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Abstract

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ABSTRACT

This paper focuses on two issues in self-tuning control, integral action and integral windup. Particular attention is given to the problems arising when self-tuning controllers are cascaded with other controllers. When control loops are coupled via utilization of a flow from a common source, the coupling may increase these problems.

INTRODUCTION

The process configuration discussed in this paper was encountered in an activated sludge system in a waste-water treatment plant, with parallel almost identical processes for degradation of biological waste. The processes are oxygenized by air flows, see Fig 1. The air production system has a number of compressors, which supply all processes. The processes have individual air flow rate controllers, which will interact when air flows are changed. The set point is given by another (possibly self-tuning) controller, see Fig. 2. The maximum available air flow to each process is time-varying.

The air flow supply is a common control problem, see Shinskey (1978). The header pressure is controlled (by PC). The pressure set point is either constant or computed by a valve position controller (VPC), that will make the most-open control valve almost wide-open, see Fig. 3. Then at least one control valve operates close to saturation, and the air flow is produced at lower power demand. This type of process arrangement may be usual in process industry. The flow may be any gas or liquid, which is supplied to multiple users from one production unit.

The characteristic features of this control problem are varying process dynamics, load disturbances and saturations with varying limits. Windup in the cascaded self-tuning controller is analysed. A few antiwindup solutions will be given. Results from the implementation of self-tuning dissolved oxygen control in a wastewater treatment plant will be given.

INTEGRAL ACTION IN SELF-TUNING CONTROLLERS

This section considers integral action in implicit self-tuning controllers with least squares estimation, see Åström (1983). The subject has been studied by several authors. Here, the approach is mainly to study the underlying design equation for minimum variance control of known time-invariant systems. It is assumed that if the forgetting factor $\lambda = 1$ and the parameters converge, they converge to the solution of the design equation.

If the forgetting factor $\lambda < 1$, the parameters are assumed to converge to a neighbourhood of the solution. If the process is time-varying, then λ must be less than one, else the controller is unable to track parameter variations. In Examples 1 and 2 below, the output variance of the closed loop as a function of controller parameters will be used to show that the parameters approach the solution of the design equation.

In a non-integrating control law the adaptation mechanism itself provides integral action. Using the R, S, T - notation for the controller, it was noted in Wittenmark and Åström (1984) that the covariance conditions for inputs and outputs are valid only if $\hat{R}(1) = 0$, when the process has a load disturbance. If $\hat{R}$ has only one parameter the output deterioration may be severe, see Example 1 below.

Several methods to achieve integral action in self-tuning controllers can be found in the literature, e.g. in Åström (1980), Allidina and Hughes (1982), Wittenmark and Åström (1984), and Tuffs and Clarke (1985). In Tuffs and Clarke (1985), the following controller structure can be found.

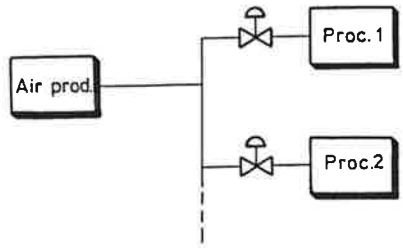

Fig 1 Process configuration.

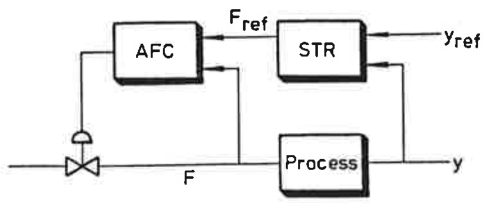

Fig 2 Air flow rate control and self-tuning process control.

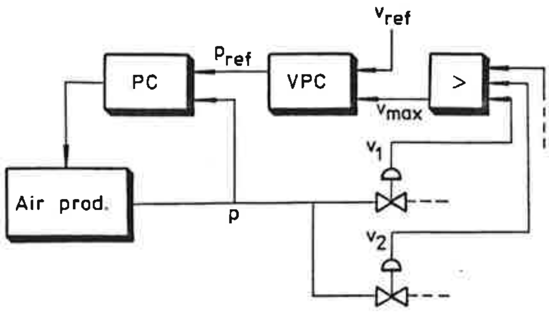

Fig 3 Pressure control and valve position control.

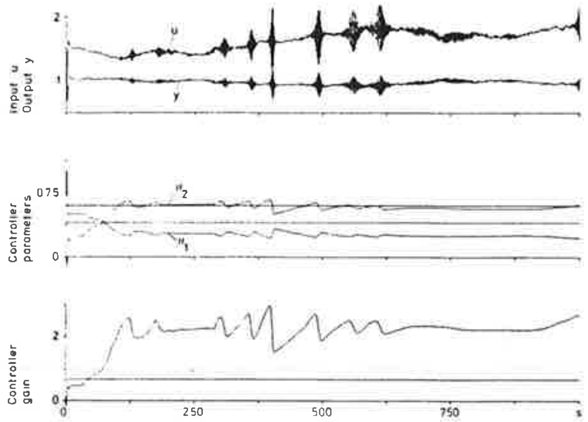

Fig 4 Non-integrating control (6a) of the process in Example 1.

The process model is

$$A(q^{-1})y(t) = q^{-d}B(q^{-1})u(t) + \frac{C(q^{-1})}{1 - q^{-1}}\, e(t) \qquad (1)$$

i.e. the load is filtered, integrated white noise. B is stable. Tuffs and Clarke treat the case C = 1, but here a general C will be used.

To achieve integral action, R is factored into $R'\cdot\Delta$, where $\Delta = 1 - q^{-1}$. Further S is here chosen as $S = T(1) + S'\cdot\Delta$. T is a known polynomial and u_c the reference value. The controller is then

$$T\, u_c(t) = R'\Delta\, u(t) + \left[T(1) + S'\Delta\right] y(t) \qquad (2)$$

where $R' = R_1B$. R' and S' are to be estimated in the adaptive case. Then the closed loop is given by

$$y(t) = \frac{q^{-d}T\, u_c(t) + R_1 e(t)}{AR_1\Delta + q^{-d}(T(1) + S'\Delta)} \qquad (3)$$

In stationarity, q = 1, the gain from u_c will be unity, irrespective of R_1 and S'. Further, the design equation for minimum variance control is

$$AR_1\Delta + q^{-d}(T(1)+S'\Delta) = C \qquad (4)$$

which can be solved for unique R_1 and S' if $\deg(R_1) = d-1$, $\deg(S') = \deg(A)-1$, and $T(1) = C(1)$.

To obtain a minimum variance controller $T(q^{-1})$ should be chosen as $C(q^{-1})$, which is unknown in the adaptive case. Then, for almost any choice, $T(1) \neq C(1)$, and (4) cannot be solved. Still the self-tuning controller may converge to the minimum variance solution, the reference value being mean value.

If αR_1 and $\alpha S'$, $\alpha > 0$, are substituted for R_1 and S' in (2), the MV design equation becomes

$$\alpha AR_1\Delta + q^{-d}(T(1)+\alpha S'\Delta) = \alpha C \qquad (5)$$

which can be solved if $\alpha = T(1)/C(1)$. Then the stationary gain from u_c is still unity. In the adaptive case, $\hat{R}'$ and $\hat{S}'$ will simply approach αR_1B and $\alpha S'$, respectively.

Thus a self-tuning controller based on this algorithm will always have unit stationary gain from reference input, and may approach the minimum variance solution.

Example 1: This example compares integrating and non-integrating implicit self-tuning control of a first order system given by $A = 1-0.4q^{-1}$, $B = 0.6$, $C = 1$, and $d = 1$ in (1). The noise variance is $\sigma^2 = 10^{-4}$. With the exception of C, this process model and the same noise sequence will be used in all examples throughout the paper.

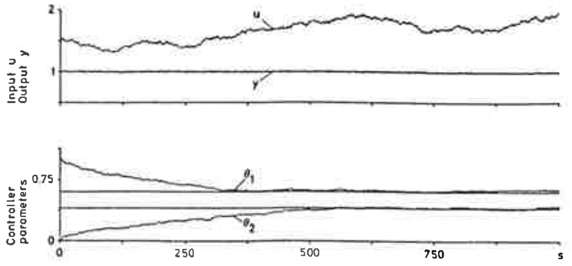

Fig 5 Integrating control (6b) of the process in Example 1.

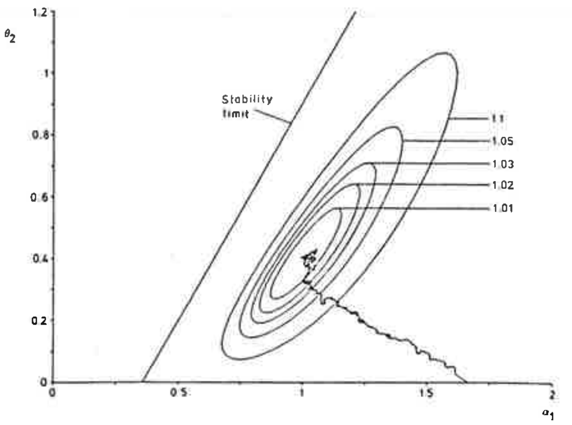

Fig 6 Contour levels for (8) and parameter estimates from Fig 5.

Choose T = 1. Then the non-integrating controller is

$$\hat{\theta}_1 u(t) = u_c(t) - \hat{\theta}_2 y(t) \qquad (6a)$$

and the integrating controller is

$$\hat{\theta}_1 \Delta u(t) = u_c(t) - y(t) - \hat{\theta}_2 \Delta y(t) \qquad (6b)$$

(6a) is the controller to be used if the process has no load disturbance, but in this case its performance is bad. Using (6a) the closed loop is given by

$$y = \frac{q^{-1}}{A\hat{\theta}_1 + q^{-1}\hat{\theta}_2}\, u_c + \frac{\hat{\theta}_1}{A\hat{\theta}_1 + q^{-1}\hat{\theta}_2}\, \frac{1}{1-q^{-1}}\, e \qquad (7)$$

This structure cannot cancel the integrator, and will thus (for constant parameters) have infinite variance. The only way for the self-tuning controller to eliminate the noise is letting $\hat{\theta}_1 \rightarrow 0$, which will give infinite gain in the controller.

In Fig. 4 a simulation of this case with forgetting factor $\lambda = 0.998$ is shown. As can be seen, the gain increases (above the 'stability limit') until good identification is obtained. Then the gain is reduced and the procedure is repeated.

In Fig. 5 the same process is controlled by (6b), using $\lambda = 0.998$ with good performance. The output variance (with $\sigma^2 = 1$, $a = 0.4$) as a function of $\alpha_1 = \theta_1/0.6$ and θ_2 is

$$V = \frac{\alpha_1^2\left[\theta_2 - a\alpha_1 - \alpha_1\right]}{\left[\theta_2 - a\alpha_1 + \alpha_1\right]\left[2\theta_2 - 2a\alpha_1 - 2\alpha_1 + 1\right]} \qquad (8)$$

Contour levels and the parameter estimates from Fig. 5 are shown in Fig. 6. As is easily seen, the parameters approach the solution of the design equation. □

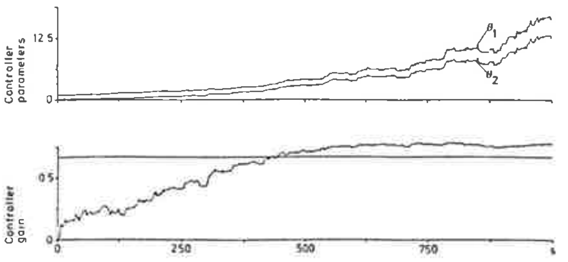

Fig 7 Integrating controller on process without load disturbance. Only gain and parameters are shown.

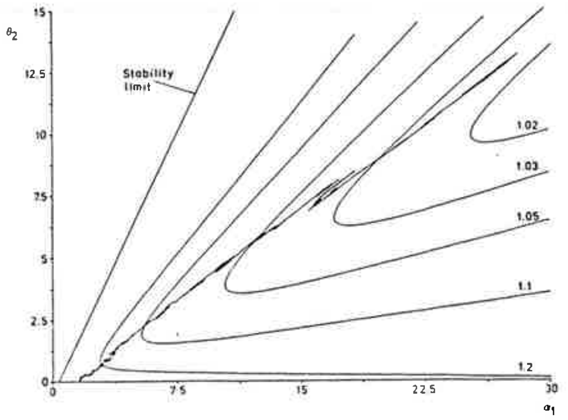

Fig 8 Contour levels for (10) and parameter estimates from Fig 7.

If, on the other hand, the integrating controller (2) is used on a process without load disturbance, there may be another type of deterioration. This case corresponds to letting $C = C' \cdot \Delta$ in (1), i.e. cancelling the integrator. Then $C(1) = 0$, which implies that the scale factor α must be infinite, else there is no solution to (5). In the limit ($\alpha = \infty$), (5) turns into

$$AR_1 + q^{-d}S' = C' \tag{9}$$

i.e. the design equation for minimum variance control of a process without load disturbance. The estimated parameters $\hat{R}'$ and $\hat{S}'$ will grow towards $\alpha R_1 B$ and $\alpha S'$, where α is large and R_1 and S' are given by (9).

Thus this algorithm is able to eliminate the integral action if it isn't necessary. This may cause problems if a load is switched on and off, and it is off for a long period, see Example 2.

Example 2: A, B, d and σ^2 is the same as in Example 1. C = Δ, i.e. the disturbance is pure white noise. First, in Fig. 7, it is shown that the parameters drift away (towards infinity) when (6b) is used, but the gain $\hat{\theta}_2/\hat{\theta}_1$ is bounded. This can also be seen in Fig. 8, where contour levels for the closed loop output variance as a function of $\alpha_1 = \theta_1/0.6$ and θ_2 are shown together with the parameter estimates from Fig. 7. The variance ($\sigma^2 = 1$ and $a = 0.4$) is given by

$$V = \frac{-2\alpha_1^2}{\left[\theta_2 - a\alpha_1 + \alpha_1\right]\left[2\theta_2 - 2a\alpha_1 - 2\alpha_1 + 1\right]} \tag{10}$$

which has no local minimum in the stable area. Further (10) can be compared with the output variance when using the non-integrating controller (6a) instead.

$$V = \frac{-\alpha_1^2}{\left[\theta_2 - a\alpha_1 + \alpha_1\right]\left[\theta_2 - a\alpha_1 - \alpha_1\right]} \tag{11}$$

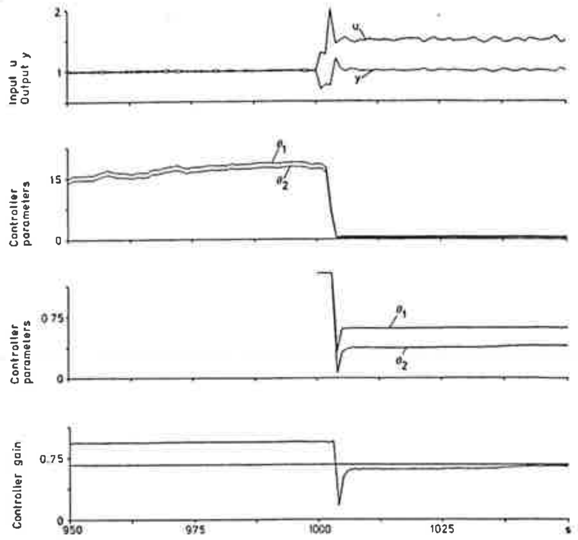

Fig 9 A constant load is added, continuation from Fig. 7.

Fig 10 Constant integrating controller.

When the parameters in (10) grow large then (10) is approximately equal to (11). (11) is a function of θ_2/α_1 only. Thus only the gain is required to converge. □

Example 3: In Fig. 9, a constant load is introduced, when the parameters are large. The disturbance is then a constant load and white noise. In Fig. 10 a comparison with a constant gain integrating controller is done. The conclusion is that integral action is lost for a few samples in Fig. 9. Before the load change it is minimum variance control in Fig 9, but not in Fig 10. □

INTEGRAL ACTION IN CASCADED SELF-TUNING CONTROLLERS

Using a self-tuning controller cascaded with another controller, see Fig. 2, creates special problems during saturation conditions. Saturation in the control output of the self-tuner is more easily taken care of (internally in the algorithm), see Wittenmark and Åström (1984), but when the cascaded controller saturates, this information must be fed back to the self tuner. Otherwise it will give two types of windup, control output windup due to integral action, and parameter windup, if the estimation continues.

The process configuration considered, see Fig. 1-3, enhances the saturation problem, since (at least) one throttle valve operates close to saturation. The actual upper limit for the control output from the self-tuner is time-varying and unknown.

In Fig. 11 it is shown what a saturation may look like, when the available control authority decreases. The thick line (u) is the continuous time control input to the process, and u_{ref} is the output from the self-tuner. In the subsequent examples, this type of saturation will be studied.

The means to be used to handle windup problems are different limits for the control output, and that the controller could be run in different modes. In the sequel the controller will have absolute and rate limits for the control output. Automatic mode and estimation can be switched on and off independently, and an external control signal is output in manual mode.

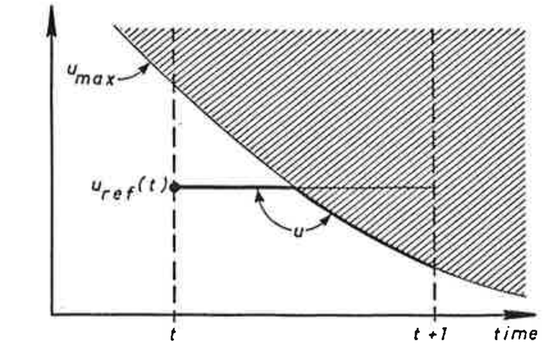

Fig 11 Continuous time control signal and limit.

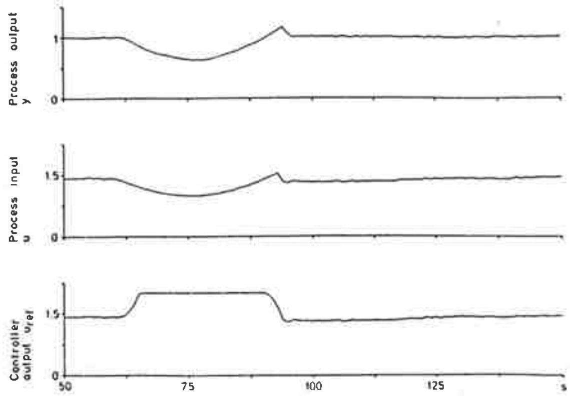

Fig 12 Reset windup, constant integrating controller.

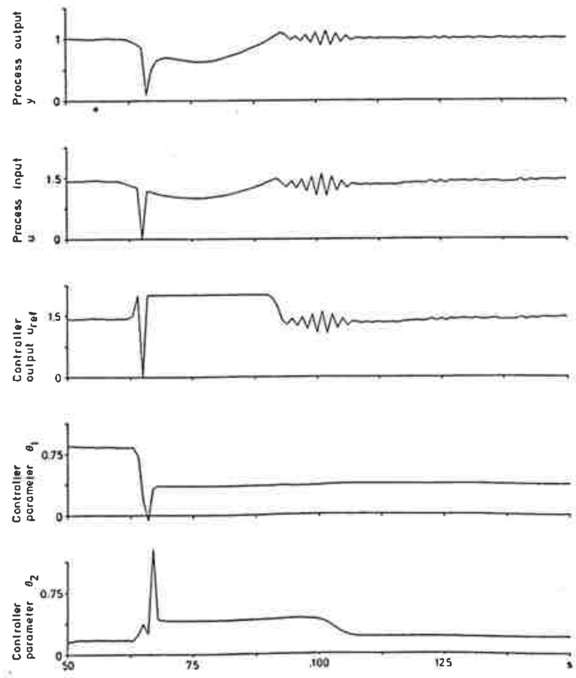

Fig 13 Reset windup, adaptive integrating controller.

The following notation will be used.

Analog signals		Logical signals	
HI	Upper limit	AUTO	Automatic/manual
LO	Lower limit	ADAPT	Adaptation on/off
DH	Positive rate limit		
DL	Negative rate limit		
UEXT	External control signal		

In addition to the process output y(t), the following signals are available to the controller. The measured control input $u_m(t)$, the valve position v(t), which is a nonlinear function of $u_m(t)$, and logical signals indicating saturation of the valve. These signals can be used by the controller to compute limits, switch off estimation etc, thus avoiding windup.

In the simulations both process and controller are in discrete time. Special care is then taken to account for the effect of the saturation of u(t).

In Example 4 below, the two types of windup will be demonstrated. A few attempts to avoid windup will be described in Examples 5-9. A Pascal-like notation will be used, where HIGH indicates upper saturation of the valve, and LOW lower saturation.

In these Examples, the process in Example 1, controller (6b) and the saturation is used. The set point for the self-tuner is 1. The lower limit for the control value is 0, and the upper limit u_{max} is 2, except for the interval [50,100], where it is given by

$$u_{max}(t) = 2 + \sin\left(\frac{2\pi t}{100}\right) \tag{12}$$

The controller uses the limits 0 and 2, unless anything else is said.

Example 4: No information on saturations is used in this example. In Fig 12-13 both reset windup and parameter windup is shown. The reset windup for constant parameters in Fig 12 is quite large, but the estimation using false data makes the situation in Fig 13 much worse. □

Example 5: The rate limit is zeroed when the limit is hit. Further, the parameter estimation is stopped, i.e.

if HIGH then DH=0, ADAPT=0;
if LOW then DL=0, ADAPT=0;

The result can be seen in Fig 14. The control output u_{ref} is constant during the period. At the end of the limit period, a small reset windup can be seen in the process output, because the load is slightly smaller at the end of the period. If the load is larger at the end, it simply takes longer time before the output is normal, but there is no windup. □

Example 6: Here the absolute limits are given the same value as the measured control input u_m and the estimation is switched off at saturation. The estimation and the full control space is used immediately when the valve is unsaturated, i.e.

if HIGH then HI=u_m, ADAPT=0;
if LOW then LO=u_m, ADAPT=0;

The result can be seen in Fig 15. As long as the limit u_{max} decreases, there are no problems, but when it starts to increase, the behaviour is violent. □

Example 7: The method in Example 6 is changed in the following way. The estimation is not switched on until the second unsaturated sampling instant. Else the method is unaltered. The result can be seen in Fig 16. When the limit u_{max} increases, the control output u_{ref} oscillates, but the data is not used in the estimation. Thus the parameter windup is avoided. The reset windup is handled by limiting u_{ref} to the measured control signal u_m. □

Comparing the three examples, the control output u_{ref} in Example 5 is constant and at the same level as when the saturation started. Only the logical information HIGH or LOW is used. Here the saturation lasts until the available control signal is larger than the value at which the saturation started.

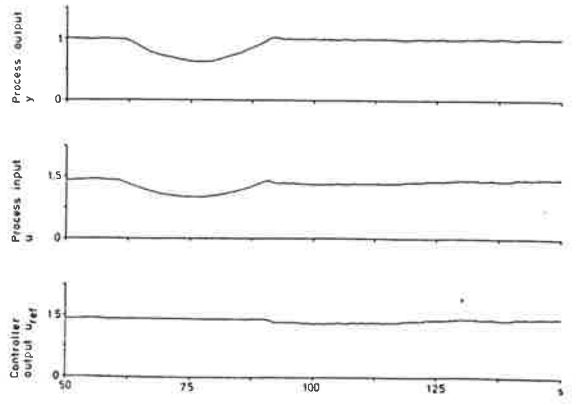

Fig 14 Antiwindup solution in Example 5.

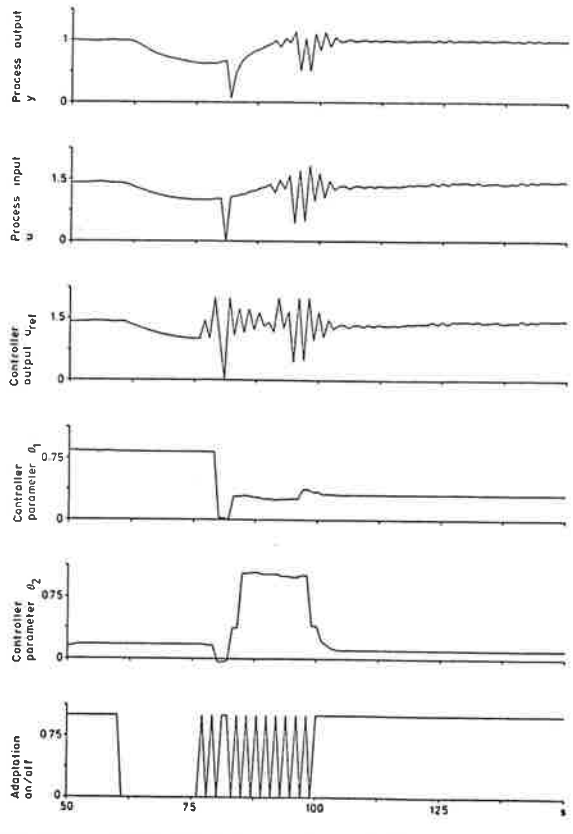

Fig 15 Failing antiwindup in Example 6.

In Examples 6-7, the measured control signal u_m is also used. To handle the increasing control signal, the estimation must not be switched on until the second unsaturated sampling instant. Then this method is better than the first method, since it will not give any windup at all.

Examples 8-9 do not use the logical signals. Instead the valve position v(t), which varies between 0 (closed valve) and 1 (open valve), is used for determining the control signal limits. It is also used to switch off the estimation when the valve is almost fully opened or closed.

Example 8: Using the valve position v, this method estimates the allowable change in control output, when the valve is close to either of the limits.

if v > 0.9 then DH=k·(1-v);
if v < 0.1 then DL=k·v;
if (v > 0.98) or (v < 0.05) then ADAPT=0;

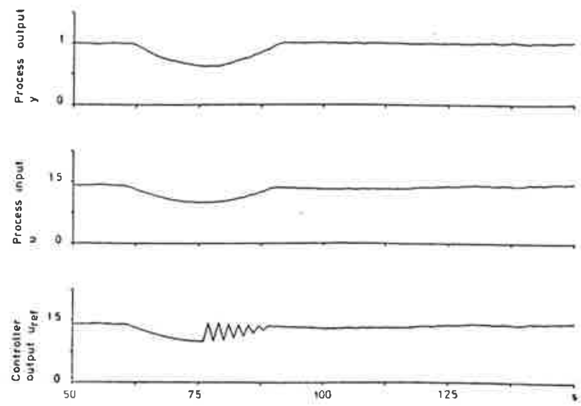

Fig 16 Antiwindup solution in Example 7.

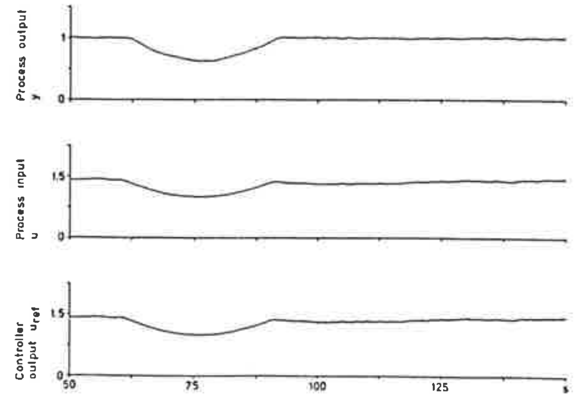

Fig 17 Antiwindup solution in Example 9.

The result is not shown, but is almost identical to the result in Example 5 (Fig 14). □

Example 9: This method uses the measured control signal u_m and the valve position to estimate the control signal limits.

if v > 0.9 then DH=k·(1-v), HI=min(u_m+DH,2);
if v < 0.1 then DL=k·v, LO=max(u_m-DL,0);
if (v > 0.98) or (v < 0.05) then ADAPT=0;

Combining DH and HI in this way is good when $u_m \neq u_{ref}$, which is often the case at saturation. This prevents the small reset windup at the end of the saturation period, see Fig 14 and 17. It also prevents the oscillation in u_{ref}, which can be seen in Example 7 (Fig 16). □

Both these methods switch off estimation close to the valve limits. Unlike Example 7, Example 9 does not need any delay in switching on the estimation. Proper gains and limits are required in Examples 8-9. Examples 7-9 are sensitive to calibration and drift in transducers, AD-converters etc.

AN IMPLEMENTATION EXAMPLE

Self-tuning dissolved oxygen control has been implemented on the activated sludge process at the Käppala Sewage Works, Lidingö, Sweden, which serves the northern parts of metropolitan Stockholm. The Käppala plant has six parallel activated sludge systems and six compressors in the air production system. The liquid is oxygenized by an air flow through diffusors.

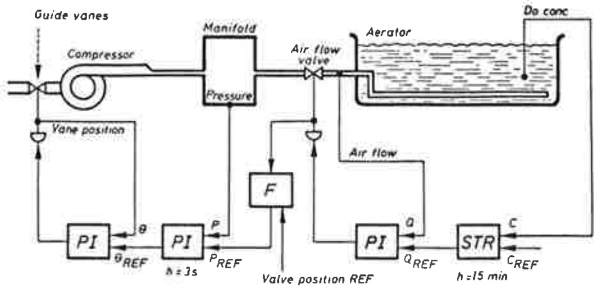

Fig 18 Block diagram of the Käppala plant.

Bacteria consume biodegradable substrates in the liquid under aerobic conditions. The dynamics of the process is affected by several variables, i.e. influent flow rate, influent substrate concentrations, temperature, pH level, salinity etc. A common approach is to control the dissolved oxygen (DO) concentration at the tail end of the aerator. The DO concentration is crucial for plant economy and for the biological conditions. The DO dynamics is approximately described by the bilinear differential equation

$$\frac{dc}{dt} = -a_0 c + (a_1 F + a_2)(c_s - c) - R, \tag{13}$$

see Olsson (1984), where c is DO concentration, c_s is DO saturation concentration, F is air flow rate and R is the respiration of the bacteria, which is time-varying. If the air flow rate and the respiration rate are constant over a sampling period, the differential equation can be solved to obtain a discrete first order model.

The sampling interval is 15 minutes. Since the respiration is a load disturbance, an integrating controller is required. Here a pole placement self-tuning controller, see Åström (1983), is used, where the closed loop pole is placed in 0.4. The control law is similar to (6b), but instead T = 0.6. The forgetting factor is 0.98.

The DO controller and the valve position controller use constant set points, while all other controllers have cascaded set points. The pressure control includes starting and stopping compressors and adjusting their guide vanes. The air flow rate controllers and the guide vane controllers are standard PI controllers. The other controllers are all implemented in an Asea Novatune control computer. The pressure controller is a PI algorithm, and the pressure set point is computed with an integral controller (F), see Fig 18.

During a ten day period in January 1984, an evaluation between three comparable aerators were made. Air flow rates and DO concentrations for two of them are shown in Fig 19-20. In the table below, their averages and standard deviations are listed.

Aerator	Air flow rate (m^3/min)	DO conc. (mg/l)
No control	73.2±6.0	5.4±0.6
Manual	75.2±7.8	3.1±1.1
Self-tuning	72.7±9.0	5.95±0.15

Automatic DO control reduces the average air flow demand compared with manual DO control. The variance in the DO concentration is significantly lower during self-tuning control compared with PID-control, although it was not minimum-variance control, see Olsson et al (1985). During periods without air flow limitation, the standard deviation is as low as 0.02 mg/l. Minimum variance control (closed loop pole in origin) was not successful, the control signal was too noisy.

When the air flow rate is insufficient, due to limitations in the air production system, the DO concentration is lower than the set point, see Fig 19. To avoid windup problems in the self-tuning controller the method in Example 5 was used.

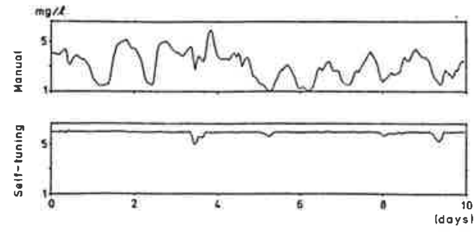

Fig 19 DO concentration during manual control and self-tuning control at the Käppala plant.

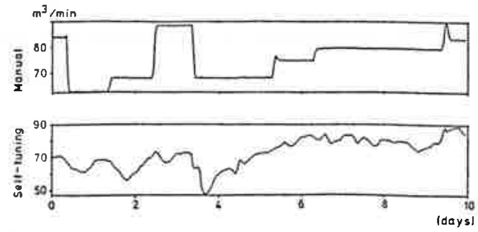

Fig 20 Air flow rate during manual control and self-tuning DO control at the Käppala plant.

SUMMARY AND CONCLUSIONS

This paper has investigated integral action in implicit self-tuning controllers. Further, feedback from the primary actuator (control valve), has been shown necessary when using cascaded (self-tuning) controllers. Methods to avoid reset windup and and parameter windup in cascaded self-tuning controllers are given.

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