2000-01-01

A summary of PI and PID controller tuning rules for processes with time delay. Part 2: PID controller tuning rules

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Preprints of Proceedings of PID '00: IFAC Workshop on Digital Control, Terrassa, Spain, April 4-7, 2000, pp. 242-247.

A SUMMARY OF PI AND PID CONTROLLER TUNING RULES FOR PROCESSES WITH TIME DELAY. PART 2: PID CONTROLLER TUNING RULES.

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Abstract: The ability of proportional integral (PI) and proportional integral derivative (PID) controllers to compensate many practical industrial processes has led to their wide acceptance in industrial applications. The requirement to choose either two or three controller parameters is perhaps most easily done using tuning rules. A summary of tuning rules for the PID control of single input, single output (SISO) processes with time delay is provided in this paper.

Keywords: PID controllers, rules, time delay.

1. INTRODUCTION

This paper summarises some of the most directly applicable tuning rules for PID controllers that have been developed to compensate SISO processes with time delay, modeled in either first order lag plus delay (FOLPD) form or integral plus delay (IPD) form. It is a companion paper to that of O'Dwyer (2000a) and the two papers have similar structure. A comprehensive summary of PID controller tuning rules for processes with time delay is available from the author (O'Dwyer, 2000b).

The ideal continuous time domain PID controller for a SISO process is expressed in the Laplace domain as follows:

$$G_c(s) = K_c(1 + \frac{1}{T_i s} + T_d s) \qquad (1)$$

with K_c = proportional gain, T_i = integral time and T_d = derivative time. Many tuning rules have been defined for this PID structure. Tuning rules have also been defined for a range of alternative PID controller structures. One example of such structure is the 'classical' form of the PID controller:

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s}\right)\left(\frac{1 + T_d s}{1 + T_d s/N}\right) \qquad (2)$$

Tuning rules for these and other such PID controller structures are explicitly indicated; in all cases, numerical data is quoted to a maximum of two places of decimals. Most authors recommend application of the tuning rules for a range of model time delay to time constant (τ_m/T_m) between 0.1 and 1.0; this data, together with other relevant comments, is provided by O'Dwyer (2000b). Results from the analytical calculation of robustness criteria associated with a number of tuning rules, for a range of τ_m/T_m values, are presented in Section 4. A list of symbols and abbreviations used in the paper is provided in the appendix.

2. PID TUNING RULES – $\frac{K_m e^{-s\tau_m}}{1 + sT_m}$ MODEL

Rule	K_c	T_i	T_d
Ideal controller – $G_c(s) = K_c(1 + \frac{1}{T_i s} + T_d s)$			
Process reaction			
Ziegler and Nichols (1942)	$\frac{aT_m}{K_m\tau_m}$, a = [1.2,2]	$2\tau_m$	$0.5\tau_m$

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Rule	K_c	T_i	T_d
Astrom and Hagglund (1995)	$\frac{0.94T_m}{K_m\tau_m}$	$2\tau_m$	$0.5\tau_m$
Chien *et al.* (1952) –regulator – 0% o.s.	$\frac{0.95T_m}{K_m\tau_m}$	$2.38\tau_m$	$0.42\tau_m$
Chien *et al.* (1952) – regulator – 20% o.s.	$\frac{1.2T_m}{K_m\tau_m}$	$2\tau_m$	$0.42\tau_m$
Chien *et al.* (1952) – servo – 0% o.s.	$\frac{0.6T_m}{K_m\tau_m}$	T_m	$0.5\tau_m$
Chien *et al.* (1952) – servo – 20% o.s.	$\frac{0.95T_m}{K_m\tau_m}$	$1.36T_m$	$0.47\tau_m$
Cohen and Coon (1953)	[1] $K_c^{(1)}$	$T_i^{(1)}$	$T_d^{(1)}$
Regulator			
Murrill (1967) – min. IAE	$\frac{1.44}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.92}$	$\frac{T_m}{0.88}\left(\frac{T_m}{\tau_m}\right)^{0.75}$	$0.48T_m\left(\frac{\tau_m}{T_m}\right)^{1.14}$
Murrill (1967) – min. ISE	$\frac{1.50}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.95}$	$\frac{T_m}{1.10}\left(\frac{T_m}{\tau_m}\right)^{0.77}$	$0.56T_m\left(\frac{\tau_m}{T_m}\right)^{1.01}$
Zhuang and Atherton [2] (1993) – min. ISE	$\frac{1.47}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.97}$	$\frac{T_m}{1.12}\left(\frac{T_m}{\tau_m}\right)^{0.75}$	$0.55T_m\left(\frac{\tau_m}{T_m}\right)^{0.95}$
	$\frac{1.52}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.74}$	$\frac{T_m}{1.13}\left(\frac{T_m}{\tau_m}\right)^{0.64}$	$0.55T_m\left(\frac{\tau_m}{T_m}\right)^{0.85}$
Murrill (1967) – min. ITAE	$\frac{1.36}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.95}$	$\frac{T_m}{0.84}\left(\frac{T_m}{\tau_m}\right)^{0.74}$	$0.38T_m\left(\frac{\tau_m}{T_m}\right)^{1.00}$
Zhuang and Atherton [2] (1993) – min. ISTSE	$\frac{1.47}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.97}$	$\frac{T_m}{0.94}\left(\frac{T_m}{\tau_m}\right)^{0.73}$	$0.44T_m\left(\frac{\tau_m}{T_m}\right)^{0.94}$
	$\frac{1.52}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.73}$	$\frac{T_m}{0.96}\left(\frac{T_m}{\tau_m}\right)^{0.60}$	$0.44T_m\left(\frac{\tau_m}{T_m}\right)^{0.85}$
Zhuang and Atherton [2] (1993) – min. ISTES	$\frac{1.53}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.96}$	$\frac{T_m}{0.97}\left(\frac{T_m}{\tau_m}\right)^{0.75}$	$0.41T_m\left(\frac{\tau_m}{T_m}\right)^{0.93}$
	$\frac{1.59}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.71}$	$\frac{T_m}{0.96}\left(\frac{T_m}{\tau_m}\right)^{0.60}$	$0.41T_m\left(\frac{\tau_m}{T_m}\right)^{0.85}$
Servo			
Rovira *et al*. (1969) – min. IAE	$\frac{1.09}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.87}$	$\frac{T_m}{0.74-0.13\frac{\tau_m}{T_m}}$	$0.35T_m\left(\frac{\tau_m}{T_m}\right)^{0.91}$
Zhuang and Atherton [2] (1993) – min. ISE	$\frac{1.05}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.90}$	$\frac{T_m}{1.20-0.37\frac{\tau_m}{T_m}}$	$0.49T_m\left(\frac{\tau_m}{T_m}\right)^{0.89}$
	$\frac{1.15}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.57}$	$\frac{T_m}{1.05-0.22\frac{\tau_m}{T_m}}$	$0.49T_m\left(\frac{\tau_m}{T_m}\right)^{0.71}$
Rovira *et al.* (1969) – min. ITAE	$\frac{0.97}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.85}$	$\frac{T_m}{0.80-0.15\frac{\tau_m}{T_m}}$	$0.31T_m\left(\frac{\tau_m}{T_m}\right)^{0.93}$
Zhuang and Atherton [2] (1969) – min. ISTSE	$\frac{1.04}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.90}$	$\frac{T_m}{0.99-0.24\frac{\tau_m}{T_m}}$	$0.39T_m\left(\frac{\tau_m}{T_m}\right)^{0.91}$
	$\frac{1.14}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.58}$	$\frac{T_m}{0.92-0.17\frac{\tau_m}{T_m}}$	$0.38T_m\left(\frac{\tau_m}{T_m}\right)^{0.84}$
Zhuang and Atherton [2] (1969) – min. ISTES	$\frac{0.97}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.90}$	$\frac{T_m}{0.98-0.25\frac{\tau_m}{T_m}}$	$0.32T_m\left(\frac{\tau_m}{T_m}\right)^{0.89}$
	$\frac{1.06}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.58}$	$\frac{T_m}{0.89-0.17\frac{\tau_m}{T_m}}$	$0.32T_m\left(\frac{\tau_m}{T_m}\right)^{0.83}$
Direct synthesis			
Smith and Corripio (1985) – regulator	$\frac{T_m}{K_m\tau_m}$	T_m	$0.5\tau_m$
Smith and Corripio (1985) – servo	$\frac{5T_m}{6K_m\tau_m}$	T_m	$0.5\tau_m$
Smith and Corripio (1985) – servo – 5% o.s.	$\frac{T_m}{2K_m\tau_m}$	T_m	$0.5\tau_m$
Abbas (1997)	$K_c^{(2)}$ [3]	$T_m+0.5\tau_m$	$\frac{T_m\tau_m}{2T_m+\tau_m}$

[1] $K_c^{(1)}=\frac{1}{K_m}\left(1.35\frac{T_m}{\tau_m}+0.25\right)$, $T_i^{(1)}=T_m\left(\frac{2.5\frac{\tau_m}{T_m}+0.46\left(\frac{\tau_m}{T_m}\right)^2}{1+0.61\frac{\tau_m}{T_m}}\right)$

$T_d^{(1)}=0.37\tau_m/(1+0.2[\tau_m/T_m])$

[2] For $0.1\le\frac{\tau_m}{T_m}\le 1$ and $1.1\le\frac{\tau_m}{T_m}\le 2$, respectively

[3] $K_c^{(2)}=\frac{0.18+0.35\left(\frac{\tau_m}{T_m}\right)^{-1.00}}{K_m(0.53-0.36V^{0.71})}$,

$0\le V\le 0.2$, V = overshoot

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Rule	K_c	T_i	T_d
Robust			
Fruehauf *et al.* (1993)	$\frac{5T_m}{9\tau_m K_m}$	$5\tau_m$	$\le 0.5\tau_m$
	$\frac{T_m}{2\tau_m K_m}$	T_m	$\le 0.5\tau_m$
Ultimate cycle			
Zhuang and Atherton (1993) – min. ISTSE	$0.51K_u$	$\frac{0.05T_u}{(3.30K_m K_u + 1)}$ servo	$0.13T_u$
	$K_c^{(3)}$ [4]	$T_i^{(3)}$ regulator	$0.14T_u$
Classical controller – $G_c(s) = K_c\left(1 + \frac{1}{T_i s}\right)\left(\frac{1 + T_d s}{1 + T_d s/N}\right)$			
Process reaction			
Hang *et al.* (1993)	$\frac{0.83T_m}{K_m \tau_m}$	$1.5\tau_m$	$0.25\tau_m$, N = 10
Witt and Waggoner (1990)	$\frac{aT_m}{K_m \tau_m}$, a = [0.6,1]	τ_m	τ_m N = [10,20]
Regulator			
Kaya and Scheib (1988) – min. IAE	$\frac{0.98}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.76}$	$\frac{T_m}{0.91}\left(\frac{T_m}{\tau_m}\right)^{1.05}$	$0.60T_m\left(\frac{\tau_m}{T_m}\right)^{0.90}$ N = 10
Kaya and Scheib (1988) – min. IAE	$\frac{1.12}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.90}$	$\frac{T_m}{0.80}\left(\frac{T_m}{\tau_m}\right)^{0.95}$	$0.55T_m\left(\frac{\tau_m}{T_m}\right)^{0.88}$ N = 10
Kaya and Scheib (1988) – min. ITAE	$\frac{0.78}{K_m}\left(\frac{T_m}{\tau_m}\right)^{1.06}$	$\frac{T_m}{1.14}\left(\frac{T_m}{\tau_m}\right)^{0.71}$	$0.57T_m\left(\frac{\tau_m}{T_m}\right)^{1.04}$ N = 10
Servo			
Kaya and Scheib (1988) – min. IAE	$\frac{0.65}{K_m}\left(\frac{T_m}{\tau_m}\right)^{1.04}$	$\frac{T_m}{0.99 + 0.10\frac{\tau_m}{T_m}}$	$0.51T_m\left(\frac{\tau_m}{T_m}\right)^{1.08}$ N = 10
Kaya and Scheib (1988) – min. ISE	$\frac{0.72}{K_m}\left(\frac{T_m}{\tau_m}\right)^{1.03}$	$\frac{T_m}{1.13 - 0.18\frac{\tau_m}{T_m}}$	$0.55T_m\left(\frac{\tau_m}{T_m}\right)^{0.86}$ N = 10
Kaya and Scheib (1988) –	$\frac{1.13}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.80}$	$\frac{T_m}{1.00 + 0.03\frac{\tau_m}{T_m}}$	$0.43T_m\left(\frac{\tau_m}{T_m}\right)^{1.01}$

4

$$K_c^{(3)} = \frac{4.43K_m K_u - 0.97}{5.12K_m K_u + 1.73}K_u,$$

$$T_i^{(3)} = \frac{1.75K_m K_u - 0.61}{3.78K_m K_u + 1.39}T_u$$

min. ITAE			N = 10
Rule	K_c	T_i	T_d
Direct synthesis			
Tsang and Rad (1995)	$\frac{0.81T_m}{K_m \tau_m}$	T_m	$0.5\tau_m$, N = 5
Tsang *et al.* (1993)	$\frac{aT_m}{K_m \tau_m}$	T_m	$0.25\tau_m$, N = 2.5

a	ξ	a	ξ	a	ξ
1.68	0.0	0.86	0.4	0.54	0.8
1.38	0.1	0.75	0.5	0.50	0.9
1.16	0.2	0.67	0.6	0.46	1.0
0.99	0.3	0.60	0.7		

Rule	K_c	T_i	T_d
Robust			
Chien (1988)	$\frac{1}{K_m}\left(\frac{T_m}{\lambda + 0.5\tau_m}\right)$ $\lambda = [\tau_m, T_m]$	T_m	$0.5\tau_m$, N = 10
	$\frac{1}{K_m}\left(\frac{0.5\tau_m}{\lambda + 0.5\tau_m}\right)$ $\lambda = [\tau_m, T_m]$	$0.5\tau_m$	T_m, N = 10
Ultimate cycle			
Shinskey (1988) min. IAE – regulator – varying τ_m/T_m	$0.95T_m/K_m\tau_m$ $0.95T_m/K_m\tau_m$ $1.14T_m/K_m\tau_m$ $1.39T_m/K_m\tau_m$	$1.43\tau_m$ $1.17\tau_m$ $1.03\tau_m$ $0.77\tau_m$	$0.52\tau_m$ $0.48\tau_m$ $0.40\tau_m$ $0.35\tau_m$
Industrial controller – $U(s) = K_c\left(1 + \frac{1}{T_i s}\right)\left(R(s) - \frac{1 + T_d s}{1 + T_d s/N}Y(s)\right)$			
Regulator			
Kaya and Scheib (1988) – min. IAE	$\frac{0.91}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.79}$	$\frac{T_m}{1.01}\left(\frac{T_m}{\tau_m}\right)^{1.00}$	$0.54T_m\left(\frac{\tau_m}{T_m}\right)^{0.78}$ N = 10
Kaya and Scheib (1988) – min. ISE	$\frac{1.11}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.90}$	$\frac{T_m}{0.93}\left(\frac{T_m}{\tau_m}\right)^{0.88}$	$0.57T_m\left(\frac{\tau_m}{T_m}\right)^{0.91}$ N = 10
Kaya and Scheib (1988) – min. ITAE	$\frac{0.71}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.89}$	$\frac{T_m}{1.03}\left(\frac{T_m}{\tau_m}\right)^{0.99}$	$0.60T_m\left(\frac{\tau_m}{T_m}\right)^{0.97}$ N = 10
Servo			
Kaya and Scheib (1988) – min. IAE	$\frac{0.82}{K_m}\left(\frac{T_m}{\tau_m}\right)^{1.00}$	$\frac{T_m}{1.09 - 0.22\frac{\tau_m}{T_m}}$	$0.44T_m\left(\frac{\tau_m}{T_m}\right)^{0.97}$ N = 10
Kaya and Scheib (1988) – min. ISE	$\frac{1.14}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.94}$	$\frac{T_m}{0.99 - 0.35\frac{\tau_m}{T_m}}$	$0.35T_m\left(\frac{\tau_m}{T_m}\right)^{0.78}$ N = 10
Kaya and Scheib (1988) – min. ITAE	$\frac{0.83}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.76}$	$\frac{T_m}{1.00 + 0.01\frac{\tau_m}{T_m}}$	$0.44T_m\left(\frac{\tau_m}{T_m}\right)^{1.11}$ N = 10

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3. PID TUNING RULES – $\frac{K_m e^{-s\tau_m}}{s}$ MODEL

Rule	K_c	T_i	T_d
Ideal controller $G_c(s) = K_c(1 + \frac{1}{T_i s} + T_d s)$			
Process reaction			
Ford (1953)	$\frac{1.48}{K_m \tau_m}$	$2\tau_m$	$0.37\tau_m$
Astrom and Hagglund (1995)	$\frac{0.94}{K_m \tau_m}$	$2\tau_m$	$0.5\tau_m$
Direct synthesis			
Cluett and Wang (1997) – designed closed loop time constant equals τ_m to $6\tau_m$, respectively	$\frac{0.96}{K_m \tau_m}$	$3.04\tau_m$	$0.39\tau_m$
	$\frac{0.62}{K_m \tau_m}$	$5.26\tau_m$	$0.26\tau_m$
	$\frac{0.47}{K_m \tau_m}$	$7.23\tau_m$	$0.21\tau_m$
	$\frac{0.38}{K_m \tau_m}$	$9.19\tau_m$	$0.17\tau_m$
	$\frac{0.31}{K_m \tau_m}$	$11.16\tau_m$	$0.15\tau_m$
	$\frac{0.27}{K_m \tau_m}$	$13.14\tau_m$	$0.13\tau_m$
Classical controller – $G_c(s) = K_c\left(1 + \frac{1}{T_i s}\right)\left(\frac{1 + T_d s}{1 + T_d s/N}\right)$			
Regulator			
Shinskey (1996) – min. IAE	$\frac{0.93}{K_m \tau_m}$	$1.57\tau_m$	$0.56\tau_m$
Shinskey (1994) – min. IAE	$\frac{0.93}{K_m \tau_m}$	$1.60\tau_m$	$0.58\tau_m$, N = 10
	$\frac{0.93}{K_m \tau_m}$	$1.48\tau_m$	$0.63\tau_m$, N = 20

4. SIMULATION RESULTS

Space considerations dictate that only representative simulation results may be provided. In these results, approximate gain margin and phase margin are analytically calculated, using the method outlined by Ho, *et al*. (1996), for processes compensated using an appropriately tuned PID controller. The MATLAB package has been used in the simulations. The same tuning rules are used in Figures 1 and 2; similarly, the same tuning rules are used in Figures 3 and 4, and in Figures 5 and 6.

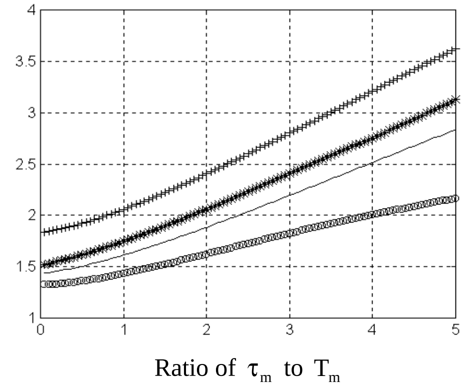

Figure 1: Gain margin

- = Ziegler-Nichols (1942)
+ = Astrom-Hagglund (1995)
o = Cohen-Coon (1953)
* = Chien *et al*. (1952) – reg – 20% o.s.

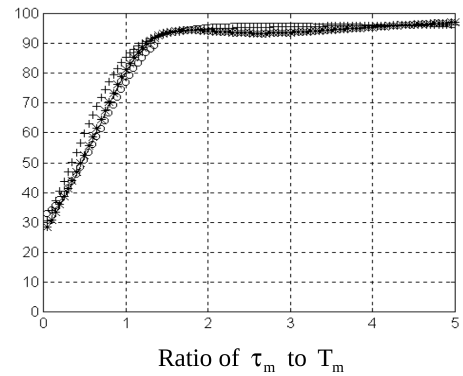

Figure 2: Phase margin

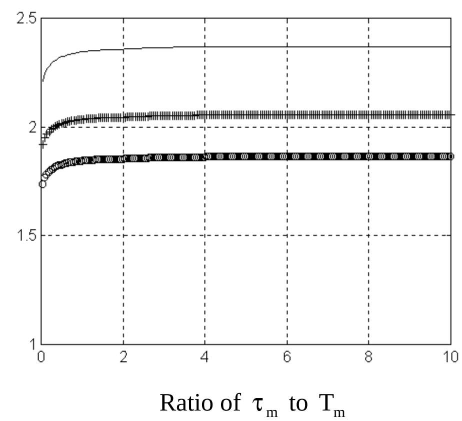

Figure 3: Gain margin

- = Abbas (1997) – 0% o.s.
+ = Abbas (1997) – 10% o.s.
o = Abbas (1997) – 20% o.s.

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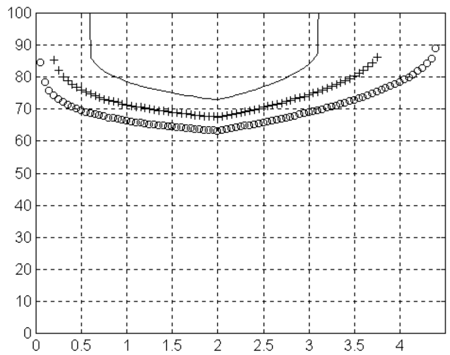
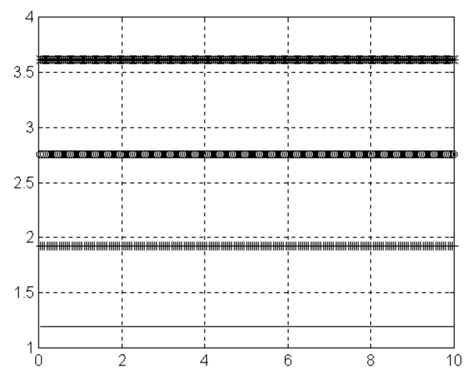


Ratio of τ_m to T_m
Ratio of τ_m to T_m

Figure 4: Phase margin



Ratio of τ_m to T_m
Ratio of τ_m to T_m

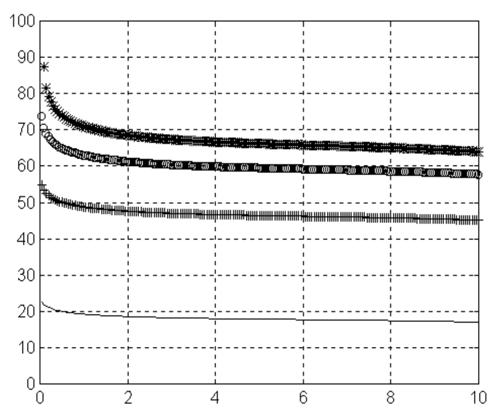
Figure 5: Gain margin

- = Tsang *et al*. (1993) – ξ = 0.1

+ = Tsang *et al*. (1993) – ξ = 0.4

o = Tsang *et al*. (1993) – ξ = 0.7

* = Tsang *et al*. (1993) – ξ = 1.0



Ratio of τ_m to T_m
Ratio of τ_m to T_m

Figure 6: Phase margin

These simulations reveal the following:

(1) Typically, the analytical calculation of the phase margin is real (and positive) in a restricted range of ratios of τ_m/T_m ; the range allowed is very limited for many tuning rules. Typically, the gain margin is real and positive over a much wider range.

(2) The process reaction curve tuning rule of Cohen and Coon (1953) gives rise to a smaller gain margin (and approximately equal phase margin) to that of Ziegler and Nichols (1942), indicating that the closed loop response associated with the application of the former tuning rule may be expected to be more oscillatory. This is compatible with application experience.

(3) Both the gain and phase margins are larger for the tuning rule of Abbas (1997), when the design criteria is to achieve 0% overshoot in the closed loop response, compared to when the design criterion is to achieve 20% overshoot. This is as expected.

(4) The tuning method of Tsang *et al*. (1993) gives a constant gain margin and an almost constant phase margin. The nature of this tuning rule has interesting similarities to the tuning rules that give rise to constant gain and phase margins when a PI controller is used (O’Dwyer, 2000a). It is also clear that the tuning rules may be used at ratios of τ_m/T_m outside the normally recommended range of 0.1 to 1.0.

(5) If the data in Figures 1 and 2 is compared with the corresponding data (O’Dwyer, 2000a), it is clear that the gain margin of the PID controller is significantly lower than that of the corresponding PI controller, when the Ziegler and Nichols (1942) tuning rules are used. The phase margin is also mostly higher for the PI controller. This indicates that the PID controller should offer a faster response (to a step input in servo mode, for example). Similar comments apply for many other tuning rules. A fuller panorama of simulation results show that stability tends to be assured when a PI controller tuning rule is used. Thus, a cautious design approach is to use a PI controller, with an appropriate tuning rule, particularly at larger ratios of time delay to time constant.

5. CONCLUSIONS

A large number of PID controller tuning rules have been defined in the literature to compensate SISO processes with time delays. The paper has presented a flavour of the variety of tuning rules defined. Some results associated with the analytical calculation of the gain margin and phase margin of compensated delayed systems, as the ratio of time delay to time constant varies, have also been presented. Future work will concentrate on further analytical evaluation of the robustness of delayed processes compensated using tuning rule based PID controllers.

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T_m

APPENDIX: LIST OF SYMBOLS AND ABBREVIATIONS USED

$G_c(s)$ = PID controller transfer function

IAE = integral of absolute error, ISE = integral of squared error

ISTES = integral of squared time multiplied by error, all to be squared

ISTSE = integral of squared time multiplied by squared error

ITAE = integral of time multiplied by absolute error

K_c = Proportional gain of the controller, K_m = Gain of the process model

N = Indication of the amount of filtering on the derivative term

o.s. = overshoot

R(s) = Desired variable

T_d = Derivative time of the controller**,** T_i = Integral time of the controller

T_m = Time constant of the process model, T_u = Ultimate time

U(s) = manipulated variable, Y(s) = controlled variable

λ = Parameter that determines robustness of compensated system.

ξ = damping factor of the compensated system

τ_m = time delay of the process model