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PID compensation of time delayed processes: a survey

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Abstract

An extensive literature exists on the PID compensation of time delayed processes. It is possible to identify themes that are common to many of the available techniques. The intention of the paper is to provide a framework against which the literature may be viewed.

Keywords:- Time delay, compensation, PID.

1 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 (or PID based) 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 [1, 2]. The PID controller and its variations (P, PI or PD) is the most commonly used controller in process control applications, for the compensation of both delayed and non-delayed processes. Koivo and Tanttu [3], for example, suggest that there are perhaps 5-10% of control loops that cannot be controlled by single input, single output (SISO) PI or PID controllers; in particular, these controllers perform well for processes with benign dynamics and modest performance requirements [4, 5]. PID controllers have some robustness to incorrect process model order assumptions and limited process parameter changes. The controller is also easy to understand, with tuning rules that have been validated in a wide variety of practical cases. It has been stated that 98% of control loops in the pulp and paper industries are controlled by SISO PI controllers [6] and that, in process control applications, more than 95% of the controllers are of PID type [5]. However, Ender [7] states that, in his testing of thousands of control loops in hundreds of plants, it has been found that more than 30% of installed controllers are operating in manual mode and 65% of loops operating in automatic mode produce less variance in manual than in automatic (i.e. the automatic controllers are poorly tuned); this is rather sobering, considering the wealth of information available in the literature for determining controller parameters. It is true that this information is scattered throughout papers and books; the author is not aware of a comprehensive summary, in the published literature, of PID compensation techniques for processes with time delays. This paper will provide such an overview, concentrating on papers published in control theory and applications journals in electrical, chemical and mechanical engineering; a fuller review is available from the author [8]. Other reviews, detailing elements of the topics treated, are recommended to the interested reader [3, 9-16].

The PID controller may be implemented in continuous or discrete time, in a number of controller structures [17]. The ideal continuous time PID controller is expressed in Laplace form as follows:

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

with K_c = proportional gain, T_i = integral time constant and T_d = derivative time constant. If $T_i = \infty$ and $T_d = 0$ (i.e. P control), then the closed loop measured value will always be 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.

In many cases, the design of PID controllers for delayed processes are based on methods that were originally used for the controller design of delay-free processes. However, PID controllers are not well suited for the control of dominant delay processes [18]. It has been suggested that the PID implementation is recommended for the control of processes of low to medium order, with small delays, when controller parameter setting must be done using tuning rules and when controller synthesis may be performed a number of times [1].

2 The specification of PI or PID controller parameters

2.1 Iterative methods

The choice of appropriate compensator parameters may be achieved experimentally e.g. by manual tuning [19-22]. However, such an approach is time consuming and the process typically has to be driven to its stability limit [19]. Alternatively, a graphical or analytical approach to controller tuning may be done in either the time or frequency domain. The time domain design is done using root locus diagrams; it is, however, questionable that a delayed process would be sufficiently well modelled by the necessary second order model. The frequency domain design is typically done using Bode plots [23-26] to achieve a desired phase margin [24, 27]. Similar methods are also described in the discrete time domain [27]. Iterative methods for controller design provide a first approximation to desirable controller parameters.

2.2 Tuning rules

Process reaction curve tuning rules are based on calculating the controller parameters from the model parameters determined from the open loop process step response. This method was originally suggested by Ziegler and Nichols [28], who modelled the SISO process by a first order lag plus delay (FOLPD) model, estimated the model parameters using a tangent and point method and defined tuning parameters for the P, PI and PID controllers. Other process reaction curve tuning rules of this type are also described, sometimes in graphical form, to control processes modelled by a FOLPD model [5, 29-41] and an integral plus delay (IPD) model [5, 28, 30, 42, 43]. The advantages of such tuning strategies are that only a single experimental test is necessary, a trial and error procedure is not required and the controller settings are easily calculated; however, it is difficult to calculate an accurate and parsimonious process model and load changes may occur during the test which may distort the test results [19]. These methods may also be used to tune cascade compensators [44], discrete time compensators [1, 45] and compensators for delayed multi-input, multi-output (MIMO) processes [46].

Performance (or optimisation) criteria, such as the minimisation of the integral of absolute error 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, modelled in stable FOLPD form [29, 33, 37, 47-55], unstable FOLPD form [50, 56], IPD form [29, 51, 57-59], stable second order system plus delay (SOSPD) form [51, 55, 57, 60-67] and unstable SOSPD form [46, 58, 68]. Similarly, tuning rules have been proposed to optimise the servo response of a compensated process, modelled in stable FOLPD form [37, 49, 53-55, 69-71], unstable FOLPD form [56], stable SOSPD form [55, 65-67, 69] and unstable SOSPD form [56]. Tuning rules to achieve specified servo and regulator responses simultaneously are also described [72-75]; Taguchi and Araki [76], for example, describe two degree of freedom PID tuning rules to compensate processes modelled in FOLPD, IPD, first order lag plus integral plus delay (FOLIPD), second order system plus integral plus delay (SOSIPD), SOSPD (repeated pole), SOSPD (damping factor of 0.5) and third order lag plus delay (TOLPD) form. Cascade controllers [69, 77] and discrete time compensators [1, 78-80] may also be tuned.

Ultimate cycle tuning rules are calculated from the controller gain and oscillation period recorded at the ultimate frequency (i.e. the frequency at which marginal stability of the closed loop control system occurs). The first such tuning methods was defined by Ziegler and Nichols [28] for the tuning of P, PI and PID controller parameters of a process that may or may not include a delay. The tuning rules implicitly build an adequate frequency domain stability margin into the compensated system [81]. Such tuning rules, to compensate delayed processes by minimising a performance criterion, or achieving a specified gain and/or phase margin are discussed when the SISO process is modelled in FOLPD form [10, 35, 50, 51, 53, 57, 82-88], IPD form [43, 51, 89-91], FOLIPD form [82], stable SOSPD form [50, 51, 82] or unstable SOSPD form [82]. Alternatively, ultimate cycle tuning rules, and modifications of the rules in which the proportional gain is set up to give a closed loop transient response decay ratio of 0.25, or a phase lag of 135^0, may compensate general, possibly delayed, processes [5, 18, 25, 36, 39, 41, 42, 63, 84, 92-103], sometimes to achieve a specified gain and/or phase margin [5, 10, 81, 103, 104] or a specified closed loop response [105]. Ultimate cycle tuning rules may also be used to tune cascade controllers [39, 106], discrete time compensators [1, 19, 107, 108] and compensators for delayed MIMO processes [2, 39, 109-116]. The controller settings are easily calculated; however, the system must generally be destabilised under proportional control, the empirical nature of the method means that uniform performance is not achieved in general [117], several trials must typically be made to determine the ultimate gain, the resulting process upsets may be detrimental to product quality and there is a danger of misinterpreting a limit cycle as representing the stability limit [84].

Direct synthesis tuning rules result in a controller that facilitates a specified closed loop response. These methods include pole placement strategies and frequency domain techniques, such as gain margin and/or phase margin specification. Schneider [118], for example, specified a PI tuning rule to control a FOLPD process model, which results in a closed loop response damping factor of unity. Other such tuning rules also compensate SISO processes modelled in stable FOLPD form [5, 10, 62, 71, 119-131], unstable FOLPD form [132-134], IPD form [5, 124, 127, 128, 130, 135] and SOSPD form [10, 119, 122, 128, 136-140]. Frequency domain based tuning rules are also described, for processes modelled in stable FOLPD form [39, 53, 88, 141-147], unstable FOLPD form [147-150], stable SOSPD form [26, 88, 141, 151-154], unstable SOSPD form [147], IPD form [155], FOLIPD form [155] and more general form [26, 104, 145, 156]. The methods may also be used to tune cascade compensators [125], discrete time compensators [122, 157], and compensators for delayed MIMO processes [130, 158].

The presence of unmodelled process dynamics demands a robust design approach. The Internal Model Control (IMC) design procedure, which allows uncertainty on the process parameters to be specified, may be used to design appropriate PI and PID controllers for the compensation of SISO processes modelled in stable FOLPD form [159-168], unstable FOLPD form [169], IPD form [159, 165], FOLIPD form [170], stable SOSPD form [151, 159, 161, 162, 168, 171] and unstable SOSPD form [169]. Cascade controllers [132, 167, 172, 173] and controllers for delayed MIMO processes [174, 175] may also be tuned using the strategy.

Tuning rules are easy to use, even in the absence of an accurate process model. These design methods are suitable for the achievement of a simple performance specification, for a compensated process with a non-dominant delay. A comprehensive summary of the tuning rule formulae is available [176].

2.3 Analytical techniques

Controller parameters may be determined using analytical techniques. Some methods minimise an appropriate performance index; Harris and Mellichamp [177], for instance, outline a methodology to tune a PI or PID controller to met multiple closed loop criteria. These criteria are subsumed into a single performance index that is an arbitrary function of relevant frequency domain parameters; the method reflects the important point that there is no one set of tuning values that provide the optimum response in all respects. Other such methods to determine compensators for delayed SISO processes have also been described, both in continuous time [91, 178-195] and discrete time [1, 2, 196-202]. Compensators for delayed MIMO processes have also been proposed in continuous time [203-205] and discrete time [2, 206].

Alternatively, a direct synthesis strategy may be used to determine the controller parameters. Such strategies may be defined in the time domain, possibly by using pole placement [4, 92, 207-217] or in the frequency domain, possibly by specifying a desired gain and/or phase margin [158, 218-232]. Barnes *et al.* [224], for instance, design a PID controller for a delayed process by minimising the sum of squared errors between the desired and actual polar plots. Direct synthesis strategies may also be used in the discrete time domain [1, 233-235]. Compensators for delayed MIMO processes have also been proposed in continuous time [236] and in discrete time [237].

Robust methods, based on the IMC design procedure, may be used to design analytically an appropriate PID controller for a FOLPD process model both with delay uncertainty and with general parameter uncertainty [163]. Other analytical applications of the IMC procedure are also discussed [238]. Finally, alternative design methods may be used to determine the controller parameters, such as the use of expert systems [239-245], fuzzy logic [12, 209, 246-254], genetic algorithms [254-256] or neural networks [39, 191, 192, 257, 258].

Analytical methods are suitable for the design of PI/PID controllers for non-dominant delay processes where there are well-defined performance requirements to be achieved [1].

3 Conclusions

Control academics and practitioners remain interested in the use of the PID controller to compensate processes with time delay. This paper provides a comprehensive summary of such compensation techniques that have appeared in the journals dealing with control theory and applications. It is the hope of the author that the paper will provide a convenient reference for application work.

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