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Enhancing waste management through automatic control

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Abstract: Meeting environmental requirements is recognised as one of the six 21st century business drivers for automatic control. The proportional integral (PI) and proportional integral derivative (PID) controllers are the most dominant form of automatic controllers in industrial use today. With these techniques, it is necessary to adjust the controller parameters according to the nature of the process. Thus, for effective control of a heating, cooling and air-conditioning (HVAC) application, for example, specific values need to be chosen for the P, I and D parameters, which will be different for the values required to control, for example, a distillation column. This tailoring of controller to process is known as *controller tuning*. Controller tuning is easily and effectively performed using *tuning rules* (i.e. formulae for controller tuning, based on process information). Such tuning rules allow the easy set up of controllers to achieve optimum performance at commissioning. Importantly, they allow ease of re-commissioning if the characteristics of the process change. The paper outlines the results of recent work in the collation of industry-relevant PI and PID controller tuning rules, which may be applied to a variety of applications with the aim of improving waste management.

1. INTRODUCTION

There is an increasing awareness in society of the need to protect our fragile environment. In attempting to meet environmental requirements, chemical companies, for example, use automatic control to minimise waste production because of increasing prohibitions against discharge and/or disposal of toxic substances. New plants are moving towards a "zero-discharge" concept [1]. In a Forfas report [2], greater emphasis on automatic control is suggested as a technological response of both the speciality chemicals and pharmaceutical sub-sectors to key business drivers up to 2015. In one other measure of increased interest, the use of automatic control for meeting environmental requirements was one of the major themes of the 2005 World Congress of the International Federation of Automatic Control.

PI and PID controllers have been at the heart of control engineering practice for seven decades. Historically, the first tuning rule (formula) for setting up controller parameters was defined in 1934 for the design of a proportional-derivative (PD) controller for a process exactly modelled by an integrator plus delay (IPD) model [3]. Subsequently, tuning rules were defined for PI and PID controllers, assuming the process was exactly modelled by a first order lag plus delay (FOLPD) model [4] or a pure delay model [4], [5].

The use of the PI or PID controller is ubiquitous in industry. It has been stated, for example, that in process control applications (which include waste management applications), more than 95% of the controllers are of PI or PID type [6-11]. Neglected by the academic research community until recently, work by K.J. Åström, T. Hägglund and F.G. Shinskey, among others, has sparked a revival of interest in the use of this "workhorse" of controller implementation. One illustrative statistic is worth quoting: over the decade 1992-2001, three hundred and eighty five publications on the use of the PI or PID controller for the compensation of processes with time delays were examined by the author, more than three times the corresponding number of publications in the previous five decades [12].

However, despite this development work, surveys indicating the state of the art of control industrial practice report sobering results. For example, in testing of thousands of control loops in hundreds of plants, it has been found that more than 30% of installed PI or PID controllers are operating in manual mode and 65% of loops operating in automatic mode produce less variance in manual than in automatic (thus, the automatic controllers are poorly tuned) [13]. In another interesting study of 150,000 control loops at over 250 industrial sites around the globe, it was shown that 68% of all controllers had unacceptable performance; even the best sites has only 70% of all controllers performing acceptably, while the worst site had 15% of all controllers performing acceptably [14]. Other literature [15] claims that "extensive industry testing" shows that 75% of all PID based loops are out of tune. A survey of paper processing mills is quoted, in which 60% of the 36 mills surveyed stated that less than half of their control loops were well tuned (the majority of the mills reported that they had between 2000 and 4000 regulatory control loops). In a further such comment, it is claimed [16] that only 20% of all control loops surveyed in mill audits have been found to actually reduce process variability in automatic mode over the short term. Of the problem loops, increased process variability in automatic mode could be ascribed specifically to controller tuning problems in approximately 30% of cases. Many of the points made above are re-iterated by [17]. The situation has not improved more recently, with [18] reporting that 80% of PID controllers are badly tuned; 30% of PID controllers operate in manual with another 30% of the controlled loops increasing the short-term variability of the process to be controlled (typically due to too strong integral action). It is stated that 25% of all PID controller loops use default factory settings, implying that they have not been tuned at all.

Process performance deteriorates when the controller is poorly tuned; this deterioration may be reflected, for example, in increases in energy costs and environmental emissions. The net effect will be an increase in operating costs and a reduction in overall competitiveness. However, good controller tuning, for example, can allow the recovery of up to 6% of energy costs, in a variety of industries, with an associated reduction in waste emissions [19]. Poor controller tuning is surprising, as very many tuning rules exist to allow the specification of the controller parameters. Tuning rules have the advantage of ease of calculation of the controller parameters (when compared to more analytical controller design methods), on the one hand; on the other hand, the use of tuning rules is a good alternative to trial and error tuning. It is clear that the many controller tuning rules proposed in the literature are not having an impact on industrial practice. One reason is that the tuning rules are not very accessible, being scattered throughout the control literature; in addition, the notation used is not unified. In a book published in 2003 [12], PI and PID controller tuning rules for processes with time delay have been bought together and summarised, using a unified notation. A second edition of this book is due to be published in 2006 [20].

It is timely, therefore, to outline the results of the work done in the collation of *additional* tuning rules for continuous-time PI and PID control of single-input, single-output (SISO) processes to those explored in [12]. Such rules may be specified for processes either without or with a time-delay (dead-time) term. Firstly, a brief summary of how good control can result in an improvement in waste management is provided. Then, examples of the range of PI and PID controller structures proposed in the literature, together with process models used to define the controller tuning rules, are provided. Subsequently, controller architecture and process modeling issues are outlined, followed by the outline of additional tuning rules for setting up PI and PID controllers, for a number of process models. Other reviews are also recommended to the interested reader [21-38]. Full details of sample tuning rules are subsequently communicated. The control of a pilot scale heating, ventilation and air-conditioning (HVAC) plant is detailed as a case study. Finally, conclusions to the paper are drawn.

2. IMPROVING WASTE MANAGEMENT WITH GOOD CONTROL

Improved control (in general) results in energy savings, safety improvements, better environmental performance, consistent product quality, minimises raw materials wastage and reduces manufacturing costs [14], [39], [40]. All of these benefits may be categorised as improved waste management; these benefits are well known in process control circles and are discussed in detail in Chapter 1 of a seminal process control book [41]. To take one example, typically, good control can reduce raw material and energy costs by between 2% and 6%, with a payback period (for the investment) of less than 12 months [14], [39], [42]; in addition, control is almost the only technology where major enhancements can be made between shutdowns [14].

Taking improved energy efficiency as an example, excessive comfort margins, due to poor control, are major causes of excessive energy consumption; good control can reduce comfort margins and thus reduce energy consumption by 5-15% [14], [39], [40], [43]. Good controller tuning is an important component of improved energy efficiency. A table giving priorities for control projects, from an energy saving point of view, is available [14]. Properly tuning controllers is the second most important priority in this table; implementing good controller tuning has nil capital cost and a payback period of hours.

The Carbon Trust (www.carbontrust.co.uk) has an excellent series of companion guides, good practice guides and general information reports that consider this topic in detail. On their website, the Carbon Trust declare their role to be “to help the UK move to a low carbon economy by helping business and the public sector reduce carbon emissions now and capture the commercial opportunities of low carbon technologies”. In Ireland, Sustainable Energy Ireland (SEI) has a broadly similar mandate. The reports from the Carbon Trust and SEI cover, as a means of increasing energy efficiency:

- Replacing manual control by automatic control [44];
- Using final control elements such as variable speed drives or valves, in control loops [45-51];
- Using advanced sensors and transmitters in control loops [52-53];
- Applying advanced control concepts, such as ratio control [54-55], adaptive and self-tuning control [56-58], expert systems [59-61], model predictive control [62-63], data mining [64-65] and genetic algorithms [66];
- Building services applications [67-73].

In addition, an energy wizard (an interactive energy efficiency guide) is available at http://www.actionenergy.org.uk/energywizard/. One menu on the energy wizard is labelled “Savings via Process Control”; different applications in the chemical industry and in the food and drink industries are considered.

3. CONTROLLER ARCHITECTURE AND PROCESS MODELLING

A practical difficulty with PID control technology is a lack of industrial standards, which has resulted in a wide variety of PID controller architectures. Seven different structures for the PI controller and forty-six different structures for the PID controller have been identified. Controller manufacturers vary in their choice of architecture; controller tuning that works well on one architecture may work poorly on another. Full details are given in [12], [20]; considering the PID controller, common architectures are:

1. The 'ideal' PID controller, given by

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

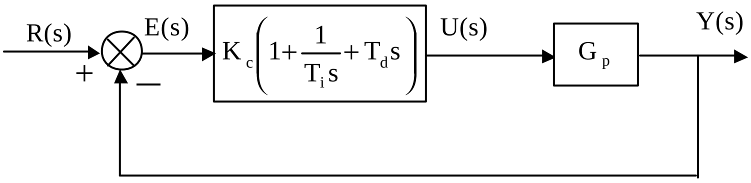


Figure 1. Ideal PID controller in a unity feedback block diagram representation (G_p = process). This controller structure, and an equivalent structure, is also labelled the parallel, ideal parallel, non-interacting, parallel non-interacting, independent, gain independent or ISA controller [12], [20]. 276 tuning rules have been identified for this controller structure.

This architecture is used, for example, on the Honeywell TDC3000 Process Manager Type A, non-interactive mode product [74].

2. The 'classical' PID controller, given by

$$G_c(s) = K_c\left(1+\frac{1}{T_i s}\right)\frac{1+sT_d}{1+s\frac{T_d}{N}}.$$

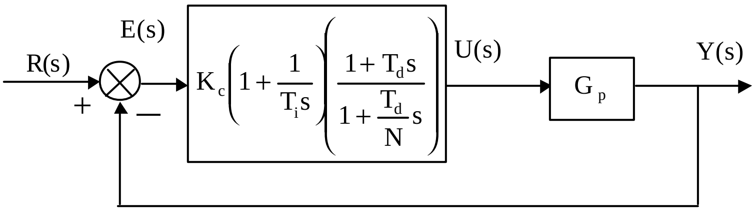


Figure 2. Classical PID controller in a unity feedback block diagram representation (G_p = process). Also labelled the cascade, interacting, series, interactive, rate-before-reset or analog controller [12], [20], 101 tuning rules have been identified for this controller structure.

This architecture is used, for example, on the Honeywell TDC3000 Process Manager Type A, interactive mode product [74].

3. The non-interacting controller based on the two degree of freedom structure, given by

$$U(s) = K_c\left(1+\frac{1}{T_i s}+\frac{T_d s}{1+\frac{T_d}{N}s}\right)E(s) - K_c\left(\alpha+\frac{\beta T_d s}{1+\frac{T_d}{N}s}\right)R(s).$$

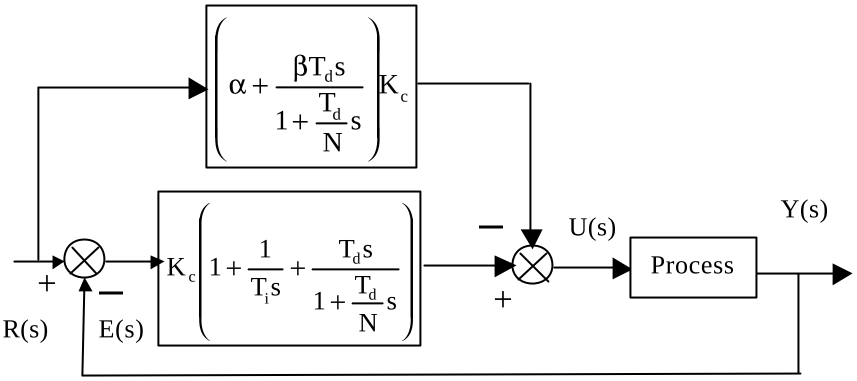


Figure 3. Non-interacting controller, based on the two degree of freedom structure, in a unity feedback block diagram representation. Also labelled the m-PID or ISA-PID controller [12], [20], 44 tuning rules have been identified for this controller structure.

This architecture is used, for example, on the Omron E5CK digital controller with $\beta = 1$ and N = 3 [74].

The most dominant PI controller architecture is the 'ideal' PI controller, given by

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

The wide variety of controller architectures is mirrored by the wide variety of ways in which processes with time delay may be modeled. Common models are:

1. Stable FOLPD model, given by

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

2. IPD model, given by

$$G_m(s) = \frac{K_m e^{-s\tau_m}}{s}.$$

3. First order lag plus integral plus delay (FOLIPD) model, given by

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

4. Second order system plus time delay (SOSPD) model, given by

$$G_m(s) = \frac{K_m e^{-s\tau_m}}{T_{m1}{}^2 s^2 + 2\xi_m T_{m1} s + 1} \text{ or } G_m(s) = \frac{K_m e^{-s\tau_m}}{(1+T_{m1}s)(1+T_{m2}s)}.$$

Some 82% of the PI controller tuning rules identified have been defined for the ideal PI controller structure, with 41% of tuning rules based on a FOLPD process model. The range of PID controller variations has led to a less homogenous situation than for the PI controller; 38% of tuning rules identified have been defined for the ideal PID controller structure, with 37% of PID tuning rules based on a FOLPD process model.

Of course, the modeling strategy used influences the value of the model parameters, which, in turn, affect the controller values determined from the tuning rules. Forty-seven modeling strategies have been detailed to determine the parameters of the FOLPD process model, for example. Space does not permit a full discussion of this issue; further details are provided in [12], [20].

4. ADDITIONAL TUNING RULES FOR PI AND PID CONTROLLERS

Before considering additional tuning rules for PI and PID controllers over those proposed in [12], it is timely to review the action of the PID controller. Considering the ideal PID controller, for example, which is given by

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

with K_c = proportional gain, T_i = integral time constant and T_d = derivative time constant. If $T_i = \infty$ and $T_d = 0$ (that is, P control), then the closed loop measured value is always less than the desired value for processes without an integrator term, as a positive error is necessary to keep the measured value constant, and less than the desired value. The introduction of integral action facilitates the achievement of equality between the measured value and the desired value, as a constant error produces an increasing controller output. The introduction of derivative action means that changes in the desired value may be anticipated, and thus an appropriate correction may be added prior to the actual change. Thus, in simplified terms, the PID controller allows contributions from present, past and future controller inputs.

PI and PID controller tuning rules may be broadly classified as follows:

- Tuning rules based on a measured step response
- Tuning rules based on minimising an appropriate performance criterion
- Tuning rules that give a specified closed loop response
- Robust tuning rules, with an explicit robust stability and robust performance criterion built in to the design process
- Tuning rules based on recording appropriate parameters at the ultimate frequency.

Tuning rules in the first four subdivisions are typically based on process model parameters; the development of a process model is typically not required for using tuning rules in the final subdivision above. Some tuning rules could be considered to belong to more than one subdivision, so the subdivisions cannot be considered to be mutually exclusive; nevertheless, they provide a convenient way to classify the rules. An outline of tuning rules in these subdivisions is now provided; these tuning rules are, with the exception of [75], additional to those considered in [12].

Tuning rules based on a measured step response are also called *process reaction* curve methods. The first (and most well-known) tuning rule of this type was suggested in 1942 [75]; in this method, the process is modeled by a FOLPD process model with the model parameters estimated using a tangent and point method, as indicated in Figure 4.

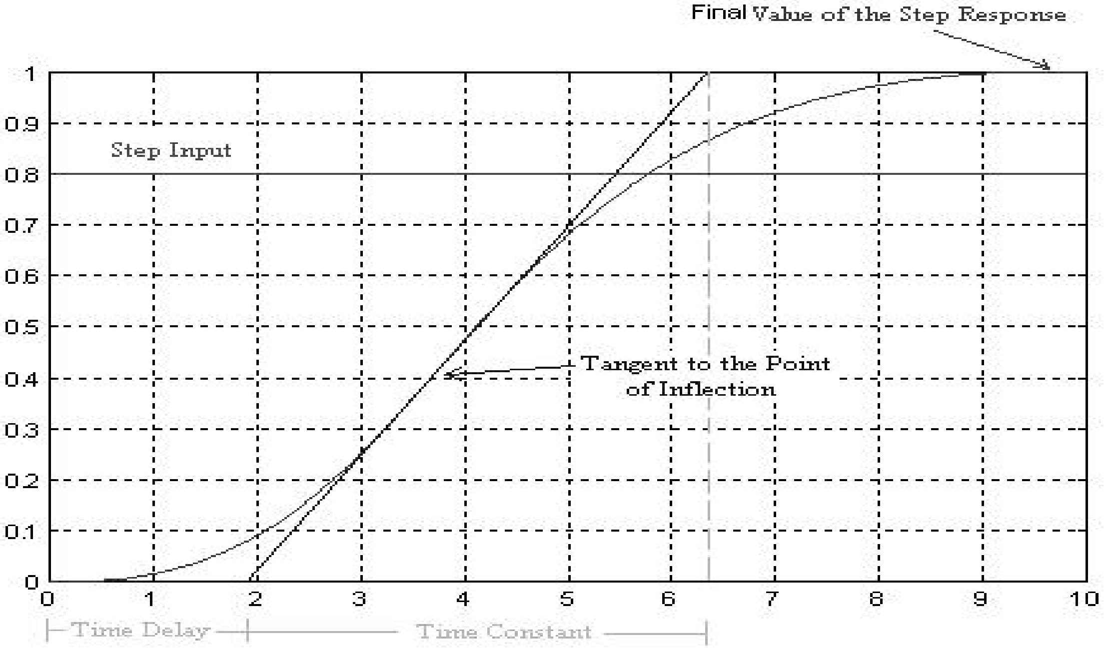


Figure 4. Tangent and point method [75] for developing a process model. K_m = model gain = ratio of the steady state change in process output to steady state change in process input, T_m = model time constant and τ_m = model time delay. 54 controller tuning rules have been identified based on the model parameters determined from this modelling method. 21 of the 46 other modelling methods for determining such a process model, prior to specifying tuning rules, are based on data gathered from the open loop process step or impulse response [20].

Simple formulae are used to define tuning parameters for PI and PID controllers. The PI controller settings are given by

$$K_c = \frac{0.9T_m}{K_m\tau_m},\ T_i = 3.33\tau_m .$$

The (ideal) PID controller settings are given by

$$K_c \in \left[\frac{1.2T_m}{K_m\tau_m}, \frac{2T_m}{K_m\tau_m}\right],\ T_i = 2\tau_m ,\ T_d = 0.5\tau_m .$$

Other process reaction curve tuning rules are also described, sometimes in graphical form, to control processes modeled by a FOLPD model [76-89], an IPD model [90-92], a FOLIPD model [91], [92] or a SOSPD model [93]. The advantage of process reaction curve tuning strategies is that only a single experimental test is necessary. However, the disadvantages of the strategy are primarily based on the difficulty, in practice, of obtaining an accurate process model; for example, load changes may occur during the test which may distort the test results and a large step input may be necessary to achieve a good signal to noise ratio [94]. Similar disadvantages will arise in any tuning method dependent on prior model development.

Tuning rules based on minimising an appropriate performance criterion may be defined either for optimum regulator or optimum servo action. Performance criteria, such as the minimisation of the integral of absolute error (IAE) in a closed loop environment, may be used to determine a unique set of controller parameter values. Tuning rules have been described, sometimes in graphical form, to optimise the regulator response of a compensated SISO process, modeled in stable FOLPD form [95-102], unstable FOLPD form [103], [104], IPD form [105], FOLIPD form [106] and stable SOSPD form [95], [107-111]. Similarly, tuning rules have been proposed to optimise the servo response of a compensated process, modeled in stable FOLPD form [98], [99], [112-118], unstable FOLPD form [103], [104], IPD form [105], FOLIPD form [106], stable SOSPD form [107], [109], [119], [120] or in pure delay form [113], [120]. Other tuning rules to minimise performance criteria, when the process is modeled in stable FOLPD form [85], [121-125], unstable FOLPD form [103], [126], IPD form [125], [127], [128], SOSPD form [123], [129] or in pure delay form [124], [125], [127], [128] are also described.

Tuning rules that give a specified closed loop response (direct synthesis tuning rules) may be defined by specifying a time domain related metric, such as the desired poles of the closed loop response. The definition may be expanded to cover techniques that allow the achievement of a frequency domain metric, such as a specified gain margin and/or phase margin. Tuning rules to achieve time domain metrics are defined to compensate processes modeled in stable FOLPD form [112], [120], [128], [130-160], unstable FOLPD form [103], [126], [147], [156-169], FOLPD form with a positive zero [170-172], IPD form [105], [128], [142], [148], [173-179], FOLIPD form [106], [128], [142], [148], [160], [173], [178], [180], SOSPD form [119], [128], [130], [131], [142], [148], [160], [173], [181-187], SOSPD form with a positive zero [138], [188], SOSPD form with a negative zero [138], unstable SOSPD form with one [162], [164], [165], [189] or two [189], [191] unstable poles, squared integrator plus delay (I^2PD) form [128], [173] and pure delay form [120], [137], [160], [182]. Tuning rules to achieve specific frequency domain metrics are also described, for processes modeled in stable FOLPD form [185], [191-205], FOLPD form with a positive zero [206], unstable FOLPD form [103], [199], [207-209], FOLIPD form [207], [210-213], stable SOSPD form [185], [191], [194], [195], [201], [204], [214-216], IPD form [191], [192], [199], [217-219], FOLIPD form [191], and pure delay form [220]. Such tuning rules are also specified when the process includes a time delay, but the model structure is of higher order or is not defined [203], [221-226], possibly with an integrator [222].

Robust tuning rules have an explicit robust stability and/or robust performance criterion built in to the design process. Tuning rules have been specified for the compensation of processes modeled in stable FOLPD form [114], [185], [193], [227-239], unstable FOLPD form [161], [236], [240], FOLPD form with a positive zero [172], FOLPD form with a negative zero [241], IPD form [105], [114], [232], [236], [242-247], FOLIPD form [236], [248], stable SOSPD form [187], [204], [236], [237], [249], [250], unstable SOSPD form [240], I^2PD form [248] and pure delay form [128], [246].

Ultimate cycle tuning rules are based on recording appropriate parameters at the ultimate frequency (that is, the frequency at which marginal stability of the closed loop control system occurs). The first such tuning rule was defined in 1942 [75] for the tuning of P, PI and PID controller parameters of a process that may or may not include a delay. Briefly, the experimental technique is as follows:

a) Place the controller in proportional mode only.
b) Increase K_c until the closed loop system output goes marginally stable; record K_c (calling it K_u, the *ultimate gain*), and the *ultimate period*, T_u; a typical marginally stable output, recorded on a laboratory flow process, is shown in Figure 5.

Simple formulae are used to define tuning parameters for PI and PID controllers. The PI controller settings are given by

$$K_c = 0.45K_u,\ T_i = 0.83T_u,$$

with the (ideal) PID controller settings given by

$$K_c = 0.6K_u,\ T_i = 0.5T_u,\ T_d = 0.125T_u.$$

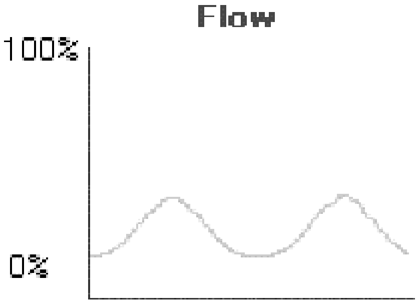


Figure 5. Typical marginally stable process variable pattern. Note that the pattern exhibits evidence of a process nonlinearity, which is common in real applications. 129 controller tuning rules have been defined, based on the data determined from such a pattern [20].

The tuning rules implicitly build an adequate frequency domain stability margin into the compensated system [251]. However, there are a number of disadvantages to the ultimate cycle tuning approach:

- the system must generally be destabilised under proportional control
- the empirical nature of the method means that uniform performance is not achieved in general [252]
- several trials must typically be made to determine the ultimate gain
- the resulting process upsets may be detrimental to product quality
- there is a danger of misinterpreting a limit cycle as representing the stability limit [253] and
- the amplitude of the process variable signal may be so great that the experiment may not be carried out for cost or safety considerations.

Some of these disadvantages are addressed by defining modifications of the rules in which, for example, the proportional gain in the experiment is set up to give a closed loop transient response decay ratio of 0.25, or a phase lag of 135^0; ultimate cycle tuning rules, and their modifications, may compensate processes modeled in FOLPD form [201], [254], [255-260], IPD form [261], FOLIPD form [257], SOSPD form [119], [181], [201] or general, possibly delayed, stable processes [84], [85], [100], [115], [123], [201], [204], [260-282], sometimes to achieve a specified frequency domain metric [204], [283], [284], [285].

5. DETAILED TUNING RULES FORMULATION

The sample tuning rules that are formulated in detail are set out in tabular form (Tables 1 to 5), allowing the rules to be represented compactly. The tables have four or five columns, according to whether the controller considered is of PI or PID form, respectively. The first column details the author of the rule and other pertinent information. The final column in all cases is labelled “Comment”; this facilitates the inclusion of information about the tuning rule that may be useful in its application. The remaining columns detail the formulae for the controller parameters.

Two hundred and twenty four (224) additional PI controller tuning rules, over those described in [12], have been identified. The total number of PI controller tuning rules that have been identified by the author is 443 [20]. Three hundred and ten (310) additional PID controller tuning rules have been specified. The total number of PID controller tuning rules that have been identified by the author is 691 [20].

Table 1. Sample tuning rules for an ideal PI controller based on a stable first order lag plus delay process model. 172 such tuning rules have been identified [20].

Rule	K_c	T_i	Comment
	Process reaction		
Callender *et al*. [4]; Model parameters assumed known. $\frac{\tau_m}{T_m} = 0.3$	$\frac{0.568}{K_m\tau_m}$	$3.64\tau_m$	Decay ratio = 0.015; Period of decaying oscillation = $10.5\tau_m$
	$\frac{0.690}{K_m\tau_m}$	$2.45\tau_m$	Decay ratio = 0.043; Period of decaying oscillation = $6.28\tau_m$

Table 2. Sample tuning rule for an ideal PI controller based on an integrator plus delay process model. 46 such tuning rules have been identified [20].

Rule	K_c	T_i	Comment
	Direct synthesis: time domain criteria		
Skogestad [128]	$\frac{0.5}{K_m \tau_m}$	$8\tau_m$	Model parameters assumed known

Table 3. Sample tuning rules for an ideal PID controller based on a stable first order lag plus time delay process model. 100 such tuning rules have been identified [20].

Rule	K_c	T_i	T_d	Comment
	Process reaction			
Callender *et al.* [4]; Model parameters assumed known $\frac{\tau_m}{T_m} = 0.3$	$\frac{1.066}{K_m \tau_m}$	$1.418\tau_m$	$0.353\tau_m$	Representative result; Decay ratio = 0.043; Period of decaying oscillation = $6.28\tau_m$
	Servo tuning: minimum performance index			
Modified minimum ITAE – Smith [115]	$\frac{0.965}{K_m}\left(\frac{T_m}{\tau_m}\right)^{0.855}$	$1.26T_m$	$0.308\tau_m$	Model parameters assumed known

Table 4. Sample tuning rule for an ideal PID controller based on an integrator plus delay process model. 22 such tuning rules have been identified [20].

Rule	K_c	T_i	T_d	Comment
	Direct synthesis: time domain criteria			
Chidambaram and Sree [177]	$\frac{1.2346}{K_m \tau_m}$	$4.5\tau_m$	$0.45\tau_m$	Model parameters assumed known

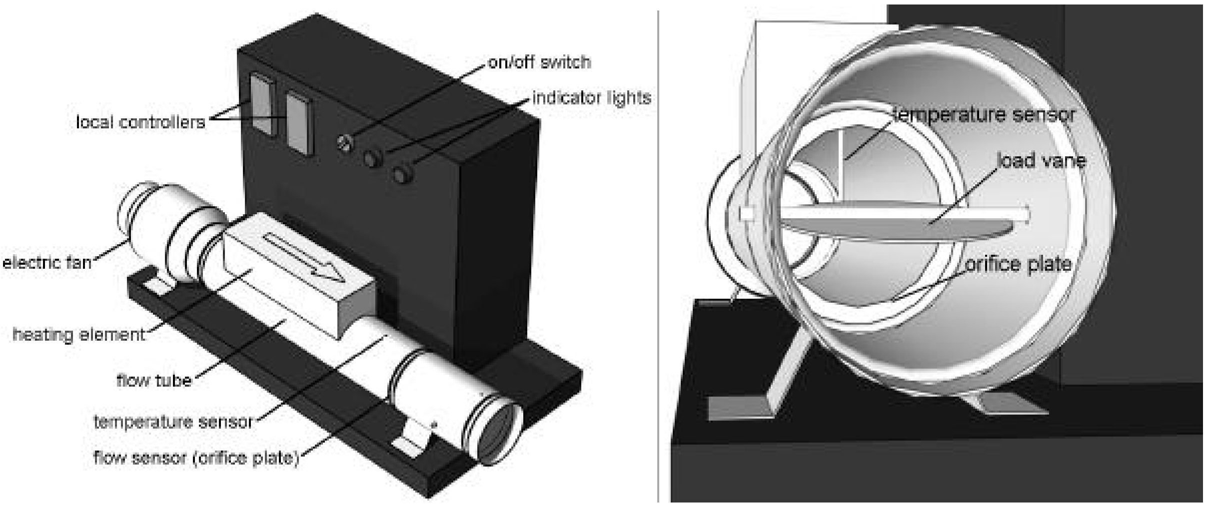
Table 5. Sample tuning rule for a non-interacting controller based on the two degree of freedom structure, based on an integrator plus delay process model. 5 such tuning rules have been identified [20].

Rule	K_c	T_i	T_d	Comment
	Direct synthesis			
Chidambaram and Sree [177]; Model parameters assumed known	$\frac{1.2346}{K_m \tau_m}$	$4.5\tau_m$	$0.45\tau_m$	$N = 0$; $\beta = 0$; $\alpha = 0.6$

6. CASE STUDY

This section details the control of a pilot scale laboratory heating and ventilation system (VVS-400 product, Instrutek A/S, Larvik, Norway [286]). The system is represented in 2x2 multi-input, multi-output (MIMO) form. A process reaction curve identification technique was used to model (in FOLPD form) the flow process and temperature process portions of the system, over a range of operating conditions. Tests revealed that both processes were continuously non-linear. A “gain scheduler” with static decoupling was designed, using look-up tables, to continuously interpolate for the most suitable PI/PID controller settings and decoupler gains.

A three dimensional diagram of the pilot scale heating and ventilation system is shown in Figure 6. An electric fan is located at one end of a non-insulated metal tube (painted white). The fan blows air over a heating element. The air exits to the surroundings at the other end of the tube. An orifice plate is situated just before the exit (see close up of inside the tube). The differential pressure across the orifice is used to determine the flow rate. A platinum resistance temperature sensor is positioned inside the tube. A load vane provides a method of restricting the airflow at the tube exit. The power supply and other electrical components of the rig are inside the housing. Two independent local controllers (Fuji PY25) for the flow and temperature processes, that have PI/PID and auto-tuning functions, are provided. The inputs to the controllers are 1-5 V, and their outputs are in the 4-20 mA range. It is possible to connect directly to the fan and the heating element, switching out the local controllers, so that the processes may be controlled via a PC.



(a) overview (b) end-elevation view

Figure 6. Instrutek VVS-400 laboratory heating and ventilation rig

A static characteristic curve for both the flow and temperature process reveals the non-linearity of both processes. The flow process curve (Figure 7) shows that limits exist on its maximum and minimum operating region. At flows less than 15% of maximum fan voltage setting (labelled as input flow in Figure 7), very little change in output occurs for a change in input. This is effectively a dead-band region of the flow. The maximum flow rate obtainable is 75%. The figure also shows that the slope of the characteristic curve is greater at high inputs, implying high process model gain at high inputs. The temperature process has an infinite number of characteristic curves, as process behaviour depends on the infinite number of possible flow rates. Characteristic curves at three flow rates were determined (Figure 8). It is clear that the higher the flow rate, the lower the maximum temperature achievable. This is sensible from an intuitive point of view as the cooling effect of the airflow would be greater at high flow rates. At high heater setting (labelled as input temperature in Figure 8), each curve tended to level off or saturate; the maximum temperature obtainable is limited by the maximum power output of the element. Each curve has a lower limit consistent with the ambient room temperature.

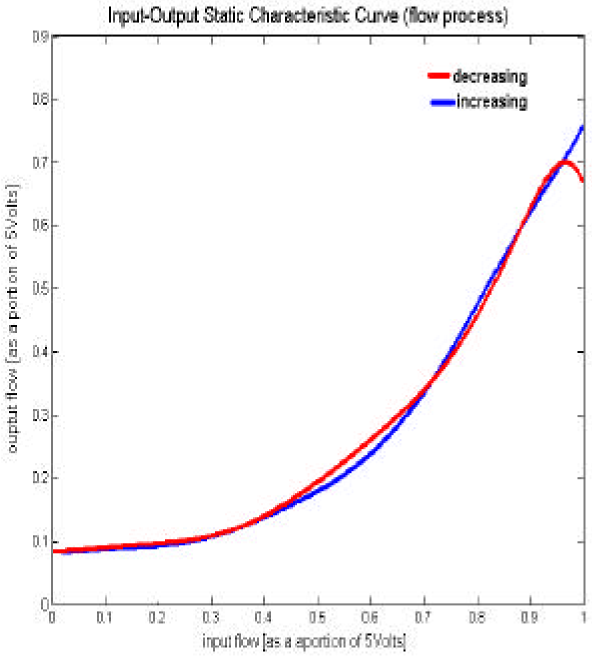


Figure 7. Flow process characteristic curve

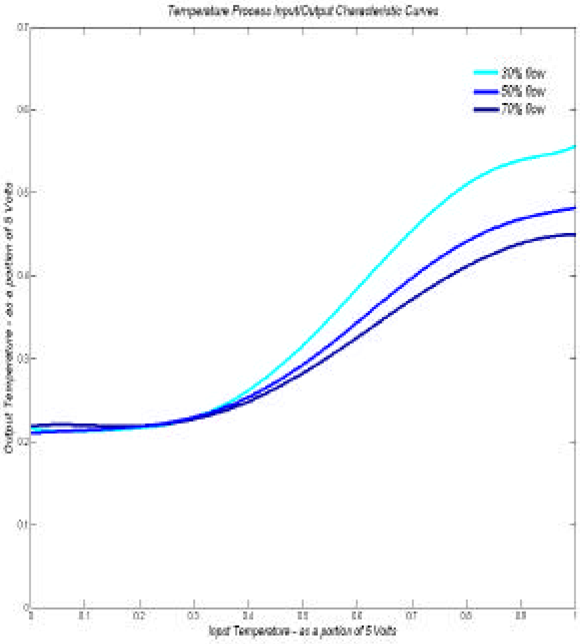


Figure 8. Temperature process characteristic curve

Due to the non-linearity, process models were determined, from the open loop step response of both the flow process and the temperature process, at three operating points for the flow process, and nine operating points for the temperature process (three heater settings at three flow settings).

PI and PID controllers were chosen to control the processes because of the relatively low time delay to time constant ratio revealed by the identification tests and also because of their wide use in industry and relatively simple implementation. Suitable tuning rules were chosen for these controllers, based on minimising the integral of absolute error (IAE) performance criterion, for both servo and regulator applications [12]; minimising IAE can be related to minimizing energy consumption, and more generally, optimising economic performance [41]. The controllers were specified for each operating point. Closed loop response tests were carried out at particular operating conditions. As examples, servo and regulator performance, when a PI controller is used, for the "medium" flow setting, and separately for the "medium" and "low" temperature settings, at a 30% (low) flow setting, are provided in Figures 9 and 10, respectively. Satisfactory performance is observed.

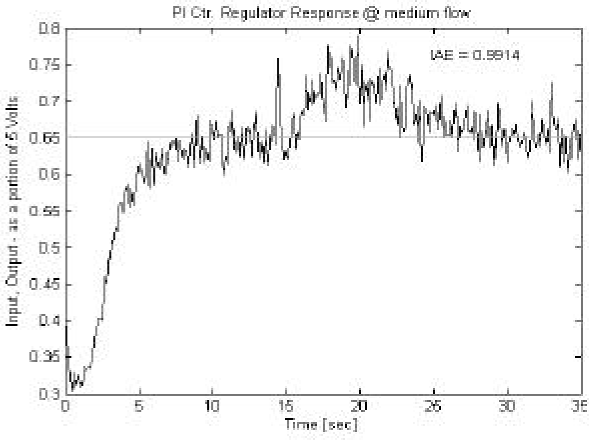


Figure 9. Responses – flow system

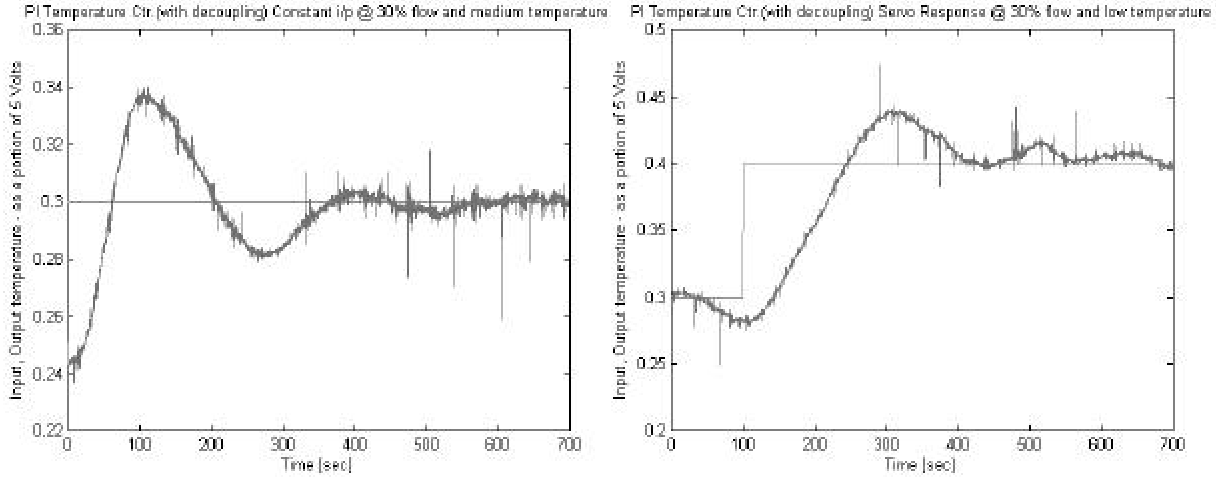


Figure 10. Responses – temperature system

7. CONCLUSIONS

Control academics and practitioners remain interested in the use of PI and PID controllers. PID controller tuning rules can be directly implemented in a variety of applications i.e. the hardware already exists, but it needs to be optimised. Such tuning rules allow plant personnel to easily set up controllers to achieve optimum performance at commissioning. Importantly, they allow ease of re-commissioning if the characteristics of the process change (for example, due to wear on actuators and valves, or changes in environmental protection legislation). The outcome of good PID controller tuning is directly measurable in, for example, energy savings and waste reduction (including greenhouse gas emission reduction). The resulting positive environmental effects may also have added benefits in terms of a 'green' image and healthier workplace environment.

This paper summarises mainly recent work in tuning rule development for such processes, updating the information provided in [12]. The most startling statistic to emerge from the complete work is the quantity of tuning rules identified to date; 443 PI tuning rules and 691 PID tuning rules, a total of 1134 separate rules. Recent years have seen an acceleration in the accumulation of tuning rules. In general, there is a lack of comparative analysis regarding the performance and robustness of closed loop systems compensated with controllers whose parameters are chosen using the tuning rules; associated with this is the lack of benchmark processes, at least until recently [287]. In addition, much work remains to be done in the evaluation of controllers designed using tuning rules in a wide variety of practical applications, including applications in waste management. The main priority for future research in the area should be a critical analysis of available tuning rules, rather than the proposal of further tuning rules.

Historical note: The 70th anniversary of the receipt of the first technical paper describing tuning rules for setting up controller parameters [4] is presently being marked. The paper was received by the Philosophical Transactions of the Royal Society of London on July 15, 1935; the paper was received, in revised form, on November 26, 1935 and was read on February 2, 1936. The lead author of the paper subsequently took out a patent on the PID controller (Callender, A. and Stevenson, A.B., *Automatic control of variable physical characteristics*, US patent 2,175,985. Filed: Feb. 17, 1936; Issued Oct. 10, 1939).

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