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RELAY AUTOTUNING OF MULTIVARIABLE SYSTEMS: APPLICATION TO AN EXPERIMENTAL PILOT-SCALE DISTILLATION COLUMN

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Abstract: This paper describes the application of multivariable sequential relay autotuning techniques to a pilot scale distillation system under industrial DCS monitoring and control environment. Implementation aspects arising in any realistic industrial environment are fully discussed such as the architecture for on-line communication and information extraction as well as valve hysteresis and backlash compensation. The performance of alternative tuning strategies is compared for both set-point changes and disturbances rejection. *Copyright © 2002 IFAC*

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1. INTRODUCTION

Decentralised controllers with PI/PID algorithm continue to find wide application in multivariable industrial processes. The main advantages of decentralised controllers over MIMO controllers are the much simpler design and way of operation, even though performance is potentially inferior. For a successful application of MIMO controllers, a good knowledge of the process and a considerable effort is required for the identification of the process and the design of the control system. In addition, in the cases of large changes of operating conditions or process parameters, the design should be repeated to maintain optimal performance. For these reasons, it can be preferable a fast and simple design of controllers, to be frequently repeated, in order to give acceptable performance in all the conditions.

These considerations motivate the interest of adopting the relay feedback for identification and autotuning of MIMO processes. The classical procedure, previously developed by Åström and Hägglund (1984) for SISO processes can be applied to design of decentralised controllers for MIMO processes, according to the method of sequential design illustrated by Loh *et al.* (1993) and Shen and Yu (1994). A relay is used to perturb each loop one at time, with all other loops closed, and to bring the system in critical conditions (marginal stability); the critical parameters of the loop where the relay is inserted can be identified and the controller is designed; the procedure is then repeated up to convergence. Palmor *et al.* (1995) and Halevi *et al.* (1997) have proposed the adoption of a simultaneous relay technique, where all the controllers are replaced by relays, and a desired multivariable critical point of the process as a whole can be identified. However, this approach relies on the fact that all the loops develop oscillations at the same frequency, but Marchetti *et al.* (2000) have showed that in some cases this does not happen and the technique is therefore not applicable.

With the simple relay feedback the identification of the process is based only on the critical point, and thus the ZN tuning rules (Ziegler and Nichols, 1942) are the obvious choice; this does not guarantee stability for some process dynamics frequently met in applications. To face this problem, Shen and Yu (1994) proposed a modification to the ZN rules for multivariable processes suggesting the adoption of larger detuning factors; these settings can sometimes be too conservative and result in a weak control action and very slow responses. For these reasons, some additional knowledge of the process at lower frequencies should be obtained: the ATV technique (Li *et al.*, 1991), can be used to identify a transfer function model, by performing three tests with relay and additional delay at each step of the iterative procedure, the controller is then designed based on the identified model; Parabita *et al.* (2000) extended this approach to the ATV$^+$ technique (Scali *et al*., 1999), which is an improvement of ATV for completely unknown processes, and also showed how the Two Channel Relay (Friman and Waller, 1997) can be used for sequential autotuning of multivariable processes.

Despite these developments, only few practical implementations are reported in the literature. This paper describes the application of multivariable sequential relay autotuning to a pilot scale distillation system under industrial DCS monitoring and control environment. A possible architecture for on-line communication and information extraction is fully discussed as well as practical aspects usually found in an industrial environment such as: valve hysteresis and backlash. The structure of the paper is the following: sections 2 describes the sequential relay autotuning for MIMO processes; section 3 presents a review of the ATV$^+$ identification technique; section 4 describes the application to the pilot plant, with detailed description of the plant and the control system, and comparison of closed loop results; conclusions follow.

2. SEQUENTIAL RELAY AUTOTUNING OF MIMO PROCESSES

The relay feedback test was initially proposed by Åström and Hägglund (1984) for the identification of the critical point of SISO processes. By replacing the controller with a relay, the system can be brought under limit cycle conditions, with the advantage that the amplitude of the oscillations can be controlled. The critical parameters can then be found as:

$$k_u = \frac{4 \cdot h}{\pi \cdot a} \qquad \omega_u = \frac{2 \cdot \pi}{P_u} \tag{1}$$

where h is the relay height, a and P_u the amplitude and period of the resulting output oscillations.

Relay autotuning can be extended to multiloop systems following the procedure outlined in Loh *et al*. (1993) and in Shen and Yu (1994). Consider the case of a 2x2 system as illustrated in figure 1. The procedure goes through the following steps:

1. The controller C_1 is replaced by a relay, while the second control loop is open (C_2=0); this allows the identification of the critical parameters of $g_{11}(s)$ and the design the first controller C_1;
2. A relay is used in place of the controller C_2 in order to identify the dynamics between the second manipulated variable and the second controlled variable, while the first loop is closed with the C_1 controller as designed in step 1. The critical parameters are identified and the controller C_2 is designed
3. An iterative procedure is started by repeating steps 1 and 2 until convergence is achieved on the controller parameters.

The extension to a *nxn* system is straightforward by closing the relay on one loop at a time with the loops previously tuned already closed at their settings. The number of iterations needed to achieve convergence is usually quite small. In particular it is suggested by Loh *et al*. (1993) that, if the fastest loop is tuned first, no iterations may be needed since the effect of the slow loop dynamics on the fast loop can be almost negligible. With respect to the alternative technique of independent design which, for a n^{th} order system goes through the open loop identification of n^2 elements, the sequential design presents the advantages that only n transfer functions need to be identified; moreover, since every loop is identified with the other control loops closed, the effect of the interaction is present also during the identification phase and can thus be accounted for.

Shen and Yu (1994) point out that the response of a system having overdamped open loop dynamics can become underdamped when other loops of the process are closed. In this case the system can be represented by the following transfer function:

$$G(s) = \frac{k}{\tau^2 s^2 + 2\tau\xi s + 1} \cdot \frac{\alpha s + 1}{\beta s + 1} \cdot e^{-\theta s} \tag{2}$$

A system with this structure represents a typical case in which the Ziegler-Nichols controller may produce an unstable behaviour. For this reason Shen and Yu (1994) proposed a modification to the original technique: the identification is still limited to the simple relay test, but since for systems whose dynamics is given by equation (2) the ZN settings originate quite wide regions of instability, the authors propose stronger detuning factors. However, this criterion is still based only on the position of the critical point and in some cases these settings might turn out to be too conservative. To overcome these drawbacks the ATV$^+$ technique can be used to provide a more effective controller tuning: at each step of the sequential procedure three tests with relay and additional delay are performed, a transfer function model is identified, and the controller is then designed based on the identified model. A review of the ATV$^+$ technique is given in next section.

3. THE ATV$^+$ IDENTIFICATION TECHNIQUE

Relay tests can also be used to build a parametric

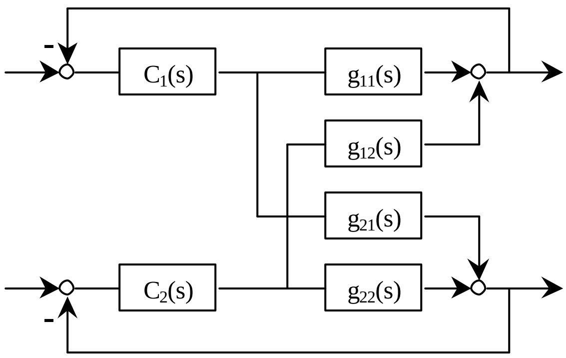

Figure 1: Structure of a 2x2 decentralised control system

model, following the ATV+ technique (Scali *et al.*, 1999), proposed as an improvement of the original ATV (Li *et al.*, 1991) for application to completely unknown processes, whereas the original ATV technique requires that the process dead time is known *a priori*. The first step of the procedure is a standard relay test, which provides the critical parameters of the process. The identification of other points of the Nyquist curve is made possible by introducing a delay element between the relay and the process, as shown in figure 2. When stable oscillations are developed the overall phase shift is again 180°, but only a part derives from the process, as the additional delay is also characterised by a phase lag. This last contribution is known and so the position of the identified point can be easily calculated. The values of the additional delay are chosen so that they correspond to phase lags of the delay element of ≅45° and ≅75° respectively, so that the identified point lies in the third quadrant.

From the position of the identified point a complex equation can be written as:

$$G(i\omega) = X_j + i \cdot Y_j \qquad (3)$$

where X and Y are the real and imaginary coordinates of the point identified in the j^{th} test, and the model parameters appear as unknowns in $G(i\omega)$. By separating the real and imaginary parts the previous gives two equations and by repeating the procedure for the three points we obtain a system of six equations. If the dead time θ is known (this is the case of the ATV identification) the system is linear, so it can be written in matrix form and solved in a least-squares sense through a pseudo-inversion. When the delay is not known the system must be solved for several trial values of θ. This calculation is repeated for all the candidate models and it is finally possible to choose the model which best suits the experimental data by comparing the value of the residual square error. If three relay tests are performed, a model with up to six unknown parameters could be identified, ranging from first to third order, with the possibility of a process zero in the transfer function. In practice it is chosen to use only models with a maximum of 5 parameters, in order to allow for some robustness and tolerance to errors. Further details about the ATV+ procedure can be found in Scali *et al.* (1999).

PI tuning parameters can then be calculated based on the identified model: at first an advanced IMC controller is designed, then it is reduced to PI structure by neglecting terms of higher order in *s*, as proposed in a previous work by Semino and Scali (1998). The models that are obtained from the ATV+

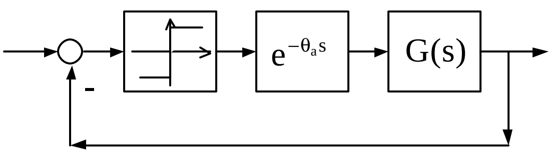

Figure 2: Setup of relay with additional delay

identification can also be used for the design of model-based controllers using the IMC framework, as showed in Marchetti and Scali (2000).

4. ON-LINE AAPLICATION TO A PILOT-SCALE PLANT

4.1. *Description of the plant*

The pilot plant consists of a distillation column with a diameter of 230 mm, equipped with 12 sieve trays positioned with an inter-tray spacing of 300 mm. An external thermosiphon reboiler (heated with live steam) is located at the base of the column to provide the necessary vapour boilup, and two condensers are placed at the top of the column for the condensation and cooling of the overhead vapours. Under the condensers the distillate is collected in a small drum, from which the reflux and the distillate are extracted. The column separates a mixture of water and ethanol which is approximately 25% by weight in ethanol; the feed location is not fixed, but it is possible to switch easily between plate number six, eight or ten (plate numbering is from the top), in the current plant setup the feed is introduced on plate ten. The top product contains approximately 83% by weight of ethanol (close to the composition of the azeoptrope), whereas the waste stream is removed with a residue ethanol concentration of 2% by weight. After separation, both the distillate and the bottom streams are returned to the feed tank and mixed again for re-use. Before returning to the feed tank, the bottom stream is passed through a plate heat exchanger to cool it down and thus reduce the loss of ethanol (the feed tank is vented to the atmosphere and the volatile ethanol would evaporate if stored at high temperature). The top of the column and the condensers are also vented to the atmosphere, so that the pressure at the top of the column can be considered equal to atmospheric pressure (101.3 kPa); due to the pressure head exerted by the liquid on the trays the pressure increases towards the bottom of the column where it is usually of the order of 110÷115 kPa). This means that in the lower trays in the column and in the reboiler temperatures up to 103 degrees can be found.

4.2. *Data acquisition and implementation architecture*

The column is monitored and controlled with an ABB MOD300 distributed control system (DCS). The column is well monitored, with thermocouples on trays number 1, 3, 5, 8, 10 and 12. The flow rates of all the streams (feed, distillate, bottom, reflux, steam) and the levels of the bottom of the column and of the distillate tank placed under the condenser are also available. The compositions of the feed, of the product streams, and of the liquid on several plates in the column can also be measured, thanks to an automated sampling system and a density meter:

samples of liquid are extracted from the specified point in the column and sent to the density meter, and the actual concentration can be inferred from the density and temperature of the sample. However, only one density meter is present and it is switching sequentially between eight different samples; since a cycle time of two minutes is required between sample changes (in order to ensure a good flushing of the tubes and avoid mixing between the different samples) the concentration measurement of the desired product stream is available only with a sample time of 16 minutes. This leads to unacceptably large dead times and thus prevents the use of these measurement for on-line composition control. The purity of the top and bottom products is thus controlled indirectly by measuring and controlling the temperature of opportunely selected pilot trays. In a previous study on this system (Noorai and Romagnoli, 1995) it has been pointed out that the best trays to control the purity of the top and bottom product are number 5 and 12 respectively. The LV control configuration has been used, with the reflux and steam flow rates used to control the pilot tray temperature on the top and bottom sections respectively; the distillate flow rate is used to control the level in the distillate tank, and the bottom flow rate to maintain the liquid level in the column bottom and reboiler. All the controllers are arranged in a cascade scheme, with the temperature (or level) controller as the master and the corresponding flow rate controller as the slave.

All the temperatures, flow rates and levels can be controlled within the DCS environment. The MOD300 controller offers all standard PID control capabilities, but in order to apply the relay tests and to perform the ATV^+ identification it is necessary to interface it with another PC-based control platform. The perfect tool for this purpose has been found in UNAC (produced by *Unac Advanced Solutions - A Division of Hunter Control*), an advanced control platform that runs on personal computers with the Microsoft Windows NT operating system. UNAC has the possibility of emulating the communication protocols of standard PLCs, and thus it can be used to communicate with the MOD300 controller; the connection is realised through a serial cable using the Modbus RS-232 protocol. UNAC can be used directly to control the plant with different control strategies (standard and adaptive PID, IMC, relay, etc.), and all the plant data that UNAC receives from the DCS can also be made available to other applications on the PC (such as MATLAB or Microsoft Excel) through DDE (Dynamic Data Exchange).

4.3. Results and discussion

Before focusing on the design of the multivariable temperature control system, the ATV^+ technique has been used to identify and re-tune the flow rate controllers that are used as slave in the cascade scheme. The results are not shown here for sake of brevity, but it is however worth describing one practical aspect that emerged during this application: the control valve that is used to regulate the steam flow rate turned out to be affected by hysteresis. As shown by Cheng and Yu (2000), this is an inconvenience often encountered that can seriously affect the accuracy of the relay feedback test results and the resulting control performance. To remove this inconvenience they propose that two tests are performed with different relay amplitudes, and due to the presence of hysteresis different values of the ultimate gain will be estimated in the two tests. From the values of the apparent critical parameters both the hysteresis and the real critical parameters of the process can be identified; full details about this procedure can be found in Cheng and Yu (2000). This technique can also be applied to correct the results of the relay tests performed for ATV^+: only one preliminary test is required, then the amplitude of the relay is changed and the usual three tests with relay and additional delay are performed. The amount of hysteresis affecting the actuator can be evaluated from the first test and the correction is then applied to the results of all the ATV^+ tests. This enables to compensate for the hysteresis during the identification, but with a standard controller the valve will still be affected by backlash, not responding promptly to changes in the direction of the control action. This behaviour can be corrected in UNAC, where it is possible to modify the PI controller with a backlash compensation algorithm, so that the effect of the valve hysteresis is completely removed.

Once the design and tuning of the slave control loops was completed, the sequential identification of the temperature loops was started: the procedure was started from the bottom of the column, because this showed to be the faster-responding loop. The autotuning procedure was performed three times using different identification strategies and controller tuning rules: at first only the standard relay test was performed and the controller was tuned with the ZN rules; the second time the SY rules were used to tune the controllers, still based on the results of the simple relay test; finally, the ATV^+ technique was applied at each step, with three tests with relay and additional delay.

In all cases it was found that activating the controller on the top loop after the second step had only a little effect on the controller parameters calculated for the bottom loop (variations of both parameter were contained under 10%), and so the procedure was always stopped after the third iteration. This may suggest that the system is not interacting or only weakly interacting. In fact, as it will be confirmed later by the closed loop results, the system under study is characterised by strong interaction only in one direction: changes in the bottom loop (i.e. the steam flow rate) rapidly and largely affect the temperatures also in the top part of the column, whereas changing the reflux has a slower and weaker effect on the bottom section of the column. This triangular nature of the system had also been observed by Rodriguez and Romagnoli (2000).

The ATV^+ technique can require longer times than the other simpler methods, because three relay tests are required at every step (and also because the second and third tests are characterised by oscillations with longer periods due to the presence of the delay). In the case under study, even if the different procedures were completed with the same number of iterations, the total time required by ATV^+ was ≅5.3 times longer than the time necessary to complete the tests with the ZN or SY techniques (the whole procedure was anyway completed in slightly more than two hours).

The performance of the different controller has been evaluated by varying the set-point of the two loops and introducing disturbances in the system, several examples are reported here. In all the following figures the solid line represents the response obtained with the ATV^+ controller, whereas the dashed and dotted lines show the responses of the Ziegler-Nichols (ZN) and Shen-Yu (SY) respectively; on each figure the top plot shows the variations in the temperature of the top pilot tray, and the bottom half refers to the bottom pilot tray. Figure 3 shows the responses of the three different controllers when a decrease in the pilot tray temperature for the top loop (i.e. an increase in the distillate purity) is required. The ZN controller provides the fastest response, although it shows a moderate overshoot and some oscillations. The ATV^+ controller shows a slightly slower initial response, but the new set-point is anyway reached and maintained in a shorter time; the SY controller shows a very slow response and the set-point is reached only after more than 15 minutes. It can be seen that there is very little interaction with the bottom loop (the deviation from the set-point is lower than 0.5 ºC). The responses of the dfferent controllers when the previous set-point is restored are shown on figure 4: the ZN and the ATV^+ controller have similar initial speed of response but the former shows a slightly higher overshoot and a very oscillating response. The SY controller has again a very slow response. Figures 5 and 6 show the system responses to set-point changes in the bottom loop. The Ziegler-Nichols controller shows again a faster but more aggressive and oscillating response, whereas the SY proves to be quite slow, especially in counteracting the effect of the interaction on the top loop; the ATV^+ controller provides a good trade-off, with relatively fast responses, limited oscillations and good control of the interaction. Figure 7 shows the response of the three controllers when the feed flow rate is reduced from 2.0 to 1.6 l/min. The first thing that is observed is that the ZN controller produces an unstable behaviour, large oscillations appear in the bottom temperature loop and soon propagate also to

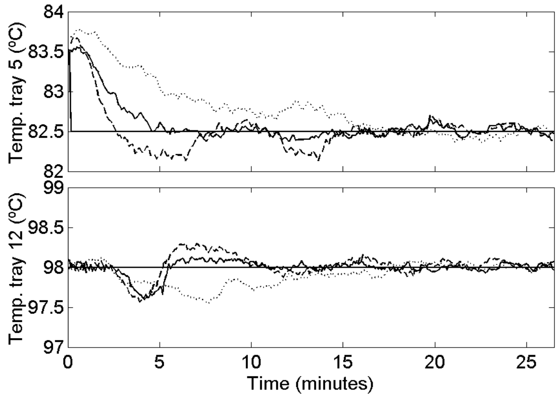

Figure 3: Different controller responses for a reduction in the top pilot tray set-point. —— ATV^+ controller, - - - ZN controller, · · · · SY controller

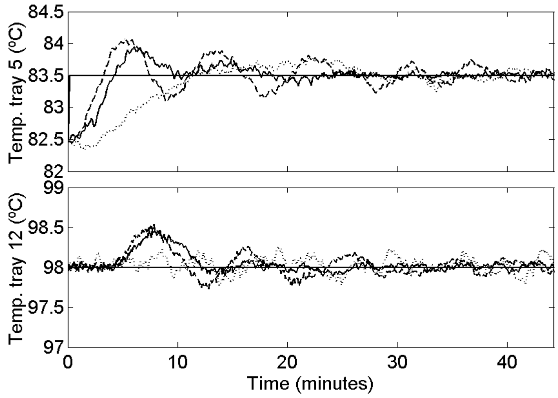

Figure 4: Different controller responses for an increase in the top pilot tray set-point.

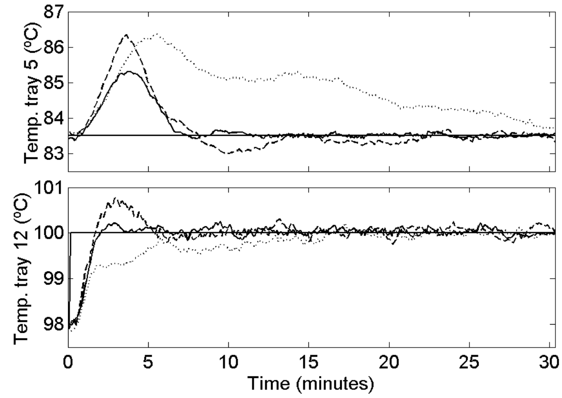

Figure 5: Different controller responses for an increase in the bottom pilot tray set-point.

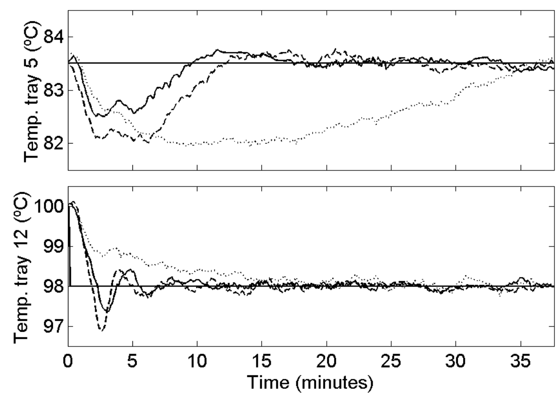

Figure 6: Different controller responses for a reduction in the bottom pilot tray set-point.

the top section of the column. The SY controller is again very slow, whereas the ATV+ restores the set-point in a shorter time, although with some oscillations. Finally, figure 8 shows the responses of the three controllers when the initial feed flow rate (2.0 l/min) is restored: it can again be observed that the ZN controller is characterised by a fast, oscillating behaviour, the SY is very sluggish (especially in the control of the top temperature) and the ATV+ offers again a reasonable compromise.

5. CONCLUSION

Application of different autotuning techniques for multivariable processes to a pilot-scale distillation plant was presented in this paper. The plant is monitored and controlled with standard industrial hardware and software, thus providing all the challenges of a pseudo-industrial environment. Results show that among the proposed autotuning techniques, ATV+ can achieve better performance when compared with conventional approaches. This is realised with longer identification times, but without introducing additional implementation complexities.

6. REFERENCES

Åström, K.J. and T. Hägglund (1984). Automatic Tuning of Simple Regulators with Specifications on Phase and Amplitude Margins. *Automatica*, **20**, 645-651

Cheng, Y.-C. and C.-C. Yu (2000). Relay Feedback Identification under Imperfect Actuator. *Int. Conf. on Process Control and Instrumentation (PCI 2000)*, Glasgow (UK), 256-261

Friman M. and K.V. Waller (1997). A Two-Channel Relay for Autotuning. *Ind. Eng. Chem. Res.*, **36**, 2662-2671

Halevi, Y., Z.J. Palmor, and T. Efrati (1997). Automatic Tuning of Decentralised PID Controllers for MIMO Processes. *Journal of Process Control*, **7**, 119

Li, W., E. Eskinat and W.L. Luyben (1991). An Improved Autotune Identification Method. *Ind. Eng. Chem. Res.*, **30**, 1530-1541

Loh, A.P., C.C. Hang, C.K. Quek and V.U. Vasnani (1993). Autotuning of Multiloop Proportional-Integral Controllers Using Relay Feedback. *Ind. Eng. Chem. Res.*, **32**, 1102-1107

Marchetti, G. and C. Scali (2000). Use of Modified Relay Techniques for the Design of Model Based Controllers for Chemical Processes. *Ind. Eng. Chem. Res.*, **39**, 3325-3334

Marchetti, G., P. Parabita and C. Scali (2000). Sequential versus Simultaneous Relay Techniques for Autotuning of Multivariable Processes. *Int. Conf. on Process Control and Instrumentation (PCI 2000)*, Glasgow (UK), 268-273

Nooraii, A., and J.A. Romagnoli (1995). Advanced Operational Techniques for an Experimental Column within a DCS Environment. *Ph.D. Thesis, University of Sydney*

Palmor, Z.J., Y. Halevi and N. Krasney (1995). Automatic Tuning of Decentralised PID Controllers for TITO Processes. *Automatica*, **31**, 1001-1010

Parabita, P., G. Marchetti and C. Scali (2000). Sequential Identification and Autotuning by Relay Techniques of Decentralised Controllers for MIMO Processes. *Proceedings of IFAC ADCHEM 2000*, Pisa (Italy), 767-772

Scali, C., G. Marchetti and D. Semino (1999). Identification and Autotuning of Completely Unknown Processes. *Ind. Eng. Chem. Res*, **38**, 1987-1997

Rodriguez, J.A. and J.A. Romagnoli (2000). Supervisory Control of Nonlinear Processes: a Pilot Scale Application. *Ph.D. Thesis, University of Sydney*

Semino, D. and C. Scali (1998). Improved Identification and Autotuning of PI Controllers for MIMO Processes by Relay techniques. *Journal of Process Control*, **8**, 219-227

Shen, S.H. and C.-C. Yu (1994). Use of Relay-Feedback Test for Automatic Tuning of Multivariable Systems. *AIChEJ*, **40**, 627-646

Ziegler, J.G. and N. B. Nichols (1942). Optimum Settings for Automatic Controllers. *Trans ASME*, **65**, 433-444

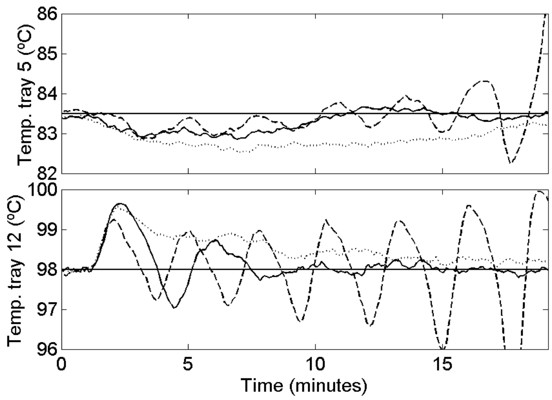

Figure 7: Different controller responses for a reduction in feed flow rate

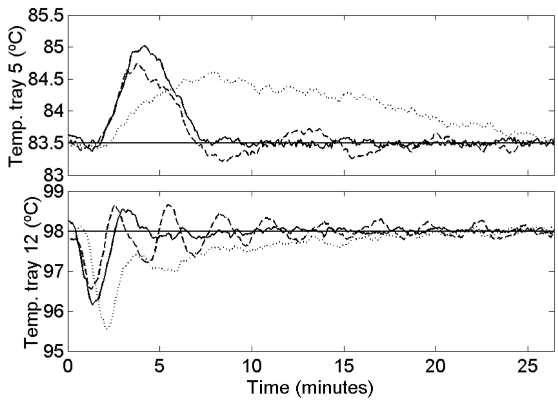

Figure 8: Different controller responses for an increase in feed flow rate