Self-Tuning Control of Chip Level in a Kamyr Digester

P. R. BELANGER, L. ROCHON

Department of Electrical Engineering
McGill University
Montreal, Quebec, Canada

G. A. DUMONT

Pulp and Paper Research
Institute of Canada
University of British Columbia
Vancouver, British Columbia, Canada

and

S. GENDRON

Consolidated-Bathurst, Inc.
Montreal, Quebec, Canada

A study is presented of the application of a self-tuning regulator to the control of the level of wood chips in a Kamyr digester, used in the production of wood pulp. Following an initial phase of experiments and model structure selection, two control schemes were studied, using respectively the blow flow and the outlet device speed as manipulated variables. The approach finally adopted uses the outlet device as the primary control. The control has been in operation for several months and has provided significantly improved control and a high degree of operator acceptance.

SCOPE

The objective of this study is to improve the control of the chip level in a Kamyr digester. Good level control is necessary for steady operation of the digester. It is difficult to achieve because chip level is not easily measured and because the dynamics change appreciably with different types of wood chips. It is not clear whether the chip level should be controlled by manipulating the blow flow or the outlet device (or scraper).

Some attempts at adaptive control were made by Cegrell and Hedgvist (1974) and Sastry (1978). Very little information is available about the first; the second was finally abandoned.

CONCLUSIONS AND SIGNIFICANCE

This paper describes a successful application of the self-tuning regulator (STR) to chip level control in a Kamyr digester. The development of the study is described, from parameter identification experiments and initial STR trials, through model and control algorithm refinements, to practical modifications and final implementation. Two different variables were tried as control inputs: the outlet device, which controls the outflow of solids, and the blow flow, which is the outflow of the diluted liquor carrying the solids. The two performed almost identically as control variables, but the use of the outlet device proved to have certain operational advantages. A reduction of 45% was observed in the standard deviation of the chip level fluctuation. In practice, this has meant much less frequent alarms and operator interventions. The new control has been in operation since May 1983.

INTRODUCTION

About 50 million tons of wood pulp are produced every year by more than 300-Kamyr digesters in the world (Lundqvist, 1982). Although a significant number of these digesters are under computer control, it is felt that the control systems are not as efficient as they could be. There are many incentives for improving the control of Kamyr digesters, including large production volumes, higher energy and raw material costs, and increasing pressure to produce high-quality pulp. The most important objective of Kamyr digester operation is to control of the degree of delignification. This generally results in increased yield, which may result in increased production or reduced steam, wood, and chemical usage. The Kappa number is a measure of the percentage of lignin. It is obtained by a titration test performed in the laboratory at two-hour intervals. Due to the long sampling period, feedback actions based on the Kappa number can only cope with relatively slow disturbances. It is therefore important to eliminate disturbances as much as possible through faster, lower-level loops. One very important such loop is the chip level control loop. Good chip level control is important for two reasons. First, it is necessary for achieving steady, uninterrupted digester operation. Most level control systems are designed to stop chip feed when a high level condition is recognized. This upsets both the chemical balance and retention time in the digester. Avoiding such a condition is a major concern for the operator. Second, at constant production rate, constant level means constant retention time. Minimizing variations in the retention time is one of the factors that helps to reduce variations in the Kappa number.

The principal features of a Kamyr digester are shown in Figure 1. The chips are fed to the unit through the top separator. The separator is a cylinder inside which a slow-moving vertical screw conveyor pushes the chips downward into the digester. Vertical slots in the separator allow the liquor to be withdrawn for recirculation.

Measurement of the chip level in a hydraulic Kamyr digester is difficult and no direct measurement is yet available. In this study, separator amperage is used. The top separator amperage varies in the same direction as the chip level, but in a poorly defined and nonlinear fashion. Also, when the chip level is below the top separator it goes undetected.

Whether the chip level should be controlled from the bottom of the digester (Fuchs and Smith 1971), from the top (Fuchs and Single, 1976), or by a combination of both methods (Al-Shaikh and Tu, 1978) is a matter of some controversy. In this study, the control is from the bottom, using either the blow flow or the outlet device (Figure 1). The outlet device basically scrapes fiber from the bottom of the digester, and this fiber is mixed with the dilution flow and carried out through the blow valve. The outlet device acts on the level by taking out fiber, at a rate governed by its speed; the blow flow acts by removing liquid.

Whichever solution is adopted, the resulting controller is generally difficult to tune because the process dynamics are nonlinear and are subject to change as the characteristics of the chips vary either because of poor control or of grade change. This is why a self-tuning regulator (STR) for chip level control has been proposed by Cegrell and Hedqvist (1974) and by Sastry (1978). Not much information is available about the first application; the second had to be abandoned due to lack of reliability of the STR.

The development of the control strategy was carried out in two phases. Phase 1 was concerned with the issues of model structure and sampling rate. Simulation studies were carried out and STR experiments were done at the Consolidated-Bathurst mill in Pontiac, Quebec.

In phase 2, the model was revised after examination of the results of phase 1. Two control strategies were tried, based respectively on the use of the blow flow and of the outlet device speed as control variables. While the two strategies yielded similar performances, practical considerations led to the choice of the outlet device speed as the control variable. Following a few modifications, the control system was commissioned. It has been running successfully for several months at Consolidated-Bathurst's Wayagamack mill in Trois-Rivieres, Quebec.

THEORY OF THE SELF-TUNING REGULATOR

Several review articles (Astrom and Wittenmark, 1980; Belanger, 1982) may be consulted for an exposition of self-tuning control. A summary is given here in order to define symbols. The starting point is an autoregressive moving-average (ARMA) model:

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

where A, B, and C are polynomials in the unit delay operation q^{-1}. A useful equivalent model is the so-called predictor form

$$Cy(t+k) = Fy(t) + Gu(t) + QC\,e(t+k), \quad (2)$$

where $G = BQ$ and Q, F satisfy the polynomial equation

$$AQ + q^{-k}F = C. \quad (3)$$

The control law

$$Fy(t) + Gu(t) = 0 \quad (4)$$

is optimal, since it forces $y(t+k) = Qe(t+k)$, a linear combination of future noise samples. It is necessary for stability that $B(q^{-1})$

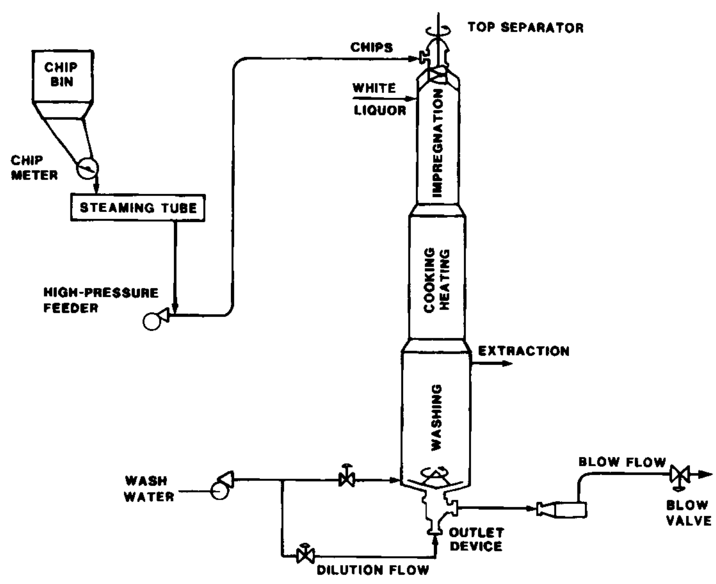

Figure 1. Schematic diagram of Kamyr digester.

be nonzero for $|q| > 1$ (minimum-phase condition).

In the STR, the coefficients of the polynomials F and G are estimated, and the estimates are used in place of the true values in Eq. 4.

In Clarke and Gawthrop (1975), a variable $\phi(t) = y(t) + \rho u(t-k)$ is introduced. A predictor equation of the form.

$$C\,\phi\,(t+k) = Fy(t) + Gu(t) + QC\,e(t+k) \tag{5}$$

is obtained (with different F, G, and Q). The control law of Eq. 4 minimizes $E[\phi^2(t)]$. This modification has the advantage of introducing a weight on the control; the size of $u(t)$ is reduced, at the expense of an increase in the output variance.

Since the linear model is valid only for small deviations from the nominal, the output is taken to be $y - y_{sp}$, where y_{sp} is the output set point. The model input is $u - u_{sp}$, where u_{sp} is that constant input for which $y = y_{sp}$ in the steady state. Since u_{sp} is not known, a prior estimate is used, in which case Eq. 5 becomes

$$C\,\phi\,(t+k) = F(y - y_{sp}) + G(u - \hat{u}_{sp}) + G(\hat{u}_{sp} - u_{sp}) + QC\,e(t+k) \tag{6}$$

Since $\hat{u}_{sp}$ and u_{sp} are constants, the third term on the righthand side of Eq. 6 is also a constant, δ, and thus

$$C\,\phi\,(t+k) = F(y - y_{sp}) + G(u - u_{sp}) + \delta + QC\,e(t+k) \tag{7}$$

The minimum-variance control law is

$$\hat{F}(y - y_{sp}) + \hat{G}(u - \hat{u}_{sp}) + \hat{\delta} = 0 \tag{8}$$

where the circumflex ^ indicates that the parameters are to be replaced by their estimates.

It turns out that the coefficients of F and G, as well as δ, can be estimated by least squares using Eq. 7 with $Q = C = 1$. To summarize the algorithm, define

$$\theta^T = [f_0 f_1 \cdots f_{m-1}\, g_0 g_1 \cdots g_{m+k-1} \delta]$$

$$\psi^T(t) = [\Delta y(t-k) \cdots \Delta y(t-k-m+1)\;\; \Delta u(t-k) \cdots \Delta u(t-m-2k+1)\; 1].$$

where

$$\Delta y(t) = y(t) - y_{sp},\; \Delta u(t) = u(t) - \hat{u}_{sp}.$$

The least-squares algorithm is

$$\hat{\theta}(t) = \hat{\theta}(t-1) + K(t)\,[\phi(t) - \psi^T(t)\hat{\theta}(t-1)]$$
$$K(t) = P(t)\psi(t)/[1 + \psi^T(t)P(t)\psi(t)]$$
$$P(t) = \frac{1}{\lambda}\{P(t-1) - K(t-1)K^T(t-1)\,[1 + \psi^T(t-1)P(t-1)\psi(t-1)]\} \tag{9}$$

where λ, $0 < \lambda < 1$, is called the "forgetting factor." With $\lambda < 1$, old data are progressively discounted, and eventually neglected. With $\lambda = 1$, $P(t)$ and hence $K(t)$, tend to zero and the parameter estimates cease to be updated. If the plant parameters are slowly varying rather than truly constant, it is necessary to have $\lambda < 1$ for the estimates to track the parameters.

Although theoretically correct, the least-squares algorithm of Eq. 9 is fraught with numerical difficulties. The UD factorization algorithm (Bierman, 1977) is preferred and was used here.

PHASE 1

Model Structure

The complexity of the physical description of the dynamics led us to use input-output models, derived experimentally. Two models were obtained, the first to serve as a plant model, the second to serve as a control model.

Preliminary experiments were carried out in order to select the model structure. A binary sequence of blow flow set points was generated by flipping a coin. At every 2.5 min (half the sampling time used in Cegrell and Hedqvist, 1974) the blow flow setpoint increased or decreased from a constant level by 2% of that level (about 120/min). A 3 h experiment yielded 73 samples.

A cross correlation of the input and output yields an unbiased estimate of the impulse response, if the input is a white sequence. The first impulse response estimate to be significantly different from zero proved to be the fourth sample, suggesting a delay of 4.

A similar experiment was carried out simultaneously with the outlet device speed setpoint, but the impulse response estimates turned out not be significantly different from zero. In hindsight, we believe that the outlet device was near saturation, in effect scraping nearly all the available fiber, so that speed changes had little effect.

The experimental data were used to estimate the parameters of a series of plant models of the form

$$A(q^{-1})y(t) = B(q^{-1})u(t-k) + e(t) \tag{10}$$

using conventional least-squares estimation.

Delays of 3, 4, and 5 were tried, with model orders of 1, 2, 3, and 4. The input and output variables were normalized by dividing by their respective peak values. Three tests were tried for model selections:

i) The Akaike (1974) test where the model selected is one that minimizes the statistic $Ak = N\ln \hat{var} + 2n_p$. (11)
ii) The Schwartz (1978) test where the quantity to be minimized is $Sch = N\ln \hat{var} + n_p \ln N$. (12)
iii) The quantity $\hat{var}$ itself, i.e., the average of the squares of the residuals.

Table 1 gives the test information. The Akaike and Schwartz tests show little discrimination between delays 3 and 4, but do appear to reject the delay of 5. On the other hand, the variance estimate has a pronounced dip for a delay of 4, for all model orders. Because the STR requires that the delay not be underestimated, it was deemed prudent to use a delay of 4 (10 min).

The choice of model order was more difficult. The variance estimate always decreases monotonically with system order, and cannot be used to choose model order unless accompanied with a test of significance.

TABLE 1. LEAST-SQUARES IDENTIFICATION; TEST INFORMATION

System Order, n	Test: Akaike	Test: Schwartz	Est. Noise Variance, Var
$k^* = 2$			
$n = 1$	−452	−445	0.00144
$k = 3$			
$n = 1$	−451	−444	0.00132
$n = 2$	−445	−434	0.00124
$n = 3$	−440	−424	0.00115
$n = 4$	−428	−403	0.00116
$k = 4$			
$n = 1$	−448	−442	0.00125
$n = 2$	−438	−427	0.00124
$n = 3$	−432	−416	0.00116
$n = 4$	−421	−401	0.00116
$k = 5$			
$n = 1$	−436	−430	0.00135
$n = 2$	−425	−414	0.00137
$n = 3$	−416	−401	0.00132
$n = 4$	−406	−387	0.00132

$^*k$ = delay

Both the Akaike and Schwartz tests, although not very discriminating, suggest models of order 1, which we were reluctant to use because of the small number of free parameters. The variance drop between orders 2 and 3 suggests a model of order 3. This model is

$$\begin{aligned} y(t) - 1.02y(t-1) + 0.35y(t-2) \\ - 0.26y(t-3) = -0.36u(t-4)t - 0.14u(t-5) \\ - 0.24u(t-6) - 0.03u(t-7) + e(t) \end{aligned} \quad (13)$$

This model was used to simulate the plant.

The transfer function y/u has a pole near $z = 1$, actually at $z = 0.942$; given the sampling period of 2.5 min, this corresponds to a time constant of 40 min. There are two complex poles which correspond to s-plane poles at $= 0.26 \pm j0.628$; since $1/0.26 \simeq 4$, the envelope of the transient has a 4 min time constant, or 1/10 the dominant time constant. This suggests that, for control purposes, a first-order model might indeed be justified. Further analysis suggests that the simple delay plus first-order (without zeros) model might be adequate.

For a first-order model without zeros, the predictor form of Eq. 2 has the following structure:

$$\begin{aligned} y(t+k) = f_0 y(t) + (g_0 + g_1 q^{-1} \\ + g_2 q^{-2} + g_3 q^{-3})u(t) + e(t) \end{aligned} \quad (14)$$

In self-tuning control, it is safer to have too many rather than too few parameters. A third-order model will represent a second-order plant, while a first-order model will not. An overparametrized model will converge, abeit slowly; an underparametrized model may diverge. Caution dictated that, in a first STR experiment, the control model should have more rather than fewer parameters. In order to modify Eq. 14, it was reasoned that poles represent the natural modes of the system. To enrich the dynamics behavior, one must allow greater flexibility in the modeling of poles. In Eq. 14 the poles are the kth (complex) root of f: in effect, there is only one parameter available to fit the poles. The control model was modified as follows:

$$\begin{aligned} y(t+k) = (f_0 + f_1 q^{-1} + f_2 q^{-2})y(t) \\ + (g_0 + g_1 q^{-1} + g_2 q^{-2} + g_3 q^{-3})u(t) + e(t) \end{aligned} \quad (15)$$

Choice of Sampling Period

Given the ARMA model $A(q^{-1})y(t) = B(q^{-1})e(t)$, with $e(\cdot)$ zero mean, white, and with variance σ_e^2, the variance of y is evaluated, using the algorithm given in Astrom (1970).

For the model of Eq. 13 in the open-loop case (i.e., $u = 0$), this yields

$$E[y^2] = 6.1\sigma_e^2 = 4.18 \quad (16)$$

A controller with transfer function

$$\frac{u(z)}{y(z)} = -\frac{F(z^{-1})}{G(z^{-1})} \quad (17)$$

applied to the system of Eq. 10 yields

$$(AF + q^{-k}GB)y(t) = Fe(t) \quad (18)$$

If a minimum-variance controller is selected, there results

$$E[y^2] = 2.87\sigma_e^2 = 1.97 \quad (19)$$

Given the model for a sampling period of 2.5 min, it is possible to derive the model for a sampling period of 5 min, and to calculate the performance under minimum-variance control. This leads to

$$E[y^2] = 4.30\sigma_e^2 = 2.95 \quad (20)$$

The variance with a 2.5 min sampling period is seen to be 1.5 times smaller than with a 5 min period, a significant improvement. Given the dominant time constant of 40 min, 2.5 min would seem to be small enough.

Simulation Work

The plant of Eq. 13 was simulated, controlled by the Clarke-Gawthrop modification of the self-tuning regulator. The purpose of the simulation was to investigate the effect of three design parameters: the initial covariance matrix, P, the control weight, and the forgetting factor.

Values of $P = 100I$ and $P = 10I$ were used, with little apparent difference. The value $P = 100I$ was retained for the later work.

As for the control weight, it was determined that a value between -1 and -5 would be adequate. It was observed that the use of a control weight was very useful in cutting down the switch-on transient when turning on the STR. It was also observed that a substantial reduction in control amplitude from the minimum variance case was possible with rather slight increases in the output variance.

After some experimentation, the forgetting factor was set at $\lambda = 0.99$. This value is closer to 1 than in other applications, but this is expected since the sampling period is short relative to the time constant.

Plant Trials

The algorithm was tried on an industrial Kamyr digester, 60 m high and producing 550 ton of pulp a day.

Calculations were performed on a VAX 11/780 located at McGill University, 400 km from the plant. At the sampling instants, the blow flow value was read by the operator and communicated to the computer room, where it was entered. The value of the blow flow was computed and given to the process operator. Plant personnel could override this value, in which case they selected the blow flow value.

Figure 2 shows the outcome of a run with control weight $\varrho = -1$, over a period of more than 4 h (ϱ is negative because the d.c. gain is negative; i.e., an increase in flow induces a decrease in level). The outcome shows a somewhat unpleasant initial rise, followed by a smooth descent to the set point. Plant personnel often chose to override the computer during the initial rise and usually held the blow flow constant rather than letting it go too high. The rise near the 80th sample was caused by a valve malfunction that was quickly corrected. The return to setpoint was considered to be good. The behavior of the parameter esti-

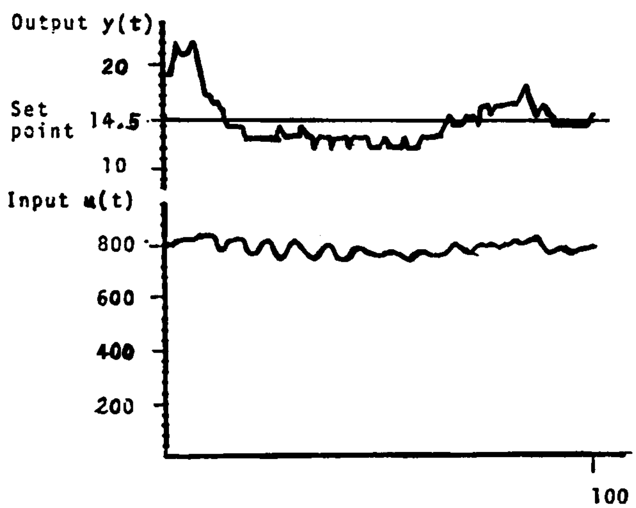

Figure 2. STR run with $\rho = -1$ and $\lambda = 0.99$.

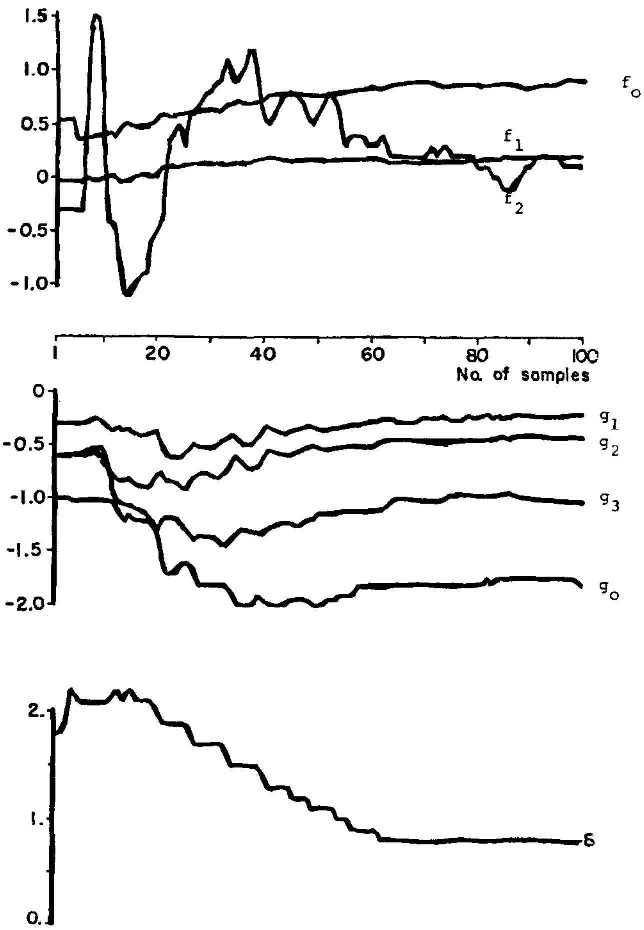

Figure 3. Parameter estimates.

mates during that run is shown in Figure 3. The initial estimates were those of the model of Eq. 13. For practical purposes, convergence was achieved in about 60 samples, corresponding to somewhat less than four time constants.

It is worth noticing the asymptotic values of f_0, f_1, and f_2, respectively, 0.85, 0.2, and 0.1. The fact that f_1 and f_2 are relatively small compared to f_0 suggests that the first-order-plus-delay model ($f_1 = f_2 = 0$) would probably have worked. A variance reduction of 20% in the top separator amperage was achieved by this control.

COMPARISON OF TWO CONTROL STRATEGIES

The study shifted to another mill for phase 2 of the study. The reason for the change was the acquisition of a new level-sensing system at the first mill, one with several "on-off" presence detectors: the absence of a continuous measurement precludes the use of the STR.

In order to decide whether the blow flow or the outlet device should be used as the primary manipulated variable, two basic strategies were designed and compared. The first uses the blow flow as manipulated variable. The top separator amperage reading is used by the STR to estimate a new set of parameters and to compute a new blow flow setpoint. That value is added to a blow flow target computed by feedforward from the chipmeter setpoint, to obtain the actual blow flow setpoint to be sent in supervisory mode to the flow controller. So as to keep blow consistency approximately constant, the outlet device speed is ratioed to the blow flow setpoint. A possible drawback of that strategy is that at low production rate, the blow valve opening required to get the blow flow needed by the STR may get so small that knots, rocks, or any foreign material present in the blow line can cause an obstruction of the flow and damage to the valve.

The second strategy uses the outlet device speed as manipulated variable. The outlet device speed setpoint is computed in exactly the same way as the blow flow setpoint in the first scheme. The blow flow setpoint is now ratioed to the chipmeter speed to keep blow consistency about constant when production rate is changed. This avoids the problem of the first strategy but it means that the blow consistency changes with the outlet device speed and may reach an undesired value. Figure 4 shows schematically the two strategies, which share many common characteristics. Because the separator amperage signal is extremely noisy, it is measured every 2 s and exponentially filtered so as to eliminate high-frequency noise. The two strategies use the same STR software with only different parameters.

In the blow flow strategy, the sampling period was changed from 2.5 to 3.5 min. This was done inadvertently, and it was found that a delay $k = 3$ gave best results. Guided by the results of phase 1, the model structure was first-order with delay, for which the predictor equation is

$$y(t+3) = f_0 y(t) + (g_0 + g_1 q^{-1} + g_2 q^{-2})u(t) + \delta + e(t) \tag{21}$$

The control weight ϱ was -0.2.

The sampling period for the outlet device strategy was reset to 2.5 min and the dead time was correspondingly reestablished at 4. A first-order model with a zero was used, with the predictor equation

$$y(t+4) = f_0 y(t) + (g_0 + g_1 q^{-1} + g_2 q^{-2} + g_3 q^{-3} + g_4 q^{-4}) \tag{22}$$

The control weight was $\varrho = -0.2$. The parameter g_0 was not estimated, but $\hat{g}_0$ was set to -2, about twice the maximum value observed in the runs of phase 1. Both strategies used a forgetting factor between 0.97 and 0.98.

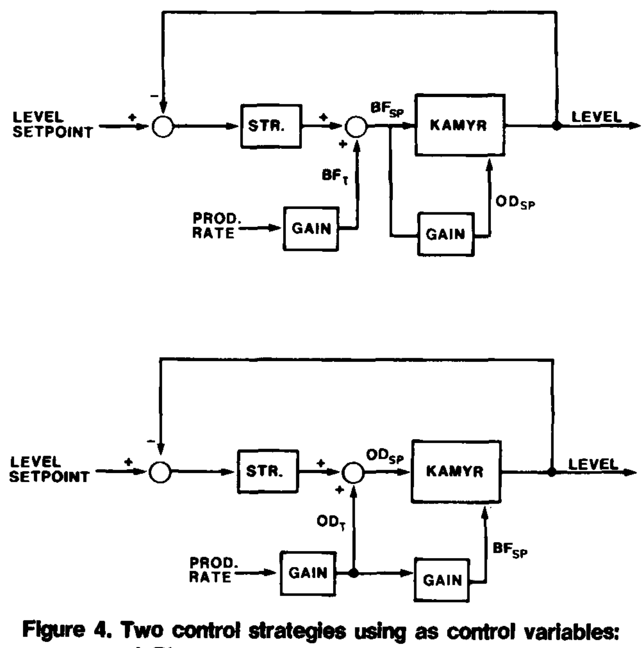

Figure 4. Two control strategies using as control variables:
a) Blow flow
b) Outlet device

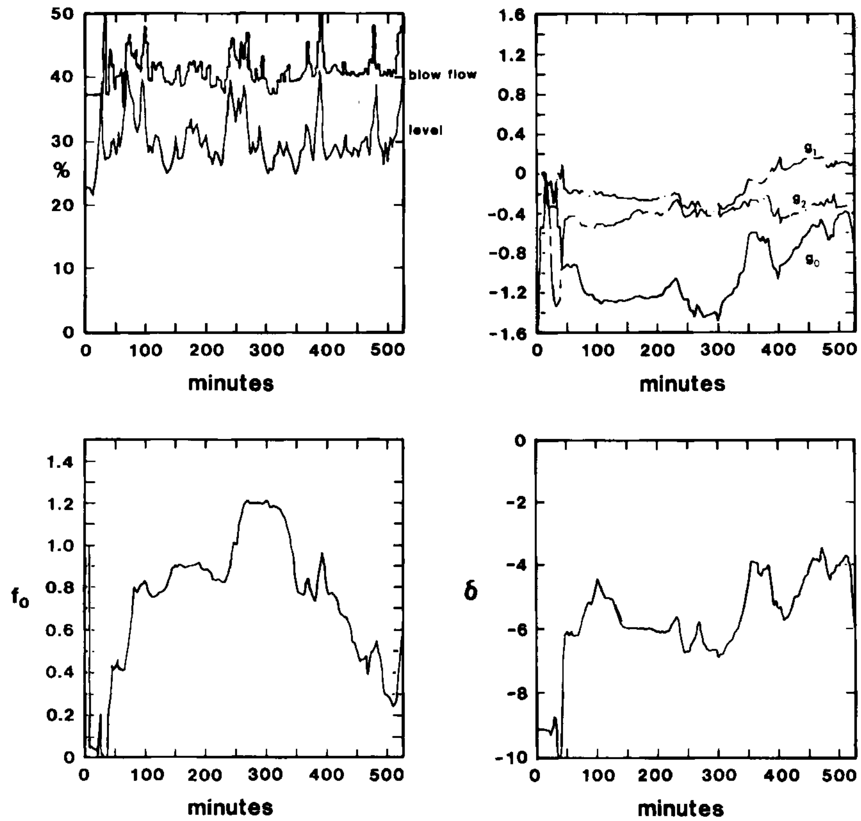

Figure 5. Behavior of STR control, using blow flow.

Both schemes were implemented in the mill and tested for several days. Figures 5 and 6 show the respective input-output behaviors of the two schemes during start-up as well as the evolution of parameter estimates.

Several comments are called for. The digester is equipped with an interlock switch to shut down chip feed; it is triggered when the top separator amperage signal rises above 42.67% of full scale. In manual control, this switch is usually triggered several times during a shift. However, neither during the 8 h period depicted in Figure 5 nor during the 27 h period depicted in Figure 6 was the switch triggered. This represents a significant improvement.

During the two test periods, the production rate of the digester was increased without noticeable effect on the chip level. In Figure 5, a production increase between $t = 300$ and $t = 350$ min caused the rather rapid change in the estimates. in Figure 6 the production increased by 11 % between samples 395 and 465. The effect of that increase is most visible on f_0 and g_1; Figure 7 shows the evolution of the d.c. gain of the regulator for the two runs. For the first test, once the initial start-up period had elapsed, its evolution was rather smooth. During the second test period, between samples 125 and 175, the regulator gain more than doubled in magnitude while the level increased rapidly and the bias estimate decreased as rapidly. That evolution in regular gain allowed swift control to bring the level back to normal. This may have corresponded to the building of a hangup. The decrease in amplitude of the regulator gain around $t = 450$ corresponds to the production rate increase previously mentioned.

Figure 8a represents the autocovariance function of the quantity ϕ (t) for the first run, which, using the Clarke-Gawthrop algorithm, should be controlled with minimum variance. The autocovariance of $\phi(t)$ should and indeed does die out after a lag of three sampling intervals, indicating near-minimum variance control. The corresponding auto-covariance of the top separator amperage is represented in Figure 8b. Figure 8c depicts the autovariance of the level for the second test. The variances of the top separator amperage for the two runs are respectively $12.4(\%)^2$ for the first, and $9.9(\%)^2$ for the second. These figures correspond to standard deviations of, respectively, 0.118 and 0.105 A. For comparison, the standard deviation in manual control was found to be 0.2 A for a 12 h period. This corresponds to a reduction of standard deviation of about 45% with the STR.

The two STR strategies gave similar performances, in terms of amperage variance. However, other factors have to be considered in choosing the most suitable strategy. The first strategy causes blow valve moves that are frequent and of significant amplitude, which for mechanical reasons are undesirable. A solution would be to increase the weight on control action but it would be at the expense of control performance. Also, as explained before, at low production rate a low blow valve opening leads to many obstructions and is not feasible. Because the blow flow is not used as the manipulated variable, the second strategy does not present these problems. However, a possible drawback of that strategy is that blow line consistency may be subject to large fluctuations. Finally, it is important to consider operator acceptance and confidence. By far, the operators preferred the second scheme, primarily because of the steadier blow flow.

PRACTICAL MODIFICATIONS

An improved control strategy is depicted in Figure 9 and has the following features:

- The principal feedback action for control of the chip level is provided by an STR giving one component of the signal to the setpoint of the outlet device speed.

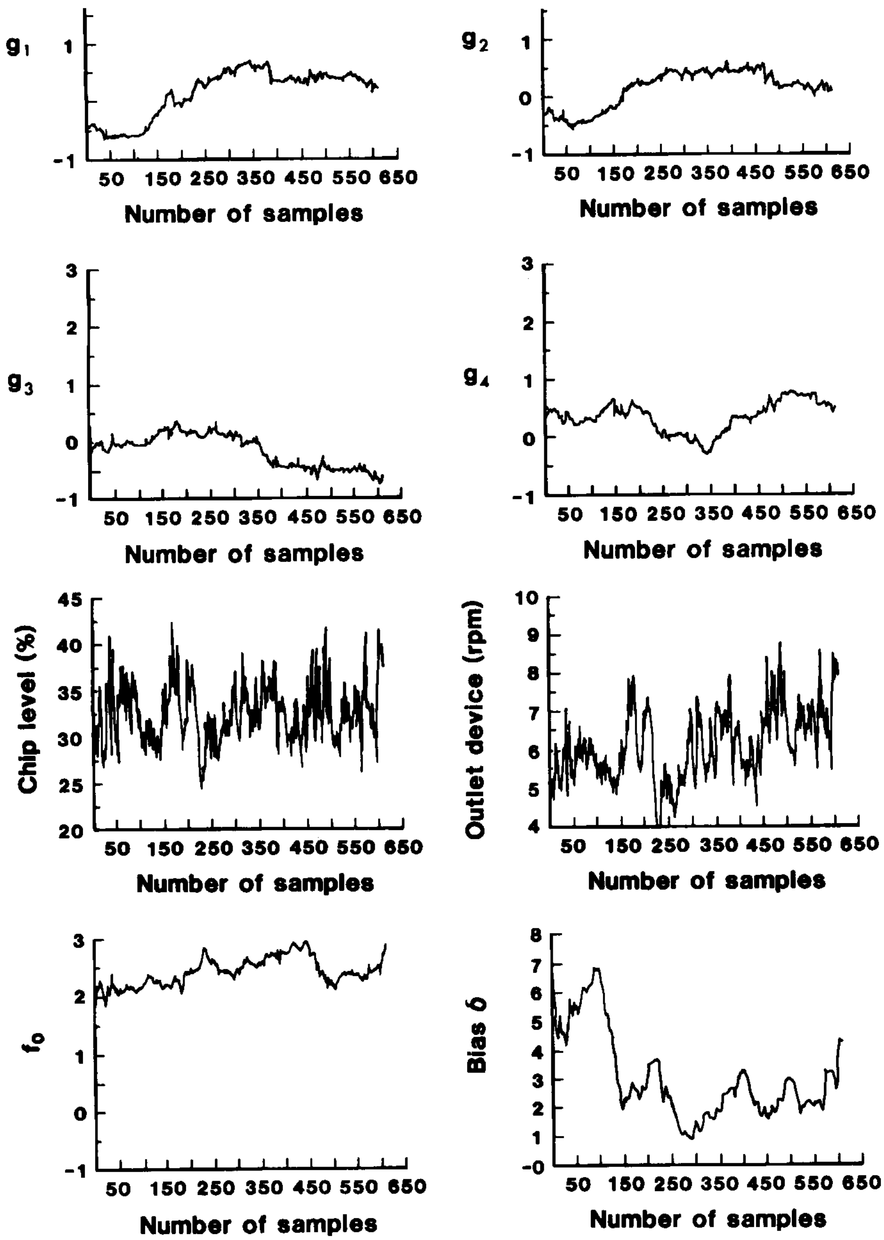

Figure 6. Behavior of STR control, using outlet device.

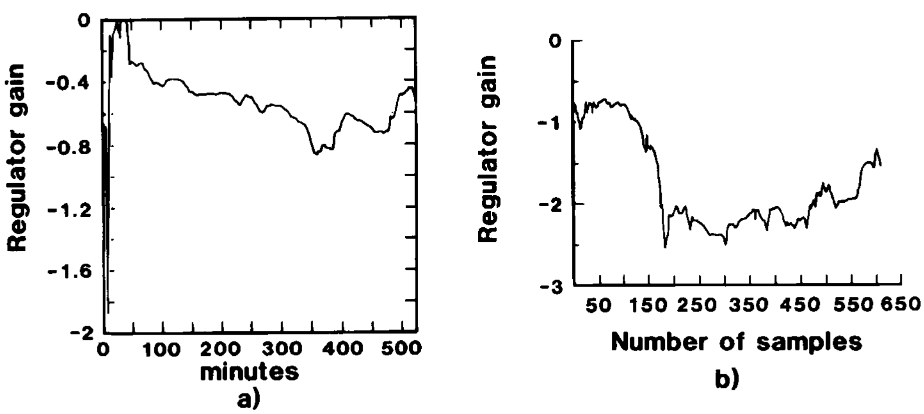

Figure 7. Evolution of the regulator d.c. gain using as controls:
a) Blow flow b) Outlet device

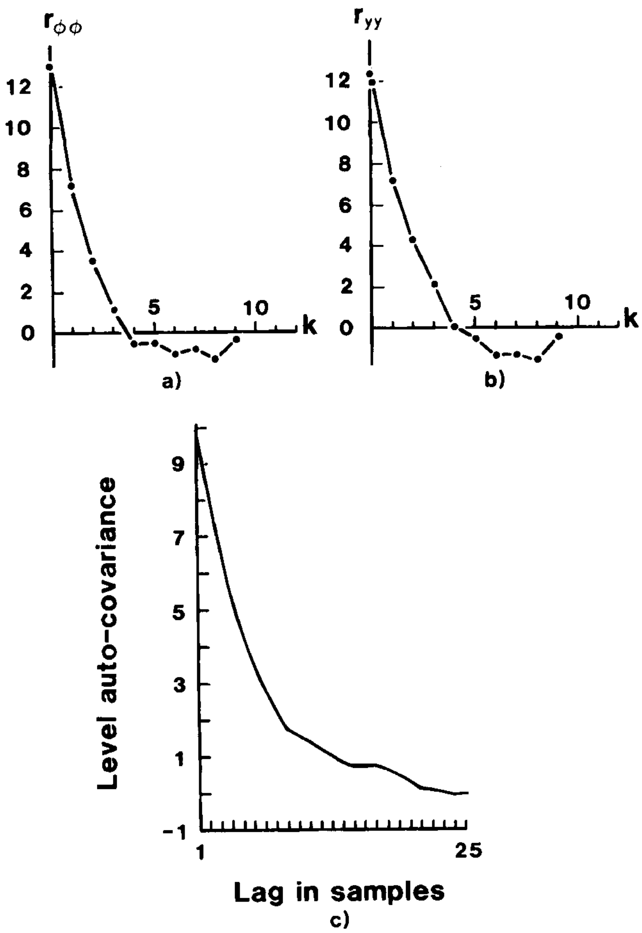

Figure 8. Correlation functions of:
a) Variable ϕ
b) Level original under blow flow control
c) Level signal under outlet device control

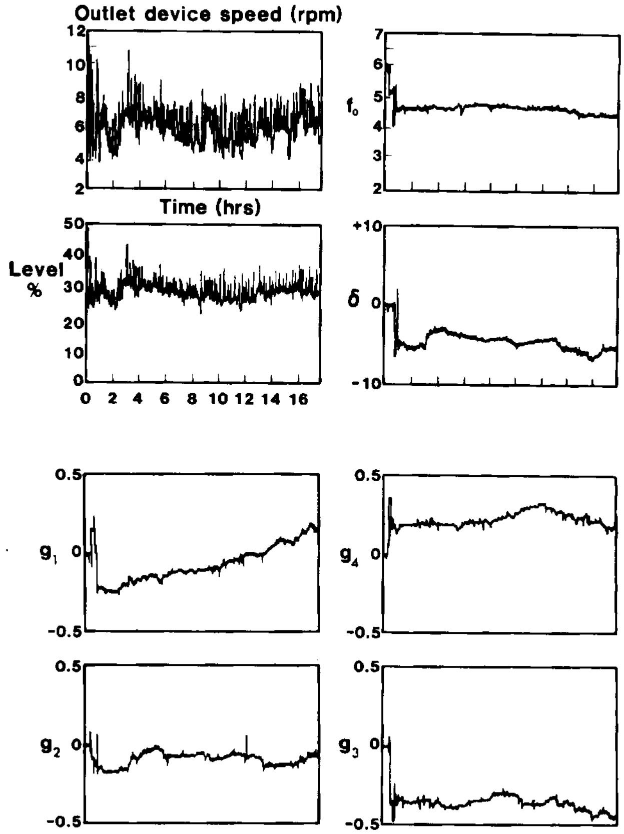

Figure 10. Behavior of STR control, using modified strategy.

- The other component of that setpoint is a feedforward signal from the chip flow setpoint.
- The blow line consistency is maintained by controlling the dilution flow. This is done by manipulating the blow flow setpoint through a slow PI regulator. The dilution flow setpoint is ratioed to the outlet device speed setpoint.
- A lower limit is imposed on the blow valve opening in order to prevent plugging.

Another practical modification was introduced in the STR. When the chip level is below the bottom of the top separator, the amperage of the separator is no longer a measurement of level, and the parameter estimates drift off to meaningless values. This effect occurs for amperage values below 30% of full scale. When the amperage signal is below 30%, the identification is suspended. Further, in order to bring the level within range more quickly, the regulator gain is increased by 20%.

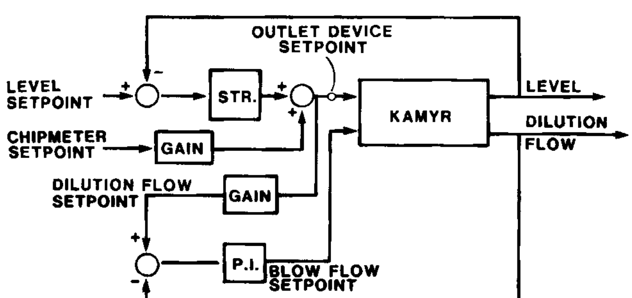

Figure 9. Modified control scheme for continuous operations.

PRODUCTION RUNS

The control system was installed at the Consolidated-Bathurst Wayagamack mill in Quebec, on a hydraulic Kamyr digester with a design production of 220 ADT/day. The chip level controller was implemented as part of an overall Kamyr digester control system developed in-house. The tasks of this Kamyr control system are distributed among three microcomputers. The first is

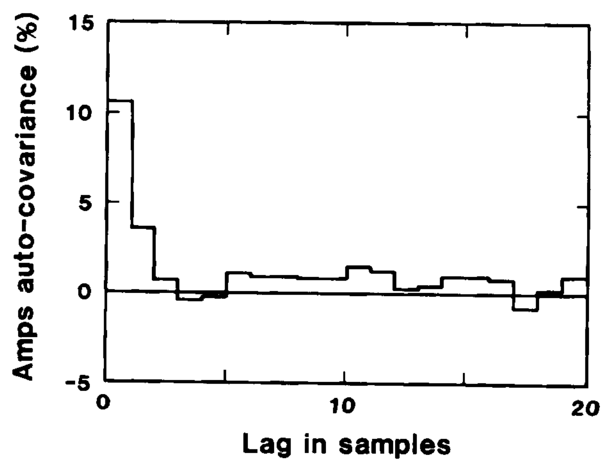

Figure 11. Autocorrelation of level signal for modified strategy.

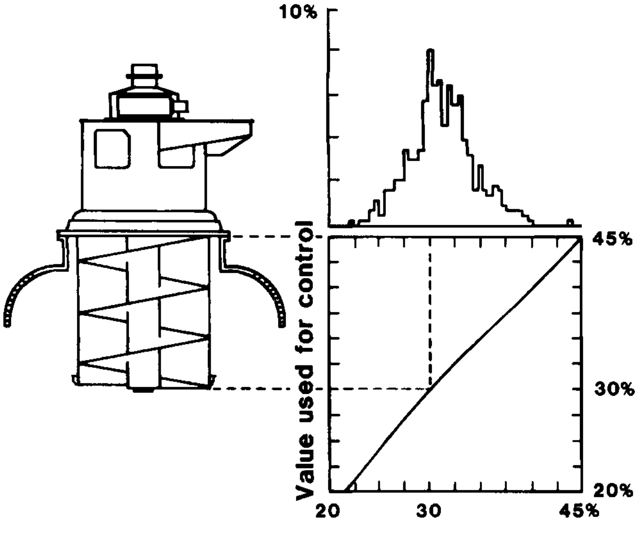

Figure 12. Histogram of level signal.

used to get all field measurements and to control the actuators. The second is used to control a color CRT to display measurements, setpoints, and other information, as well as to perform the operator interface. The actual control scheme is implemented in the third. The three microcomputers communicate via a RS232 serial link. Programs are written using a ROM BASIC interpreter.

Figure 10 shows 18 of STR following a start-up. The regulator was switched on right after the triggering of a high-level condition. The parameter estimates were all initialized at zero except f_0, which was set to 6, so that the initial regulator was a proportional controller with sufficiently high gain to generate a control signal rich enough to accelerate convergence without undue perturbation of the process. As previously, $\hat{g}_o$ was set to -2 and the forgetting factor to 0.97. The weight on the control action was now set to zero, thus providing minimum-variance control of the output. The setpoint was set at 32%. During the start-up period, the interlock was triggered once; the level remained below 30% for about 1 h, then remained around setpoint.

Figure 11 shows the autocorrelation function of the amperage signal for that period. The autocorrelation seems to indicate performance close to minimum variance. The variance of 10(%) is about the same as previously.

Figure 12 shows a histogram of the amperage signal. It is seen that the setpoint could be increased without increasing significantly the risk of triggering the high level interlock.

The dilution flow control loop was tuned manually, and some difficulties were encountered. It is executed every 1 min and had to be tuned with low gains in order to obtain a smooth evolution of the blow flow.

Figure 13a shows the evolution of the amperage signal during another start-up. It is seen that prior to the start-up of the STR, the level was very much perturbed and that during 6 h the interlock was triggered eight times. Although less perturbed, the first 4 h period in Figure 13a shows the type of level variations in manual control. The STR was started at 16:30 after an interlock triggering. The interlock was triggered once at 18:15, after which the level remained around setpoint. Figures 13b and 13c show the be-

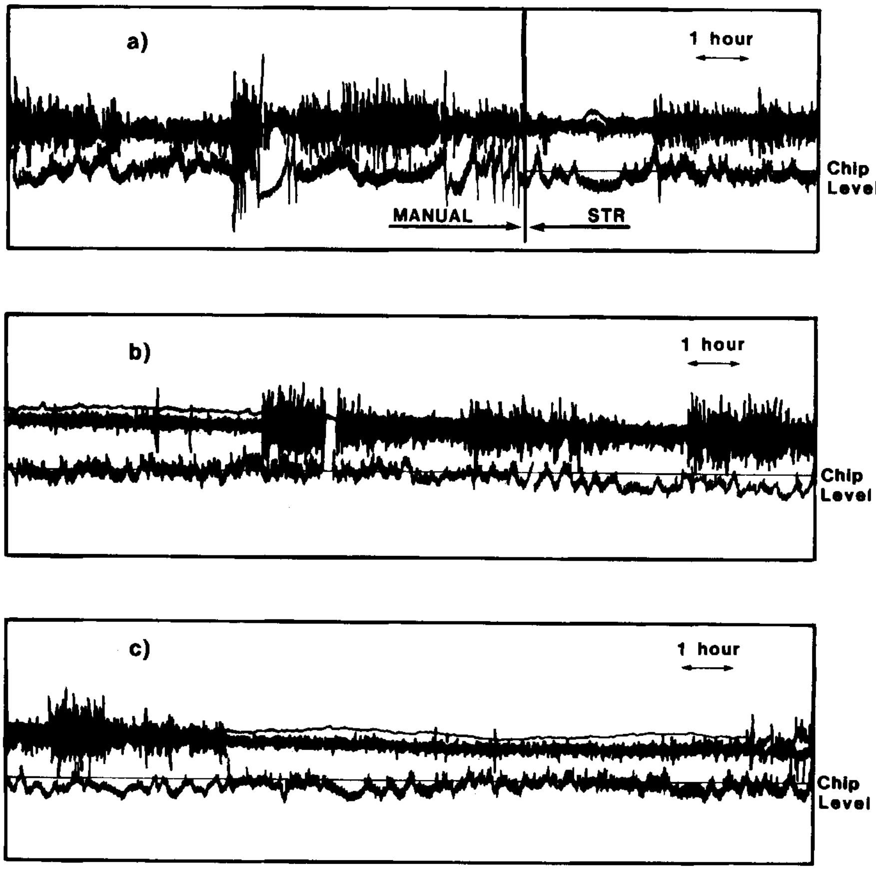

Figure 13. Three sample graphs showing input-output behavior of STR control under production conditions.

havior of the chip level once the STR start-up period has elapsed. The improvement compared to the manual control situation is obvious.

During the preliminary tests, it was hoped to be able to switch the identification off after an initial start-up period. However, all tests showed that the parameter estimates change significantly and do not seem to converge to a steady state. This seems to indicate that the process dynamics change sufficiently to justify continuous adaptation. Further evidence is provided by the convergence difficulties of the Sastry study,, where no forgetting factor was used, i.e., $\lambda = 1$, so that no tracking of changing parameters took place. If the plant parameters had been nearly constant, a well-tuned controller would have stayed well-tuned and divergence would not have occurred.

That version of the control scheme was installed in May 1983 and has been in continuous use ever since. Operator acceptance has been extremely high. This high level of operator confidence is mainly due to the fact that the number of interlock triggerings has decreased significantly, thus taking away what used to be a major concern. While previously it was common to have four or five such occurrences a shift, it is now not uncommon to have whole shifts without a single occurrence. On one occasion, the STR operated for 40 h without interlock triggering. Preliminary results indicate that the number of interlock triggerings has been reduced by a factor of at least three. The other factor contributing to operator confidence is the smooth behavior of the blow flow. Finally, that scheme improves the steadiness of the Kappa number, first by reducing the number of upsets due to interlock triggerings, second by reducing the variations in retention time.

CONCLUSIONS

This paper has presented a successful implementation of a STR in a mill environment. It was shown that the STR improves significantly the control of the chip level in a Kamyr digester.

The key to a successful STR implementation lies not only in a good understanding of the theory of STR but also in a good understanding of its practical aspects and of process operational constraints, and in building operator confidence. Although two schemes were shown to be equivalent in terms of output variance, one was less prone to operational problems and was readily accepted by the operators and consequently was chosen for continuous operation. This control scheme has now been in use for several months and is seen as an important step toward better control of the Kamyr digester.

ACKNOWLEDGMENT

The authors wish to thank the Kamyr digester operators at Wayagamack for their cooperation and to thank C. Dion for giving them access to the Kamyr digester.

NOTATION

A, B, C = polynomials of order n in q^{-1}
$e(t)$ = zero-mean, white random sequence
F = polynomial of order $n - 1$ in q^{-1}
G = polynomial of order $n + k - 1$ in q
$K(t)$ = gain in least-squares algorithm
k = integer, delay
N = integer, number of data points
n = integer, system order
n_p = integer, number of model parameters
$P(t)$ = covariance matrix of identification error
Q = polynomial of order $k - 1$ in 1
q^{-1} = unit delay operator
$u(t)$ = control input
u_{sp} = constant input value required for an output y
$\widehat{var}$ = estimate of noise variance
$y(t)$ = output, i.e., the level
y_{sp} = output setpoint

Greek Letters

δ = bias
$\Delta y(t), \Delta u(t)$ = deviation of y and u from y_{sp} and u_{sp}
λ = forgetting factor
ϱ = weight on the control
$\phi(t)$ = auxiliary output
θ = vector of parameters
ψ = vector of past outputs and inputs

LITERATURE CITED

Akaike, H. "A New Look at the Statistical Model Identification," *IEEE Trans. Aut. Control*, AC-19, (1974).

Al-Shaikh, A., and F. Tu, "Multilevel Control of Continuous Digesters: Application and Results," *Proc. IFAC 7th World Cong.*, Helsinki, 239 (1978).

Astrom, K. J., *Introduction to Stochastic Control Theory*, Academic Press, New York 126, (1970).

Astrom, K. J., and B. Wittenmark, "Self-tuning Controllers Based on Pole-zero Placement," *IEE Proc.*, 127, 120 (1980).

Belanger, P. R., "A Review of Some Adaptive Control Schemes for Process Control," *Proc. Eng. Found. Conf. Chem. Proc. Control*, T. F. Edgar and D. E. Seborg, Eds., 269–286 (1982).

Bierman, G. V., *Factorization Methods for Discrete Sequential Estimation*, Academic Press, New York (1977).

Cegrell, Y., and J. Hedqvist, "A New Approach to Continuous Digester Control," 4th IFAC/IFIP Int. Conf. Digital Compouter Appl. to Process Control, Zurich, 300 (1974).

Clarke, D. W., and P. J. Gawthrop, "Self-tuning Controller," *Proc. IEE*, 122, 924 (1975).

Fuchs, R. E., and G. J. Single, "Advances in Computer Control of Kaymr Continuous Digesters," *Tappi*, 59, (1976).

———, "Blow Flow Control in Continuous Digesters," *Tappi*, 54, 368 (1971).

Lindqvist, S. O., "State of the Art in Continuous Digester Control," *Proc. EUCEPA Symp. Control Sys. in Pulp and Paper Industry*, Stockholm, (1982).

Sastry, V. A., "Self-tuning Control of Kamyr Digester Chip Level," *Pulp and paper Canada*, 74, T160 (1968).

Schwartz, G., "Estimating the Dimension of a Model," *Ann. Stat.*, 6, 461 (1978).

Manuscript received May 1, 1984, and revision received Feb. 22, 1985.