



2000-01-01

PID compensation of time delayed processes: a survey

Aidan O'Dwyer

Dublin Institute of Technology, aidan.odwyer@dit.ie

Follow this and additional works at: <http://arrow.dit.ie/engscheleart>

 Part of the [Controls and Control Theory Commons](#)

Recommended Citation

O'Dwyer, Aidan :PID compensation of time delayed processes: a survey. Proceedings of the Irish Signals and Systems Conference, pp. 5-12, Dublin, June, 2000.

This Conference Paper is brought to you for free and open access by the School of Electrical and Electronic Engineering at ARROW@DIT. It has been accepted for inclusion in Conference papers by an authorized administrator of ARROW@DIT. For more information, please contact yvonne.desmond@dit.ie, arrow.admin@dit.ie.



This work is licensed under a [Creative Commons Attribution-NonCommercial-Share Alike 3.0 License](#)



PID compensation of time delayed processes: a survey

Aidan O'Dwyer

School of Control Systems and Electrical Engineering,
Dublin Institute of Technology, Kevin St., Dublin 8.

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 Tantt [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:

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

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° , 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 meet 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.

4 References

1. Isermann, R., *Digital control systems Volume 1. Fundamentals, deterministic control*, Springer-Verlag, 1989.
2. Isermann, R., *Digital control systems Volume 2. Stochastic control, multivariable control, adaptive control, applications*, Springer-Verlag, 1991.
3. Koivo, H.N. and Tanntu, J.T. (1991). Proc. *IFAC Intelligent Tuning and Adaptive Control Symposium*, Singapore, 75.
4. Hwang, S.-H. (1993). *Chemical Engineering Communications*, **124**, 131.
5. Astrom, K.J. and Hagglund, T. (1995). *PID controllers: theory, design and tuning*, Instrument Society of America.
6. Bialkowski, W.L. (1996). *The Control Handbook*. Editor: W.S. Levine, CRC/IEEE Press, Boca Raton, Florida, 1219.
7. Ender, D.B. (1993). *Control Engineering*, **September**, 180.
8. O'Dwyer (2000). *Technical Report 2000-02*, <http://www.docsee.kst.dit.ie/aodweb>, April.
9. Bueno, S.S., De Keyser, R.M.C. and Favier, G. (1991). *Journal A*, **32**(1), 28.
10. Astrom, K.J., Hagglund, T., Hang, C.C. and Ho, W.K. (1993). *Control Engineering Practice*, **1**, 699.
11. Astrom, K.J., (1996). Proc. *13th World Congress of IFAC*, San Francisco, CA, USA, **Plenary Volume**, 1.
12. Chen, G. (1996). *International Journal of Intelligent Control and Systems*, **1**(2), 235.
13. Gorez, R. (1997). *Journal A*, **38**, 3.
14. Seborg, D.E., Edgar, T.F. and Shah, S.L. (1986). *AIChE Journal*, **32**, 881.

15. Fisher, D.G. (1991). *The Canadian Journal of Chemical Engineering*, **69**, 5.
16. Lelic, M. and Gajic, Z. (2000). Preprints, *Proc. PID '00: IFAC Workshop on digital control*, Terrassa, Spain, 73.
17. Astrom, K.J. and Wittenmark, B. (1984). *Computer controlled systems: theory and design*, Prentice-Hall International Inc..
18. Hagglund, T. and Astrom, K.J. (1991). *Automatica*, **27**, 599.
19. Seborg, D.E., Edgar, T.F. and Mellichamp, D.A. (1989). *Process dynamics and control*, John Wiley and Sons.
20. Pollard, A. (1971). *Process control*, Heinemann Educational Books.
21. Power, H.M. and Simpson, R.J. (1978). *Introduction to dynamics and control*, McGraw-Hill.
22. Leigh, J.R. (1987). *Applied control theory*, Revised 2nd edition, Peter Peregrinus Ltd..
23. Kuo, B.C. (1991). *Automatic control systems*, 6th Edition, Prentice-Hall Inc..
24. Philips, C.L. and Harbor, R.D. (1991). *Feedback control systems*, 2nd edition, Prentice-Hall.
25. Atkinson, P. and Davey, R.L. (1968). *Control*, **March**, 238.
26. Hougen, J.O. (1979). *Measurement and control applications*, Instrument Society of America.
27. Shahian, B. and Hassul, M. (1993). *Control system design using MATLAB*, Prentice-Hall, 1993.
28. Ziegler, J.G. and Nichols, N.B. (1942). *Transactions of the ASME*, **64**, 759.
29. Hazebroek, P. and Van der Waerden, B.L. (1950). *Transactions of the ASME*, **April**, 317.
30. Wolfe, W.A. (1951). *Transactions of the ASME*, **May**, 413.
31. Chien, K.L., Hrones, J.A. and Reswick, J.B. (1952). *Transactions of the ASME*, **February**, 175.
32. Cohen, G.H. and Coon, G.A. (1953). *Transactions of the ASME*, **July**, 827.
33. Murrill, P.W. (1967). *Automatic control of processes*, International Textbook Co..
34. Murrill, P.W. and Smith, C.L. (1966). *Hydrocarbon Processing*, **45**(2), 105.
35. Astrom, K.J. and Hagglund, T. (1988). *Automatic tuning of PID Controllers*, Instrument Society of America.
36. Parr, E.A. (1989). *Industrial Control Handbook: Volume 3*, BSP Professional Books.
37. Witt, S.D. and Waggoner, R.C. (1990). *Hydrocarbon Processing*, **June**, 74.
38. Sain, S.G. and Ozgen, C. (1992). *Control and Computers*, **20**(3), 73.
39. Hang, C.C., Lee, T.H. and Ho, W.K. (1993). *Adaptive Control*, Instrument Society of America.
40. McMillan, G.K. (1994). *Tuning and control loop performance - a practitioner's guide*, Instrument Society of America.
41. VanDoren, V.J. (1998). *Control Engineering*, **December**.
42. Ford, R.L. (1953). *Proceedings of the IEE, Part 2*, **101**(80), 141, 173.
43. Tyreus, B.D. and Luyben, W.L. (1992). *Industrial Engineering Chemistry Research*, **31**, 2625.
44. Krishnaswamy, P.R. and Rangaiah, G.P. (1992). *Transactions of the Institute of Chemical Engineering*, **70**(A), 149.
45. Auslander, D.M., Takahashi, Y. and Tomizuka, M. (1975). *Transactions of the ASME: Journal of Dynamic Systems, Measurement and Control*, **September**, 280.
46. Jussila, T.T. and Koivo, H.N. (1987). *IEEE Transactions on Automatic Control*, **AC-32**, 364.
47. Lopez, A.M., Millar, J.A., Smith, C.L. and Murrill, P.W. (1967). *Instrumentation Technology*, **November**, 57.
48. Miller, J.A., Lopez, A.M., Smith, C.L. and Murrill, P.W. (1967). *Control Engineering*, **December**, 72.
49. Kaya, A. and Scheib, T.J. (1988). *Control Engineering*, **July**, 62.
50. Shinskey, F.G. (1988). *Process control systems - application, design and tuning*, 3rd Edition, McGraw-Hill Inc..
51. Shinskey, F.G. (1996). *Process control systems - application, design and tuning*, 4th Edition, McGraw-Hill Inc..
52. Yu, S. W. (1988). *Journal of the Chinese Institute of Chemical Engineers*, **19**(6), 349.
53. Zhuang, M. and Atherton, D.P. (1993). *IEE Proceedings, Part D*, **140**, 216.
54. Marlin, T.E. (1995). *Process Control*, Mc-Graw Hill Inc..
55. Huang, C.-T., Chou, C.-J. and Wang, J.-L. (1996). *Journal of the Chinese Institute of Chemical Engineers*, **27**(2), 107.
56. Huang, C.-T. and Lin, Y.-S. (1995). *Chemical Engineering Communications*, **133**, 11.
57. Shinskey, F.G. (1994). *Feedback controllers for the process industries*, McGraw-Hill Inc..
58. Poulin, E. and Pomerleau, A. (1996). *IEE Proceedings - Control Theory and Applications*, **143**, 429.
59. Srividya, R. and Chidambaram, M. (1997). *Process Control and Quality*, **9**, 59.
60. Wills, D.M. (1962). *Control Engineering*, **April**, 104.
61. Wills, D.M. (1962). *Control Engineering*, **August**, 93.
62. Haalman, A. (1965). *Control Engineering*, **July**, 71.
63. McAvoy, T.J. and Johnson, E.F. (1967). *Industrial and Engineering Chemistry Process Design and Development*, **6**, 440.
64. Lopez, A.M., Smith, C.L. and Murrill, P.W. (1969). *British Chemical Engineering*, **14**, 1553.
65. Sung, S.W., O., J., Lee, I.-B., Lee, J. and Yi, S.-H. (1996). *Journal of Chemical Engineering of Japan*, **29**, 990.
66. Sung, S.W. and Lee, I.-B. (1996). *Industrial Engineering Chemistry Research*, **35**, 2596.
67. Park, H.I., Sung, S.W., Lee, I.-B. and Lee, J. (1997). *Chemical Engineering Communications*, **161**, 163.
68. Poulin, E. and Pomerleau, A. (1997). *IEE Proceedings - Control Theory and Applications*, **144**, 566.
69. Wang, F.-S., Juang, W.-S. and Chan, C.-T. (1995). *Chemical Engineering Communications*, **132**, 15.
70. Rovira, A.A., Murrill, P.W. and Smith, C.L. (1969). *Instruments and Control Systems*, **December**, 67.
71. Khan, B.Z. and Lehman, B. (1996). *IEEE Transactions on Control Systems Technology*, **4**, 459.
72. Fertik, H.A. (1975). *ISA Transactions*, **14**, 292-304.
73. Polonyi, M.J.G. (1989). *Control Engineering*, **March**, 102.
74. Seem, J.E., (1998). *Automatica*, **34**(8), 969.#
75. Tan, W., Liu, J. and Tam, P.K.S. (1998). *IEE Proceedings - Control Theory and Applications*, **145**(6), 485.
76. Taguchi, H. and Araki, M. (2000). Preprints *Proc. PID '00: IFAC Workshop on digital control*, Terrassa, Spain, 95.
77. Krishnaswamy, P.R., Rangaiah, G.P., Jha, R.K. and Deshpande, P.B. (1990). *Industrial Engineering Chemistry Research*, **29**, 2163.
78. Moore, C.F., Smith, C.L. and Murrill, P.W. (1969). *Instrument Practice*, **January**, 45.
79. Rovira, A.A., Murrill, P.W. and Smith, C.L. (1970). *Instruments and Control Systems*, **August**, 101.
80. Huang, H.-P. and Chao, Y.-C. (1982). *Chemical Engineering Communications*, **18**, 51.
81. De Paor, A.M. (1993). *International Journal of Electrical Engineering Education*, **30**, 303.
82. Hwang, S.-H. (1995). *Industrial Engineering Chemistry Research*, **34**, 2406.
83. Hwang, S.-H. and Fang, S.-M. (1995). *Chemical Engineering Communications*, **136**, 45.
84. Pessen, D.W. (1994). *Transactions of the ASME. Journal of Dynamic Systems, Measurement and Control*, **116**, 553.
85. Hang, C.C., Astrom, K.J. and Ho, W.K. (1991). *IEE Proceedings, Part D*, **138**, 111.

86. Hang, C.-C. and Cao, L. (1996). *IEEE Transactions on Industrial Electronics*, **43**, 477.
87. Astrom, K.J. and Hagglund, T. (1984). *Automatica*, **20**, 645.
88. Tan, K.K., Lee, T.H. and Wang, Q.G. (1996). *AIChE Journal*, **42**, 2555.
89. Luyben, W.L. (1996). *Industrial Engineering Chemistry Research*, **35**, 3480.
90. Belanger, P.W. and Luyben, W.L. (1997). *Industrial Engineering Chemistry Research*, **36**, 5339.
91. Kookos, I.K., Lygeros, A.I. and Arvanitis, K.G. (1999). *European Journal of Control*, **5**, 19.
92. Hwang, S.-H. and Chang, H.-C. (1987). *Chemical Engineering Science*, **42**, 2395.
93. Boe, E., Hwang, S.-W. and Chang, H.-C. (1988). *Journal of the Chinese Institute of Chemical Engineers*, **19**, 359.
94. Blickley, G.J. (1990). *Control Engineering*, **2 October**, 11.
95. Corripio, A.B. (1990). *Tuning of industrial control systems*, Instrument Society of America.
96. Perry, R.H. and Chilton, C.H. (1973). *Chemical engineers handbook*, 5th edition, McGraw-Hill.
97. Yu, C.-C. (1999). *Autotuning of PID controllers*, Advances in Industrial Control Series, Springer-Verlag London Ltd..
98. Fu, M., Olbrot, A.W. and Polis, M.P. (1989). *IEEE Control Systems Magazine*, **January**, 100.
99. Pessen, D.W. (1953). *Transactions of the ASME*, **July**, 843.
100. Pessen, D.W. (1954). *Instrumentation*, **7(3)**, 29.
101. Grabbe, E.M., Ramo, S. and Woolridge, D.E. (Ed.) (1961). *Handbook of automation, computation and control. Vol. 3: System and Components*, John Wiley and Sons.
102. Harriott, P. (1964). *Process control*, McGraw-Hill, New York, U.S.A..
103. Mantz, R.J. and Tacconi, E.J. (1989). *International Journal of Control*, **49**, 1465.
104. Leva, A. (1993). *IEE Proceedings, Part D*, **140**, 328.
105. Vrancic, D., Peng, Y. and Strmcnik, S. (1999). *Control Engineering Practice*, **7(5)**, 623.
106. Hang, C.C., Loh, A.P. and Vasnani, V.U. (1994). *IEEE Transactions on Control Systems Technology*, **2**, 42.
107. Bobal, V. (1995). *International Journal of Adaptive Control and Signal Processing*, **9**, 213.
108. Bobal, V., Bohm, J. and Prokop, R. (1999). *International Journal of Adaptive Control and Signal Processing*, **13**, 671.
109. Luyben, W.L. (1986). *Industrial and Engineering Chemistry Process Design and Development*, **25**, 654.
110. Loh, A.P., Hang, C.C., Quek, C.K. and Vasnani, V.U. (1993). *Industrial and Engineering Chemistry Research*, **32**, 1102.
111. Shen, S.-H. and Yu, C.-C. (1990). *AIChE Journal*, **40**, 627.
112. Wu, W.-T., Tseng, C.-G. and Chu, Y.T. (1994). *International Journal of System Science*, **25**, 423.
113. Zhuang, M. and Atherton, D.P. (1994). *IEE Proceedings - Control Theory and Applications*, **141**, 111.
114. Palmor, Z.J., Halevi, Y. and Krasney, N. (1995). *Automatica*, **31**, 1001.
115. Halevi, Y., Palmor, Z.J. and Efrati, E. (1997). *Journal of Process Control*, **7**, 119.
116. Wang, Q.-G., Lee, T.-H. and Zhang, Y. (1998). *Industrial Engineering Chemistry Research*, **37**, 4725.
117. Hwang, S.-H. and Tseng, T.-S. (1994). *Chemical Engineering Science*, **49**, 1973.
118. Schneider, D.M. (1988). *IEEE Transactions on Industry Applications*, **24**, 186.
119. Pemberton, T.J. (1972). *Control Engineering*, **19(5)**, 66.
120. Smith, C.A. and Corripio, A.B. (1985). *Principles and practice of automatic process control*, John Wiley.
121. Gorecki, H., Fuska, S., Grabowski, P. and Korytowski, A. (1989). *Analysis and synthesis of time delay systems*, John Wiley.
122. Chiu, K.C., Corripio, A.B. and Smith, C.L. (1973). *Instruments and Control Systems*, **December**, 41.
123. Cox, C.S., Daniel, P.R. and Lowden, A. (1997). *Control Engineering Practice*, **5**, 1463.
124. Cluett, W.R. and Wang, L. (1997). *Pulp and Paper Canada*, **98(6)**, 52.
125. Juang, W.-S. and Wang, F.-S. (1995). *Journal of the Chinese Institute of Chemical Engineers*, **26**, 133.
126. Davydov, N.I., Idzon, O.M. and Simonova, O.V. (1995). *Thermal Engineering*, **42(10)**, 801.
127. Tsang, K.M. and Rad, A. B. (1995). *International Journal of Systems Science*, **26**, 639.
128. Rotach, V. Ya. (1995). *Thermal Engineering*, **42(10)**, 794.
129. Abbas, A. (1997). *ISA Transactions*, **36**, 183.
130. Chien, I.-L., Huang, H.-P. and Yang, J.-C. (1999). *Industrial Engineering Chemistry Research*, **38(4)**, 1456.
131. Bi, Q., Cai, W.-J., Lee, E.-L., Wang, Q.-G., Hang, C.-C. and Zhang, Y. (1999). *Control Engineering Practice*, **7(1)**, 71.
132. Jacob, E.F. and Chidambaram, M. (1996). *Computers in Chemical Engineering*, **20**, 579.
133. Valentine, C.C. and Chidambaram, M. (1997). *Chemical Engineering Communications*, **162**, 63.
134. Huang, H.-P. and Chen, C.-C. (1997). *IEE Proceedings - Control Theory and Applications*, **144**, 334.
135. Wang, L. and Cluett, W.R. (1997). *IEE Proceedings - Control Theory and Applications*, **144**, 385.
136. Pemberton, T.J. (1972). *Control Engineering*, **19(7)**, 61.
137. Smith, C.L., Corripio, A.B. and Martin, J. (1975). *Instrumentation Technology*, **December**, 39.
138. Wang, T.-S. and Clements, W.C. (1995). *Chemical Engineering Communications*, **132**, 1.
139. Martin, J., Corripio, A.B. and Smith, C.L. (1976). *ISA Transactions*, **15**, 314.
140. Wang, Q.-G., Lee, T.-H., Fung, H.-W., Bi, Q. and Zhang, Y. (1999). *IEEE Transactions on Control Systems Technology*, **7(4)**, 457.
141. Ho, W.K., Hang, C.C. and Zhou, J.H. (1995). *IEEE Transactions on Control Systems Technology*, **3**, 245.
142. Voda, A. and Landau, I.D. (1995). *International Journal of Adaptive Control and Signal Processing*, **9**, 395.
143. Leva, A., Maffezzoni, C. and Scattolini, R. (1994). *Automatica*, **30**, 1171.
144. Li, Z., Su, X. and Lin, P. (1994). *Advances in Modelling and Analysis C*, ASME Press, **40(2)**, 17.
145. Friman, M. and Waller, K.V. (1997). *Industrial Engineering Chemistry Research*, **36**, 2662.
146. Ho, W.K., Lim, K.W. and Xu, W. (1998). *Automatica*, **34(8)**, 1009.
147. Ho, W.K. and Xu, W. (1998). *IEE Proceedings - Control Theory and Applications*, **145(5)**, 392.
148. De Paor, A.M. and O' Malley, M. (1989). *International Journal of Control*, **49**, 1273.
149. Venkatasankar, V. and Chidambaram, M. (1994). *International Journal of Control*, **60**, 137.
150. Chidambaram, M. (1995). *Hungarian Journal of Industrial Chemistry*, **23**, 123.
151. Hang, C.C., Ho, W.H. and Cao, L.S. (1994). *ISA Transactions*, **33**, 147.
152. Ho, W.K., Hang, C.C. and Cao, L.S. (1995). *Automatica*, **31**, 497.
153. Ho, W.K., Hang, C.C. and Zhou, J. (1997). *IEEE Transactions on Control Systems Technology*, **5**, 446.
154. Wang, Y.-G. and Shao, H.-H. (1999). *Industrial Engineering Chemistry Research*, **38**, 3007.
155. Poulin, E. and Pomerleau, A. (1999). *IEEE Transactions on Control Systems Technology*, **7(4)**, 509.
156. Yang, Y.-G. and Shao, H.-H. (2000). *Automatica*, **36**, 147.

157. Zaigen, L. and Hanru, Z. (1994). *Advances in Modelling and Analysis C*, **40**(2), 1.
158. Ho, W.K., Lee, T.H. and Gan, O.P. (1997). *Industrial Engineering Chemistry Research*, **36**, 2231.
159. Brambilla, A., Chen, S. and Scali, C. (1990). *Hydrocarbon Processing*, **November**, 53.
160. Rivera, D.E., Morari, M. and Skogestad, S. (1986). *Industrial and Engineering Chemistry Process Design and Development*, **25**, 252.
161. Fruehauf, P.S., Chien, I.-L. and Lauritsen, M.D. (1993). *ISA Transactions*, **33**, 43.
162. Lee, Y., Park, S., Lee, M. and Brosilow, C. (1998). *AIChE Journal*, **44**, 106.
163. Morari, M. and Zafiriou, E. (1989). *Robust process control*, Prentice-Hall Inc..
164. Horn, I.G., Arulandu, J.R., Gombas, C.J., VanAntwerp, J.G. and Braatz, R.D. (1996). *Industrial Engineering Chemistry Research*, **35**, 3437.
165. Alvarez-Ramirez, J., Morales, A. and Cervantes, I. (1998). *Industrial Engineering Chemistry Research*, **37**, 4740.
166. Isaksson, A.J. and Graebe, S.F. (1999). *Automatica*, **35**, 1121.
167. Chun, D., Choi, J.Y. and Lee, J. (1999). *Industrial Engineering Chemistry Research*, **38**(4), 1575.
168. Chen, C.-L., Huang, H.-P. and Hsieh, C.-T. (1999). *Journal of Chemical Engineering of Japan*, **32**(6), 783.
169. Rotstein, G.E. and Lewin, D.E. (1991). *Industrial Engineering Chemistry Research*, **30**, 1864.
170. Zhang, W., Xu, X. and Sun, Y. (1999). *Automatica*, **35**, 719.
171. Jahanmiri, A. and Fallahi, H.R. (1997). *Transactions of the Institute of Chemical Engineers*, **75**(A), 519.
172. Huang, H.-P., Chien, I.-L., Lee, Y.-C. and Wang, G.-B. (1998). *Chemical Engineering Communications*, **165**, 89.
173. Lee, Y., Park, S. and Lee, M. (1998). *Industrial Engineering Chemistry Research*, **37**, 1859.
174. Friman, M. and Waller, K.V. (1994). *Industrial Engineering Chemistry Research*, **33**, 1708.
175. Semino, D. and Scali, C. (1998). *Journal of Process Control*, **8**, 219.
176. O'Dwyer, A. (2000). *Technical Report 2000-01*, <http://www.docsee.kst.dit.ie/aodweb>, February.
177. Harris, S.L. and Mellichamp, D.A. (1985). *AIChE Journal*, **31**, 484.
178. Lee, J., Cho, W. and Edgar, T.F. (1990). *AIChE Journal*, **36**, 1891.
179. Nishikawa, Y., Sannomiya, N., Ohta, T. and Tanaka, H. (1984). *Automatica*, **20**, 321.
180. Patwardhan, A.A., Karim, M.N. and Shah, R. (1987). *AIChE Journal*, **33**, 1735.
181. Zevros, C., Belanger, P.R. and Dumont, G.A. (1988). *Automatica*, **24**, 165.
182. Schei, T.S. (1994). *Automatica*, **30**, 1983.
183. Di Ruscio, D. (1992). *Modeling, Identification and Control*, **13**, 189.
184. Nakano, E. and Jutan, A. (1994). *ISA Transactions*, **33**, 353.
185. Abbas, A. and Sawyer, P.E. (1995). *Computers and Chemical Engineering*, **19**, 241.
186. Wang, L., Barnes, T.J.D. and Cluett, W.R. (1995). *IEE Proceedings - Control Theory and Applications*, **142**, 265.
187. Wang, F.-S., Yeh, C.-L. and Wu, Y.-C. (1996). *Transactions of the Institute of Measurement and Control*, **18**, 183.
188. Ham, T.W. and Kim, Y.H. (1998). *Industrial Engineering Chemistry Research*, **37**, 482.
189. Hizal, N.A. (1997). *Turkish Journal of Engineering and Environmental Sciences*, **21**, 83.
190. Astrom, K.J., Panagopoulos, H. and Hagglund, T. (1998). *Automatica*, **34**, 585.
191. Ruano, A.E.B., Fleming, P.J. and Jones, D.I. (1992). *IEE Proceedings, Part D*, **139**, 279.
192. Ruano, A.E.B., Lima, J.M.G., Mamat, R. and Fleming, P.J. (1996). *Journal of Systems Engineering*, **6**, 166.
193. Wu, C.-J. and Huang, C.-H. (1997). *Journal of the Franklin Institute*, **334B**, 547.
194. Leva, A. and Colombo, A.M. (1999). *IEE Proceedings - Control Theory and Applications*, **146**(2), 137.
195. Liu, G.P. and Daley, S. (1999). *Control Engineering Practice*, **7**, 821.
196. Cameron, F. and Seborg, D.E. (1983). *International Journal of Control*, **38**, 401.
197. Ralston, P.A.S., Watson, K.R., Patwardhan, A.A. and Deshpande, P.B. (1985). *Industrial and Engineering Chemistry Process Design and Development*, **24**, 1132.
198. Bortolotto, G., Desages, A. and Romagnoli, J.A. (1989). *Chemical Engineering Communications*, **86**, 17.
199. Vega, P., Prada, C. and Aleixandre, V. (1991). *IEE Proceedings - Part D*, **138**, 303.
200. Yang, Y., Jia, C., Chen, J. and Lu, Y. (1991). *Computers in Industry*, **16**, 81.
201. Miura, N., Imaeda, M., Hashimoto, K., Wood, R.K., Hattori, H. and Onishi, M. (1998). *Journal of Chemical Engineering of Japan*, **31**, 626.
202. Kelly, J.D. (1998). *The Canadian Journal of Chemical Engineering*, **76**, 967.
203. Wang, F.-S. and Wu, T.-Y. (1995). *Transactions of the Institute of Measurement and Control*, **17**, 27.
204. Puleston, P.F. and Mantz, R.J. (1995). *Industrial and Engineering Chemistry Research*, **34**, 2993.
205. Ham, T.W. and Kim, Y.H. (1998). *Journal of Chemical Engineering of Japan*, **31**(6), 941.
206. Woldai, A., Al-Gobaisi, D.M.K., Dunn, R.W., Kurdali, A. and Rao, G.P. (1996). *Control Engineering Practice*, **4**(5), 721.
207. Schuster, T. (1989). *Periodica Polytechnica Series - Electrical Engineering*, **33**, 263.
208. Aguirre, L.A. (1992). *Electronics Letters*, **28**, 2269.
209. Zhao, Z.-Y., Tomikuz, M. and Iskra, S. (1993). *IEEE Transactions on Systems, Man and Cybernetics*, **23**, 1392.
210. Hwang, S.-H. and Shiu, S.-J. (1994). *International Journal of Control*, **60**, 265.
211. Sung, S.W., Lee, I.-B. and Lee, J. (1995). *Industrial Engineering Chemistry Research*, **34**, 4127.
212. Prokop, R. and Meszaros, A. (1996). *Journal of Electrical Engineering*, **42**(11-12), 287.
213. Daley, S. and Liu, G.P. (1999). *IEE Computing and Control Engineering Journal*, **April**, 51.
214. Jung, C.L., Song, H.K. and Hyun, J.C. (1999). *The Canadian Journal of Chemical Engineering*, **77**, 180.
215. Jung, C.L., Song, H.K. and Hyun, J.C. (1999). *Journal of Process Control*, **9**(3), 265.
216. Atherton, D.P. (1999). *IEE Computing and Control Engineering Journal*, **April**, 44.
217. Majhi, S. and Atherton, D.P. (1999). *IEE Proceedings - Control Theory and Applications*, **146**(5), 415.
218. Edgar, T.F., Heeb, R. and Houg, J.O. (1981). *Computers and Chemical Engineering*, **5**, 225.
219. Sanathanan, C.K. and Quinn, S.B. (1987). *AIChE Journal*, **33**, 1873.
220. Devanathan, R. (1991). *Journal of Electrical and Electronics Engineering, Australia*, **11**(3), 172.
221. Thomson, M., Cassidy, P.G. and Sandoz, D.J. (1989). *Transactions of the Institute of Measurement and Control*, **11**, 40.
222. Schei, T.S. (1992). *Automatica*, **28**, 587.
223. Kim, Y.H. (1995). *Journal of Chemical Engineering of Japan*, **28**, 118.
224. Barnes, T.J.D., Wang, L. and Cluett, W.R. (1993). *Proc. American Control Conference*, San Francisco, U.S.A., 890.
225. Shafiei, Z. and Shenton, A.F. (1994). *Automatica*, **30**, 1609.

226. Shafiei, Z. and Shenton, A.F. (1997). *Automatica*, **33**, 2223.
227. Natarajan, K. and Gilbert, A.F. (1997). *ISA Transactions*, **36**(2), 139.
228. Natarajan, K. and Gilbert, A.F. (1997). *The Canadian Journal of Chemical Engineering*, **75**, 765.
229. Leva, A. (1997). *European Journal of Control*, **3**, 150.
230. Wang, Q.-G., Hang, C.-C. and Bi, Q. (1997). *Transactions of the Institute of Chemical Engineers*, **75**(A), 64.
231. Wang, Q.-G., Hang, C.-C., Zhu, S.-A. and Bi, Q. (1999). *Journal of Process Control*, **9**(4), 291.
232. Fung, H.-W., Wang, Q.-G. and Lee, T.-H. (1998). *Automatica*, **34**, 1145.
233. Pal, J., Nagar, S.K. and Sharma, J.D. (1992). *International Journal of Systems Science*, **23**, 2385.
234. Yang, J.-S. (1993). *Chemical Engineering Communications*, **122**, 227.
235. Tzafestas, S. and Kapsiotis, G. (1994). *Mathematics and Computers in Simulation*, **37**, 133.
236. Jung, J., Choi, J.Y. and Lee, J. (1999). *Industrial Engineering Chemistry Research*, **38**(4), 1580.
237. El-Shal, S.L. and El-Rabaie, N.M. (1995). *International Journal of System Science*, **26**(3), 499.
238. Maffezzoni, C. and Rocco, P. (1997). *European Journal of Control*, **3**, 125.
239. Kraus, T.W. and Myron, T.J. (1984). *Control Engineering*, **June**, 106.
240. Litt, J. (1991). An expert system to perform on-line controller tuning, *IEEE Control Systems Magazine*, **April**, 18.
241. Mahmoud, M.S., Abou-Elseoud, A.A. and Kotob, S. (1992). *Journal of Intelligent and Robotic Systems*, **5**, 129.
242. Lee, T.H., Hang, C.C., Ho, W.K. and Yue, P.K. (1993). *Automatica*, **29**, 1107.
243. Ho, W.K., Lee, T.H. and Tay, E.B. (1998). *Control Engineering Practice*, **6**, 855.
244. Acosta, G.G., Mayosky, M.A. and Catalfo, J.M. (1994). *Journal of Applied Intelligence*, **4**, 53.
245. Lawrence, A.J. and Harris, C.J. (1996). *Proceedings of the Institute of Mechanical Engineers. Part I: Journal of Systems and Control Engineering*, **210**, 14.
246. Tzafestas, S. and Papanikolopoulos, N.P. (1990). *IEEE Transactions on Industrial Electronics*, **37**(5), 365.
247. Ling, C. and Edgar, T.F. (1993). *Asia-Pacific Engineering Journal (Part A)*, **3**(1-2), 83.
248. Xu, J.-X., Liu, C. and Hang, C.C. (1996). *ISA Transactions*, **35**, 79.
249. Xu, J.-X., Liu, C. and Hang, C.-C. (1996). *Engineering Applications of Artificial Intelligence*, **9**(1), 65.
250. Xu, J.-X., Pok, Y.-M., Liu, C. and Hang, C.-C. (1998). *IEEE Transactions on Systems, Man and Cybernetics - Part A: System and Humans*, **28**, 685.
251. Bandyopadhyay, R. and Patranabis, D. (1998). *ISA Transactions*, **37**, 227.
252. Wang, L., Desarmo, M.L. and Cluett, W.R. (1999). *Automatica*, **35**, 1427.
253. Mudi, R.K. and Pal, N.R. (1999). *IEEE Transactions on Fuzzy Systems*, **7**(1), 2.
254. Visioli, A. (1999). *IEEE Transactions on Systems, Man and Cybernetics – Part A: Systems and Humans*, **29**(6), 587.
255. Wang, P. and Kwok, D.P. (1994). *Control Engineering Practice*, **2**, 641.
256. Vlachos, C., Williams, D. and Gomm, J.B. (1999). *IEE Proceedings – Control Theory and Applications*, **146**(1), 58.
257. Chan, K.C., Leong, S.S. and Lin, G.C.I. (1995). *Artificial Intelligence in Engineering*, **9**, 167.
258. Sbarbaro, D., Segovia, J.P., Alcozer, S. and Gonzales, J. (2000). *IEEE Transactions on Control Systems Technology*, **8**(1), 14.