2002-01-01

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Recommended Citation

Feeney, Michael and O'Dwyer, Aidan :Towards an expert system approach for PI controller design of delayed processes. Proceedings of the Irish Signals and Systems Conference, pp. 175-180, University College Cork, June. doi:10.21427/tgk8-e389

Proceedings of the Irish Signals and Systems Conference, University College, Cork, June 2002, pp. 175-180.

Towards an Expert System Approach for PI Controller Design of Delayed Processes

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Abstract -- **This paper will discuss the compensation of first order lag plus time delay (FOLPD) processes using PI controllers whose parameters are specified using appropriate tuning rules. The gain margin and phase margin of the compensated system, as the ratio of time delay to time constant of the process varies, are calculated for each tuning rule and an expert system is used to recommend a tuning rule for user defined requirements.**

Keywords -- **PI, time delay, gain margin, phase margin, expert system.**

I. INTRODUCTION

The ability of proportional integral (PI) and proportional integral derivative (PID) controllers to compensate most practical industrial processes has led to their wide acceptance in industrial applications. The requirement to choose either two or three controller parameters has meant that the use of tuning rules to determine these parameters is popular. The second author has previously considered this topic in detail [1-5]. A large number of tuning rules have appeared in the literature; for example, 101 tuning rules may be used to specify the PI controller terms to compensate a FOLPD process, with 181 tuning rules defined to specify the PID controller parameters for this process [5]. Typical tuning methods are based on using process reaction curve data (e.g. Ziegler and Nichols [6]), integral error criteria (e.g. Rovira *et al*. [7]), ultimate cycle methods (e.g. Ziegler and Nichols [6]), direct synthesis methods (e.g. Smith and Corripio [8]), gain and phase margin specifications (e.g. Hang *et al*. [9]) and internal model control strategies (e.g. Morari and Zafiriou [10]).

There has always been some difficulty in objectively comparing the performance and robustness of closed loop compensated systems whose controllers are determined by these tuning rules, as the time delay of the FOLPD process varies. Recently, however, Ho *et al*. [11], [12] evaluated one performance and robustness metric by analytically calculating a good approximation for the gain and phase margins of the closed loop compensated system, and applied the technique for 11 PI controller tuning rules and 10 PID controller tuning rules. This method has been extended by O'Dwyer [13] to apply to a very large number of tuning rules, to compensate both FOLPD and more general delayed process models. This paper will take part of the database generated by the latter work and explore the development of an expert system to choose the most appropriate PI controller tuning rule for user specified requirements of gain margin and phase margin.

The paper is organised as follows. Formulae for calculating analytically the performance and robustness metrics are outlined in Section II. The expert system implementation is described in Section III. In Section IV, conclusions of the work are provided.

II. ANALYTICAL DETERMINATION OF PERFORMANCE AND ROBUSTNESS METRICS

The calculations of the gain and phase margins of systems compensated by a PI controller are presented (O'Dwyer [1]). The process and controller are given by:

$$G_m(s) = \frac{K_m e^{-s\tau_m}}{1 + sT_m} \quad (1)$$

and

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s}\right) \quad (2)$$

Then

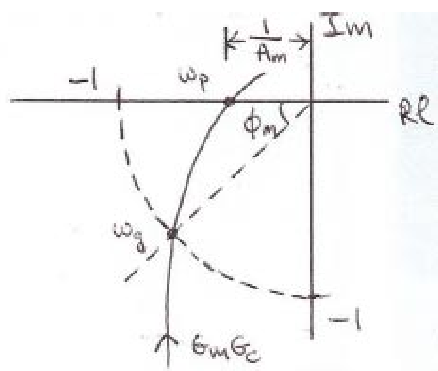
$$G_m(j\omega)G_c(j\omega) = \frac{K_m e^{-j\omega\tau_m}}{1 + j\omega T_m}\,\frac{K_c(j\omega T_i + 1)}{j\omega T_i},$$

with ω_g being found from

$$\left|G_m(j\omega_g)G_c(j\omega_g)\right| = 1$$

and ω_p found from

$$\angle G_m(j\omega_p)G_c(j\omega_p) = -\pi .$$



Then $G_m(j\omega)G_c(j\omega) = \dfrac{K_m K_c\sqrt{1+\omega^2 T_i^{\,2}}}{\omega T_i\sqrt{1+\omega^2 T_m^{\,2}}}$

$$\angle -0.5\pi + \tan^{-1}\omega T_i - \tan^{-1}\omega T_m - \omega\tau_m$$

The phase margin, ϕ_m, equals

$$\pi - 0.5\pi + \tan^{-1}\omega_g T_i - \tan^{-1}\omega_g T_m - \omega_g\tau_m \quad (3)$$

with ω_g given by the solution of

$$\frac{K_m K_c\sqrt{1+\omega_g^{\,2} T_i^{\,2}}}{\omega_g T_i\sqrt{1+\omega_g^{\,2} T_m^{\,2}}} = 1 \quad (4)$$

From this equation, ω_g may be determined analytically to be

$$\omega_g = \sqrt{\frac{T_i\left(K_c^{\,2}K_m^{\,2} - 1\right) + \sqrt{\left(K_c^{\,2}K_m^{\,2} - 1\right)^2 T_i^{\,2} + 4K_c^{\,2}K_m^{\,2}T_m^{\,2}}}{2T_i T_m^{\,2}}} \quad (5)$$

The gain margin,

$$A_m = \frac{1}{\left|G_m(j\omega_p)G_c(j\omega_p)\right|} = \frac{\omega_p T_i}{K_m K_c}\sqrt{\frac{1+\omega_p^{\,2}T_m^{\,2}}{1+\omega_p^{\,2}T_i^{\,2}}} \quad (6)$$

with ω_p given by the solution of

$$-0.5\pi + \tan^{-1}\omega_p T_i - \tan^{-1}\omega_p T_m - \omega_p\tau_m = -\pi \quad (7)$$

An analytical solution of this equation is not possible. An approximate analytical solution may be obtained if the following approximation for the arctan function is made:

$$\tan^{-1}x \approx \frac{\pi}{4}x,\ \ |x| < 1 \text{ and } \tan^{-1}x \approx \frac{\pi}{2} - \frac{\pi}{4x},\ \ |x| > 1 \quad (8)$$

This is quite an accurate approximation, as is shown by Ho *et al.* [11]. Looking at equation (7), four possibilities present themselves if the approximation in equation (8) is to be used; these possibilities are

(i) $\omega_p T_i > 1,\ \ \omega_p T_m > 1$

(ii) $\omega_p T_i > 1,\ \ \omega_p T_m < 1$

(iii) $\omega_p T_i < 1,\ \ \omega_p T_m > 1$ and

(iv) $\omega_p T_i < 1,\ \ \omega_p T_m < 1$.

Table 1 shows the formulae for ω_p that may be determined analytically for each of these cases.

Equations (3) and (6), together with equation (5) and the relevant equations from Table 1, may now be used to calculate the gain and phase margin of the compensated system, for each of the tuning rules, as a function of τ_m/T_m.

Table 1: Formulae for ω_p

$\omega_p T_i > 1,\ \omega_p T_m > 1$	$\omega_p T_i > 1,\ \omega_p T_m < 1$	$\omega_p T_i < 1,\ \omega_p T_m > 1$	$\omega_p T_i < 1,\ \omega_p T_m < 1$
$\omega_p = \dfrac{\pi \pm \sqrt{\pi^2 - 4\pi\tau_m\left(\frac{1}{T_i} - \frac{1}{T_m}\right)}}{4\tau_m}$	$\omega_p = \dfrac{\pi \pm \sqrt{\pi^2 - \frac{\pi}{T_i}\left(\frac{\pi}{4}T_m + \tau_m\right)}}{2\left(\frac{\pi}{4}T_m + \tau_m\right)}$	$\omega_p = \sqrt{\dfrac{\pi/T_m}{4\tau_m - \pi T_i}}$	$\omega_p = \dfrac{2\pi}{4\tau_m + \pi(T_m - T_i)}$

III. EXPERT SYSTEM IMPLEMENTATION

Based on the analytical work in Section II, data has been defined as MATLAB variables representing gain margin and phase margin values, as the ratio of time delay to time constant varies, for most of the 101 PI controller tuning rules for FOLPD process models [13]. This data was first exported to a Microsoft Access database file. The preliminary implementation of the expert system chose the most appropriate PI controller tuning rule for user specified requirements of gain margin, phase margin and ratio of time delay to time constant, based on this database.

a) User Interface

A Microsoft Visual Basic (VB) front end was developed using intrinsic VB controls, to provide the user with a friendly and intuitive interface. On correct completion of a logon process, the main user screen, shown in Figure 1, is loaded and a connection to the Microsoft Access database is made using a VB data control object.

The database is local to the VB programme (i.e. it is on the same PC as the VB application), though it could be put on a Local Area Network (LAN) or a Wide Area Network (WAN). The upper portion of this screen is used as an input interface. It consists of a set of text boxes and labels into which the user may enter the ratio of delay to time constant (TD/TC on Figure 1), the required gain and phase margins and an acceptable tolerance on the gain and phase margins.

The process of retrieval starts when the Execute button is clicked. A Structured Query Language (SQL) query, using parameters from the input text boxes, was used to return a recordset of matching tuning rules. A VB DBGrid object, bound to the data control object, was used to display the recordset. If the system finds fewer tuning rules than a low threshold value, or more tuning rules than a high threshold value, then the user is prompted to widen, or narrow the default tolerance of 10% respectively. No tuning rules are displayed until these thresholds are met. A secondary SQL query using the tuning rule number returned by the first query, was used to access another database containing the tuning rule sources and the formulae associated with each tuning rule. The right hand panels in the lower half of the user screen (Figure 1) were used to display this information.

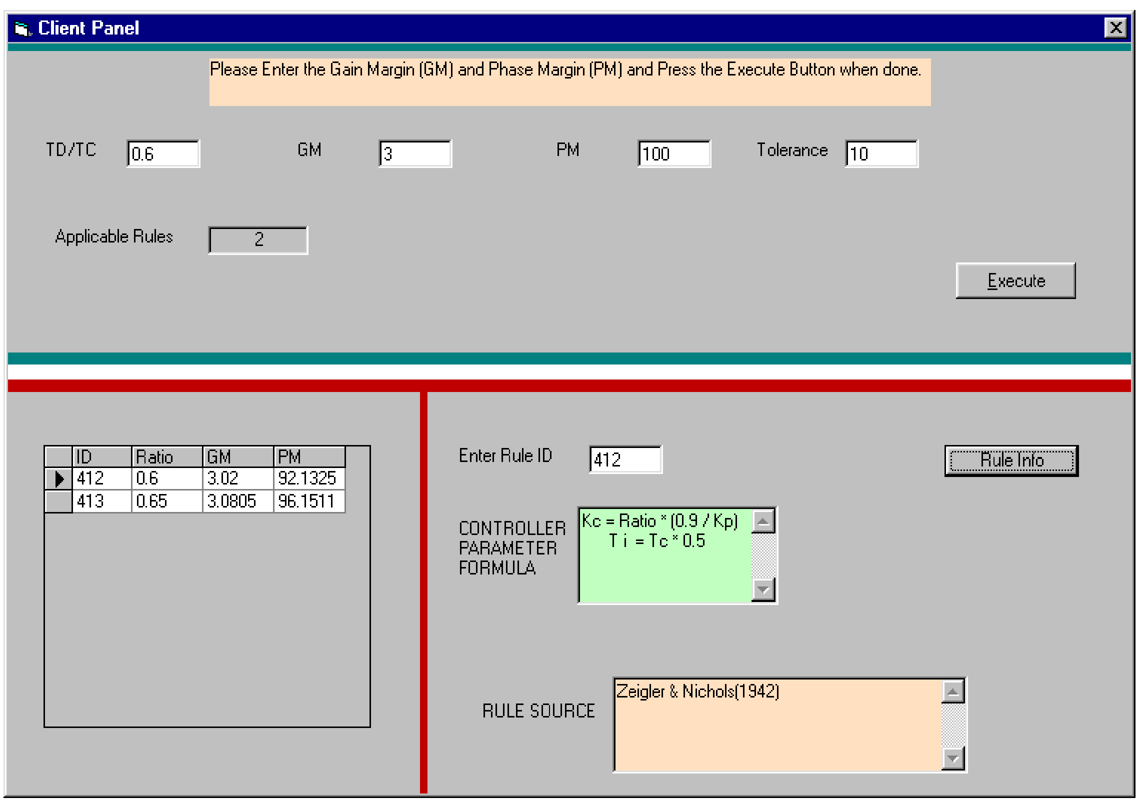


Figure 1: Main User Screen

b) Estimation of Model Parameters

Knowledge of the ratio of time delay to time constant is required for the user screen. Though process parameters may be known *a priori*, the functionality of the expert system for the average user would be increased if the expert system incorporated a system identification feature. Two methods were investigated: the well known two-point method [14], which is an open loop time domain method, and a closed loop frequency domain method.

Open Loop Time Domain Identification

Firstly, the step response of the process was obtained. For development work, the Bytronics process simulator was used. A programme (*IdcStp.mdl*) was developed in SIMULINK to obtain the step response, using HUMOSOFT to provide access to real-time data through a PC data acquisition board (Data Translation DT2811) into the SIMULINK environment. A MATLAB programme (*SysID.m*) was then written to process the step response data, and implement the two-point method, to determine the three parameters of the FOLPD process model.

The step response of the Bytronic model process, obtained using *IdcStp.mdl* is shown in Figure 2. The FOLPD parameters obtained (using *SysId.m*) were $K_m = 1.05$, $T_m = 2.03$ and $\tau_m = 1.18$ s.

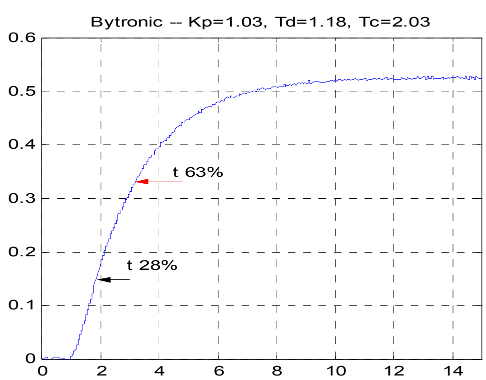


Figure 2: Data points taken: two-point method.

The simulated step response using the FOLPD parameters was compared to the actual step response of the process (Figure 3); the real plant response is shown as a continuous line, while the simulated step response is shown by + .

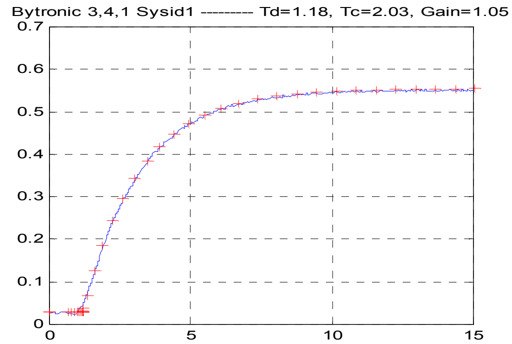


Figure 3: Simulated/actual response: comparison

Good process modelling was achieved using this method; however, the open loop nature of the method is a restriction on its application.

Closed Loop Frequency Domain Identification

An approach was developed in the MATLAB/SIMULINK/HUMUSOFT environment to obtain open loop frequency domain information (in the form of a Nyquist plot) from data obtained in *closed loop* under PI control. From this data, the gain margin and phase margin was identified; alternatively, the process model parameters could be determined (O'Dwyer [15]).

There are two parts to the approach. The first part injects distinct and separate bursts of sinusoids to the *closed loop* PI controlled process, at frequencies from the lowest frequency to the highest frequency of interest. The process output, and the controller input signal, for each burst was captured and saved as a *.mat* file in MATLAB. The second part loads the saved *.mat* files for each frequency point in turn and processes the data to extract gain and phase information for that frequency point. The gain values were obtained using the ratio of the magnitudes of the process output to controller input signals, and the phase information was obtained from the time difference between the zero crossing points of the two signals. The gain and phase values obtained were stored in a MATLAB array. In the experimental work, ten frequency values were considered (from 0.2 rads/s to 2 rads/s, in steps of 0.2 rads/s); a Nyquist plot is drawn from the ten gain and phase values. Very good correspondence between experimental frequency responses and expected frequency responses were achieved using the method; more details will be provided at the conference.

The duration of each frequency burst in the first part of the approach was 200 seconds. This ensured that, at the lowest frequencies, five to six full cycles of data were obtained. It was important to allow initial transients to decay before processing began. Ten bursts of frequency were used for each system tested, and thus about forty minutes were required for each test. Part 2 of the approach involved processing the data obtained in Part 1, one burst at a time. This was quite a laborious and error prone task. For this reason, it was desirable to automate, as much as possible, the procedure for obtaining the frequency response. The approach was further developed, using MATLAB batch files, to allow a user to start Part 1, without further intervention. The programme to implement Part 1 then cycles through the frequencies and saves the corresponding outputs. On completion of Part 1, the user then initiates the automated processing of the data to obtain the Nyquist plot of the PI controlled plant.

Table 1 below shows a comparison of the gain and phase margins obtained for a number of tuning rules, when these parameters are obtained analytically (Section II), in simulation and from the experimental frequency response (using the Bytronics process simulator). The gain margin and phase margin are determined to the nearest frequency ordinate in simulation and implementation; thus, the lower and upper bounds of these quantities are shown.

The automation of the frequency response testing process would allow for a broader frequency range and a higher resolution Nyquist plot, without the time penalties, fatigue and the human error element of the manual method. The results show broad agreement between the analytical, the simulation and the implementation results.

Tuning Rule		Analytical	Simulation	Implementation
Astrom and Hagglund [16]	Gain margin Phase margin	2.8 82	2.87 - 3.25 80.48 - 91.49	2.95 – 3.3 80.2 – 92.3
Chien *et al.* [17]; regulator	Gain margin Phase margin	3.01 92	3.04 – 3.44 85.99 – 97.57	3.1 – 3.55 84.84 – 95.15
Chien *et al.* [17]; servo	Gain margin Phase margin	4.7 76	4.36 – 5.07 67.18 – 79.57	4.3 – 5.0 69.9 – 80.82
Hang *et al.* [9]	Gain margin Phase margin	1.5 30	1.35 – 1.58 21.78 - 36	1.32 – 1.62 22.85 – 33.25
Hang *et al.* [9]	Gain margin Phase margin	2 45	1.81 – 2.12 36 – 49.34	1.87 – 2.22 33.25 – 47.37
Hang *et al.* [9]	Gain margin Phase margin	5 72	4.56 – 5.32 62.6 – 76.24	4.63 – 5.32 60.76 – 72.8
Murrill [18]	Gain margin Phase margin	1.68 42	1.47 – 1.71 25.22 – 38.75	1.49 – 1.77 25.71 – 40.13
St. Clair [19]	Gain margin Phase margin	4.73 71	4.23 – 4.93 62.83 – 76.36	4.1 – 4.74 60.76 – 71.66
Ziegler and Nichols [6]	Gain margin Phase margin	2 63	2.01 – 2.28 49.76 – 65.85	2.3 – 2.6 64.3 – 80.2

Table 1: Comparison of gain and phase margins obtained.

IV. CONCLUSIONS

Elements of an expert system approach for the PI controller design of a delayed process have been discussed. The database of gain margin and phase margin values for a wide range of tuning rules to compensate a FOLPD process model, as the ratio of time delay to time constant varies, has been set up and a client interface designed. In addition, two approaches to identify the process model parameters have been validated. The further integration of these elements is possible; for example, the process model parameters identified may be input directly to the expert system, so that the user could see, but not modify these parameters. The extension of the approach to the PID controller environment is a topic for future work.

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