4100	41.000	0.9756	24.82	100%
	Smith predictor	1.0008	5.0000	----	17.00	100%
	Zhong-Li	λ=0.3	α=5	----	17.00	100%
100	Proposed	0.3545	45.610	2.2800	27.16	100%
	IMC(τ_F=10)	0.4080	51.000	0.9804	31.02	100%
	Smith predictor	1.0005	5.0000	----	21.00	100%
	Zhong-Li	λ=0.3	α=5	----	21.00	100%

Table 5. IAE value for 0.2 disturbance step change in different θ / τ and model error

Model error	θ / τ method	50	80	100
+5%	Proposed	15.32	24.62	30.82
	IMC_PID	18.27	29.22	36.52
	Smith	13.50	divg	divg
	Zhong-Li	13.19	21.18	27.18
+10%	Proposed	17.88	28.68	35.90
	IMC_PID	21.98	35.14	43.90
	Smith	divg	divg	divg
	Zhong-Li	19.65	divg	divg
+20%	Proposed	21.60	41.44	43.08
	IMC_PID	24.36	54.74	57.00
	Smith	divg	divg	divg
	Zhong-Li	divg	divg	divg