Control of open-loop unstable processes with time delay using PI/PID controllers specified using tuning rules: an outline survey

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Abstract — **The ability of PI and PID controllers to compensate many practical processes has led to their wide acceptance in industrial applications. The requirement to choose two or three controller parameters is conveniently done using tuning rules. Starting with a general discussion of industrial practice, the paper provides a survey of tuning rules for continuous-time PI and PID control of open-loop unstable time-delayed single-input, single-output (SISO) processes.**

Keywords – **open-loop unstable processes, PI/PID controller tuning rules**.

I INTRODUCTION

A time delay may be defined as the time interval between the start of an event at one point in a system and its resulting action at another point in the system. Delays are also known as transport lags or dead times; they arise in physical, chemical, biological and economic systems, as well as in the process of measurement and computation. Methods for the compensation of time delayed processes may be broadly divided into parameter optimised controllers, such as *proportional-integral* (PI) and *proportional-integral-derivative* (PID) controllers, in which the controller parameters are adapted to the controller structure, and structurally optimised controllers, in which the controller structure and parameters are adapted optimally to the structure and parameters of the process model.

PI and PID controllers have been at the heart of control engineering practice for seven decades. The controllers are suggested as the second most important control decision and communication instrument of the 20th century [1]. 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 model [2]. Subsequently, tuning rules were defined for PI and PID controllers, assuming the process was exactly modelled by a stable first order lag plus delay (FOLPD) model [3] or a pure delay model [3], [4].

The use of the PI or PID controller is ubiquitous in industry, though there is strong evidence that PI and PID controllers remain poorly understood and, in particular, poorly tuned in many applications, as discussed thoroughly by a previous contribution [5]. This is surprising, as very many tuning rules exist to allow the specification of the controller parameters. Interestingly, many tuning rules are not restricted in application to linear processes with fixed parameters, but may be readily applied to appropriately modelled non-linear processes, and process models with varying parameters, including those with non-constant time delays. 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 accessible, being scattered throughout the control literature; in addition, the notation used is not unified. In a book published in 2003 [6], tuning rules for continuous-time PI and PID control of single-input, single-output (SISO) processes, with time delay, have been compiled and summarised, using a unified notation; subsequently, as a result of the continuing specification of new tuning rules, a second edition of the book was published in 2006 [7] and a third edition was published in 2009 [8]. The latter book reveals that, up to 2009, there are 1731 separate tuning rules specified, with 70% (or 1212 rules) based on a self-regulating (or open-loop stable) process model and 30% (or 521 rules) based on a non-self-regulating process model; of the latter data, 11% of tuning rules (or 182 rules) are based on process models which are open-loop unstable.

Twenty-four years ago, one of the first tuning rules for the control of open-loop unstable processes was proposed by De Paor and O'Malley [9]. The 'direct synthesis' approach, pioneered by these authors for the application, has provoked a rich investigative stream of further work. Therefore, it is timely to consider the development of this work.

II PROCESSES MODELLED BY UNSTABLE OPEN-LOOP PROCESS MODELS

Many real processes are modelled most appropriately by an open-loop unstable transfer function, with a time delay term. As examples, processes such as a bioreactor which exhibits output multiplicity [10], [11], an isothermal continuous stirred tank reactor [11], an ethylene to butane dimerization reactor [11], a constant volume continuous tank fermenter with sterile feed [12], a fixed-bed adiabatic tubular reactor coupled with a feed preheater [13], a gas phase polyolefin reactor [14], [15] and a batch polymerization reactor with exothermic reactions [16] may be modelled by a gain, a delay and a single right half plane pole (labeled an unstable FOLPD process model):

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

Of the 182 tuning rules specified for open loop unstable process models up to 2009, 64% (or 117) have been proposed for this model [8]. Other processes such as an isothermal continuous stirred tank reactor with non-ideal mixing [11] and a fluid catalytic reactor [11] may be modelled an unstable FOLPD process model with a negative or positive zero.

As final examples, processes such as a continuous stirred tank reactor that is being used to perform an exothermic reaction [15], [17] may be modelled as a gain, a delay, a single right half plane pole and a left half plane pole (equation 2) and processes such as a gas phase polyolefin reactor [14], [15] may be modelled as a gain, a delay and two real right half plane poles (equation 3):

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

$$G_m = \frac{K_m e^{-s\tau_m}}{(T_{m1}s - 1)(T_{m2}s - 1)} \qquad (3)$$

These are labeled as an unstable second order system plus time delay (SOSPD) model with one unstable pole and with two unstable poles, respectively. Of the 182 tuning rules specified for open loop unstable process models up to 2009, 23% (or 41) have been proposed for these process models, with 33 tuning rules proposed for process model (2) and 8 tuning rules proposed for process model (3) [8].

Of course, the modelling strategy used influences the value of the model parameters, which, in turn, affect the controller values determined from the tuning rules. Six modelling strategies have been detailed to determine the parameters of the model in equation (1), for example. Space does not permit a full discussion of this issue; further details are provided in [8].

III CONTROLLER ARCHITECTURE

A practical difficulty with PID control technology is a lack of industrial standards, which has resulted in a wide variety of PID controller architectures. Controller manufacturers vary in their choice of architecture; controller parameters that work well on one architecture may work poorly on another. In [8], the author has proposed nine unifying controller architectures. The ideal PI and PID controller structures (equations (4) and (5), respectively) are the most well known architectures:

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s}\right) \qquad (4)$$

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s} + T_d s\right) \qquad (5)$$

with K_c = proportional gain, T_i = integral time constant and T_d = derivative time constant. These architectures account for 37% (or 67) of the tuning rules specified for open-loop unstable process models up to 2009. Most of the other tuning rules are based on two-degree of freedom PID controller architectures; full details are given in [8].

IV TUNING RULES FOR PI AND PID CONTROLLERS

Before considering tuning rules for PI and PID controllers, it is timely to review the action of the PID controller. Consider the ideal PID controller, for example, given by equation (5). 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 for unstable process models may be broadly classified as follows:

- 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 into the design process.

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 for the application is now provided.

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 to optimise the regulator response of a compensated SISO process, modelled in unstable FOLPD form [10], [18]–[22], and in unstable SOSPD form with one unstable pole [19], [23], [24]. Similarly, tuning rules have been proposed to optimise the servo response of a compensated process, modelled in unstable FOLPD form [10], [19]–[22], [25], and in unstable SOSPD form with one unstable pole [19], [26]. Other tuning rules to minimise performance criteria, when the process is modelled in unstable FOLPD form [10], [27]–[29], are also described.

Tuning rules that give a specified closed loop response (also labelled 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 modelled in unstable FOLPD form [10], [11], [17], [21], [25], [27], [30]–[49], unstable FOLPD form with a zero [11], [50], [51], unstable SOSPD form with one unstable pole [11], [17], [21], [26], [32], [35], [49], [52]–[54], unstable SOSPD form with two unstable poles [52], [53], unstable SOSPD form with a zero [11], [15], [54], [55], and, finally, unstable first order lag plus integrator plus delay form [56]. Tuning rules to achieve specific frequency domain metrics are also described, for processes modelled in unstable FOLPD form [9], [11], [57]–[75], unstable SOSPD form with one unstable pole [60], [68], [76]–[78], unstable SOSPD form with two unstable poles [74], and general unstable form [79].

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 modelled in unstable FOLPD form [11], [16], [31], [80]–[104], unstable FOLPD form with a zero [11], unstable SOSPD form with one unstable pole [16], [80], [84], [86], [88], [89], [92], [95], [99]–[102], [105], [106], unstable SOSPD form with two unstable poles [16], [89], [99]–[101], [106]–[111], and, finally, unstable SOSPD form with a zero [11], [105].

V CONCLUSIONS AND FUTURE WORK

Control academics and practitioners remain interested in the use of PI and PID controllers to compensate processes with time delay. This paper summarises work in controller tuning rule development for the control of specialised, but practically important, open-loop unstable processes. It is clear that a considerable body of work is now available. 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. 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.

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