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ABSTRACT.

An implementation of a self-tuning regulator is described. The regulator algorithm consists of two steps. Firstly the parameters of a model of the process are estimated in real time using the method of least squares. Secondly a minimum variance regulator based on the estimated parameters is computed at each sampling interval. Implementation of the algorithm on a process computer is discussed. Questions concerning program structure and storage requirements are considered. Results from the moisture content control on a paper machine are presented. The experiences are very good concerning the start-up behaviour as well as the stationary behaviour of the self-tuning regulator.

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1. INTRODUCTION.

More and more industrial processes are controlled by process computers. The computers make it possible to use more complex regulators than the conventional PID-regulators. The administration of the data handling and the computation of control signals are generally done by a special program package (DDC package). The program packages consist of a collection of standardized regulators and data handling routines that can be used for different control loops. Often it is also possible for the user to include his own subroutines. The regulators are mostly discrete time versions of PID-regulators, sometimes with addition of dead-time compensation based on the idea originally proposed by O.J.M. Smith. These standardized regulators have simple structures which are characterized by few parameters. In many applications it is, however, desirable to have more complex regulators, but these seldom are implemented since they are difficult to tune. A badly tuned complex regulator can make a poorer control than a well-tuned simple regulator. It is thus desirable to have some kind of automatic tuning of the regulator parameters.

One way is to use an adaptive controller that automatically can adjust its parameters depending on the changing environment in which the regulator works. One special type of adaptive controllers are the <u>self-tuning regulators</u>, which are discussed in [2], [3] and [6]. The regulator tunes its parameters on-line. It is assumed that the processes to be controlled have constant but unknown parameters. Further, it is assumed that the processes have one single input and one single output and that they are minimum phase. The algorithm of the self-tuning regulator can be divided into two steps, identification and control. The algorithm performs a real time identification of the parameters in a model of the process using the method of least squares. The control law is a minimum variance regulator based on the estimated parameters. The regulator can be used to tune parameters in feedback as well as feedforward loops. Other types of self-tuning regulators are discussed e.g. in [4] and [5].

The theoretical aspects of the self-tuning regulators, considered in this report, are thoroughly discussed in [2] and [6]. The main result is that if the parameter estimates converge, certain covariances of the output and cross-covariances between the output and the input are equal to zero. Further, if the number of parameters of the regulator is large enough and the process to be controlled can be described by a linear finite dimensional model the regulator will converge to the minimum variance regulator that could be obtained if the parameters of the process were known. In practice, the algorithm has shown good convergence properties. Experiments on laboratory as well as industrial processes have shown that self-tuning regulators are well suited for industrial applications.

In this report it is discussed how the self-tuning regulators can be implemented on process computers and results are given from control experiments on a paper machine. The algorithm which is quite general can be applied to many types of processes.

In Section 2 it is discussed how the self-tuning regulators can be used and how program structure and data bases can be organized. Moisture content control on a paper machine is described in Section 3. Results from experiments on a paper machine at the Gruvön Mill of Billerud Company in Sweden are given in Section 4. Experiences of the experiments are summarized in Section 5.

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2. IMPLEMENTATION OF SELF-TUNING REGULATORS ON PROCESS COMPUTERS.

2.1. The Use of Self-Tuning Regulators.

Sometimes it is necessary to use a regulator with many parameters. This is for instance the case when:

- the process has several time-delays,
- feedforward compensation is used.

In these cases it can be favourable to use a self-tuning regulator, because it is difficult to do the tuning manually.

The theoretical results concerning the self-tuning regulators are obtained under the assumption that the parameters of the process controlled are constant but unknown. In [6] it is discussed how the algorithm can be modified to follow slowly time-varying parameters by introducing a weighting factor, λ, less than one.

The self-tuning regulators can be used in different ways:

- A self-tuning regulator can be used at the installation or retuning of a regulator loop. It can be removed when a proper parameter set is obtained.

- The self-tuning regulator can be installed among the other system programs in the computer and periodically serve different control loops.

- If the process has time-varying parameters, it may be desirable to have the self-tuning regulator connected to the regulator loop all the time.

2.2. Program Structure.

When implementing the algorithm on a process computer it is sometimes advantageous to divide the algorithm into two parts, one for the estimation and one for the control. If the algorithm is implemented on a computer having a DDC package the control part in many cases can be implemented using the standard set of regulators defined in the DDC package. The estimation or tuning part then delivers the regulator parameters to the data base used by the DDC package. If a regulator structure is used that is not available among the standard routines it is necessary to write a special routine for the control part.

The tuning part must be specially written and included in the system programs. This routine can be used for many different loops if special care is taken concerning the storage of data.

If the routines are written straightforwardly using standard FORTRAN, the program length will be about 31 statements for the tuning part and about 28 statements for the control part. When compiled on an IBM 1800 with floating point hard-ware the storage requirement will be about 448 memory cells for the tuning part and about 310 memory cells for the control part. The storage requirements can be considerably reduced if the structure of the estimator equations is utilized.

The data needed for the self-tuning algorithm can be divided into three types: state variables, dummy variables and constants. The state variables are input-output signals, parameter estimates and their covariances. The dummy variables are temporary variables used at only one interval of time. The constants define the regulator structure.

Let the number of parameters of the regulator be r and assume that there are k steps of time-delay in the process. The data storage of the two routines together will be

State variables	$0.5r^2 + 2.5r + 3k + 6$
Dummy variables	r
Constants	5

It has then been utilized that the covariance matrix is symmetric. The control routine needs 4 constants and 2r state variables. If the tuning algorithm serves only one loop at a time it can use the same data area for all loops.

2.3. Selection of Parameters and Start-Up Procedure.

Simulations and experiments have shown that the choice of parameters in the algorithm is not crucial. The only parameter that must be chosen with some care is the number of time-delays, k. An under-estimation of k can be serious, while an over-estimation of k with one or two sampling intervals is not serious. The choice of parameters is discussed thoroughly in [6].

The start-up procedure can be made in different ways. It is always suitable to limit the control signal. Such a limit test is included in most DDC packages. The initial values of the parameters can be arbitrary. It is suitable, however, to limit the control signal comparatively much in the beginning. After a short period of time the parameter estimates are good enough to give successful control, and the limit of the control signal can be eased.

Another way to start up is to use good initial values of the parameters. For instance, these values can be obtained by letting the control routine work as a simple PI-regulator for a short period of time with fixed parameters, while the tuning routine is running. The estimates of the regulator parameters and the value of the covariance matrix obtained in this way generally work very well as initial values when the real tuning starts.

3. MOISTURE CONTROL ON PAPER MACHINES.

One of the control problems when producing paper is to keep the moisture content of the paper on a desired level. The moisture content is influenced by many variables e.g. the basis weight, the degree of refining and the quality of the pulp.

The moisture content control loop at the Gruvön Mill will now be described. The experiments in the next section were made on a machine producing fluting. The production is approximately 130 000 ton/year. The basis weight range of the fluting is 112 - 150 g/m^2. The paper machine as well as the refiners and the digesters are controlled from an IBM 1800 computer. A DDC package, PPCP (Process and Production Control Package), is available on the computer [1].

The moisture content of the paper is controlled primarily with a feedback loop from a capacitive moisture gauge, to the steam pressures of the drying cylinders of the last two drying sections. See Figure 3.1. The moisture gauge is kept in a fixed position. No averaging of the moisture content over the machine width is done.

The moisture content is influenced by several process variables and it is advantageous to use feedforward compensation. The thick stock flow, which influences the basis weight, or the reference value of the refiners are signals that can be used for feedforward control of the moisture. On the paper machine used in the experiments a feedforward signal from the couch vacuum was used. This has the advantage that disturbances from the refiners as well as basis weight fluctuations originating from the head box and the wire are taken into account.

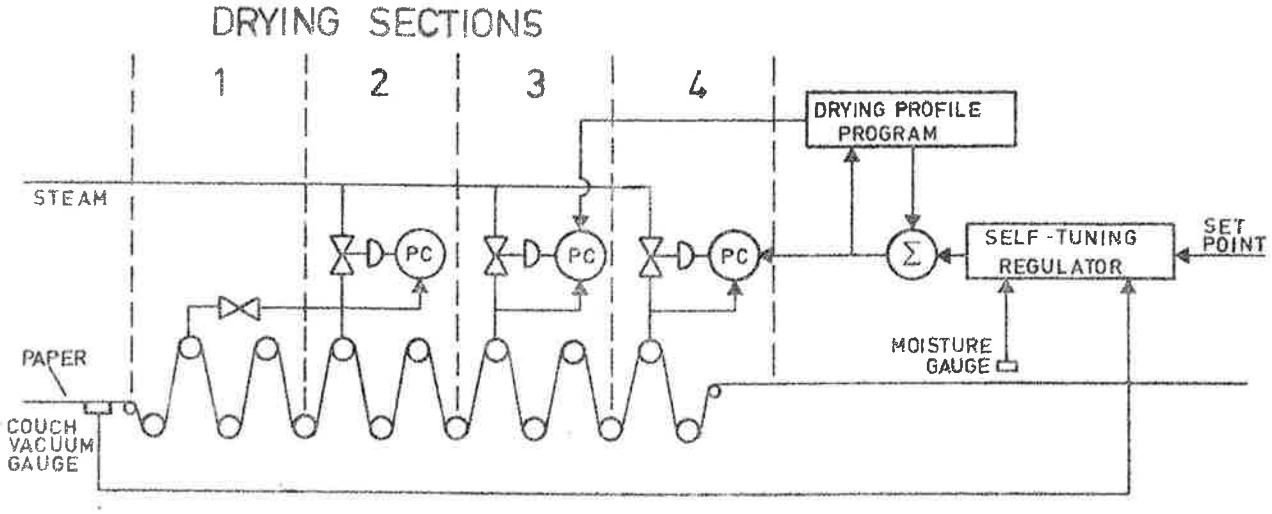


Fig. 3.1 - Schematic figure of the drying sections and the moisture content regulation at the Gruvön Mill when the self-tuning regulator was used.

It is desirable to have a certain drying profile, i.e. to have a certain relationship between the pressures of the different drying sections. Therefore, a special program which is able to adjust the drying profile is included in the system. The pressure of the fourth section is allowed to vary in the interval 0 - 1 kp/cm^2 below the pressure of the third drying section. The drying profile program changes the pressure of the third section if a pressure outside the limits of the fourth drying section is required.

The reference value of the fourth drying section thus can be influenced by the moisture and couch vacuum signals and the drying profile program.

When the self-tuning regulator was used to control the moisture content the sampling interval was 16 seconds. The moisture and couch vacuum signals were measured and filtered every 8th second. The filter used for the moisture signal was part of the DDC package and had a short time constant.

4. EXPERIMENTS AT GRUVÖN.

Several experiments with the self-tuning algorithm were made using different regulator structures. The number of regulator parameters and the number of time-delays were varied. The regulator was tested under different operating conditions including great process disturbances. Basis weight changes and machine speed adjustments were also investigated.

Two examples will be discussed, where the self-tuning regulator controlled the moisture content of the paper machine. The structure of the regulator was different in the two cases.

Example 1. The number of regulator parameters was 6. Four parameters were used in the feedback loop and two in the feedforward loop. The regulator had the structure

$$\nabla u(t) = \alpha_1 y(t) + \alpha_2 y(t-1) - \beta_1 \nabla u(t-1) - \beta_2 \nabla u(t-2) +$$

$$+ \gamma_1 \nabla v(t) + \gamma_2 \nabla v(t-1)$$

where

∇u - incremental control signal
y - moisture content deviation
∇v - increment in coach vacuum signal.

The time-delay in the process, k, was assumed to be four sampling intervals.

The following process variables were registered during the experiment:

- moisture content (the set point is indicated by a line) [%]
- incremental control signal (∇u) [engineering units]
- steam pressure of the fourth drying section (u) [kp/cm^2]
- steam pressure of the third drying section (reference value) [kp/cm^2]
- couch vacuum signal [m H_2O]

The experiment started by letting the tuning algorithm run for about ten minutes having a PI-regulator with fixed parameters to compute the control signal. The estimated parameters obtained were used as initial values when the self-tuning regulator started to control. The results obtained are shown in Fig. 4.1 - 4.8.

Changes in refiner energy often are possible to observe in the couch vacuum registration.

At 21.42 the refiner energy was decreased by the process operator. This adjustment can be observed in the moisture content and couch vacuum registrations (Fig. 4.1 and 4.5). The self-tuning regulator compensated for the change by decreasing the steam pressure, which best can be seen in Fig. 4.4.

At 22.28 the process operator increased the refiner energy. After that the couch vacuum variations were rather small until about 24.00. Then some disturbances influenced the process, and the variations in the moisture content were increased.

The self-tuning regulator was able to change the steam pressure fast enough to maintain good control. The estimated standard deviation of the moisture content in Fig.

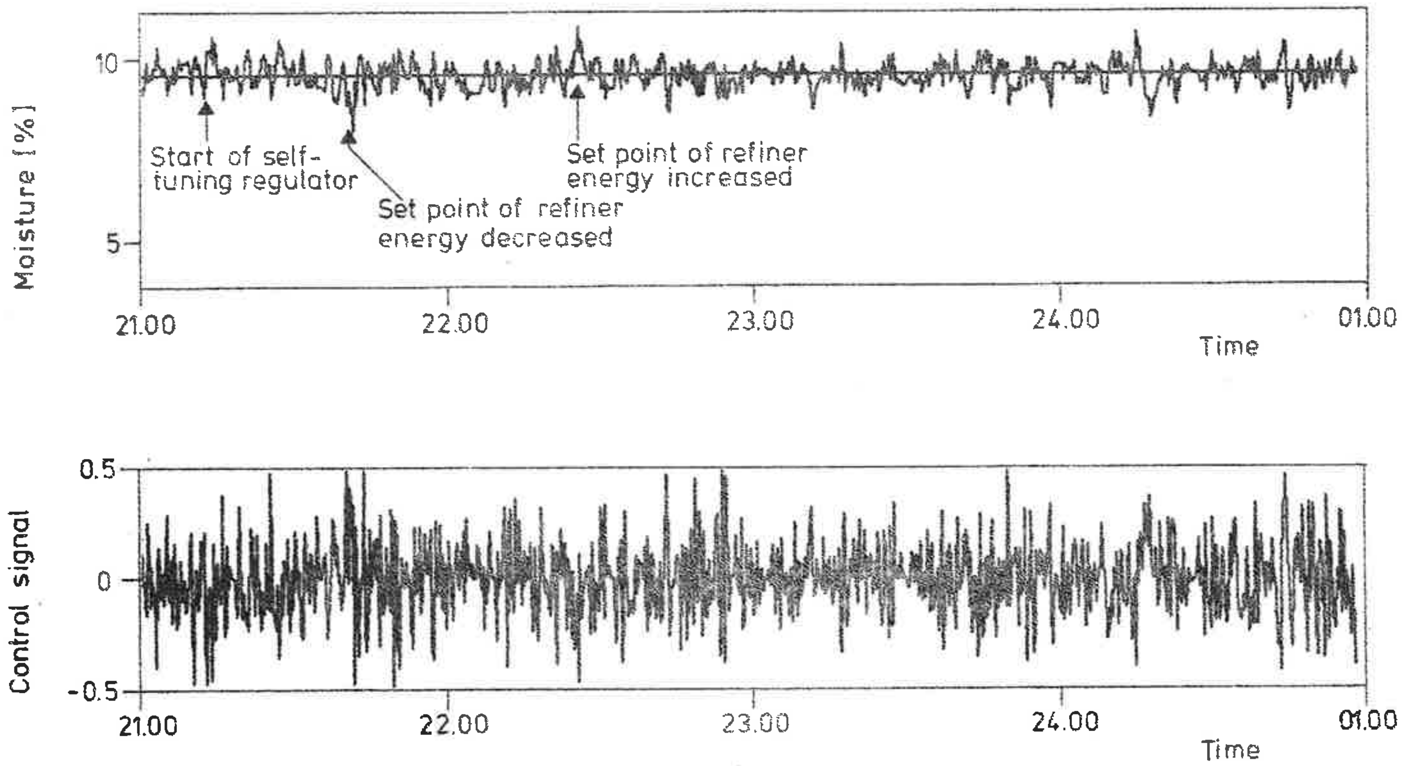


Fig. 4.1 - 4.2 - Moisture content signal and control signal (u) in Example 1. The regulator contains 6 parameters.

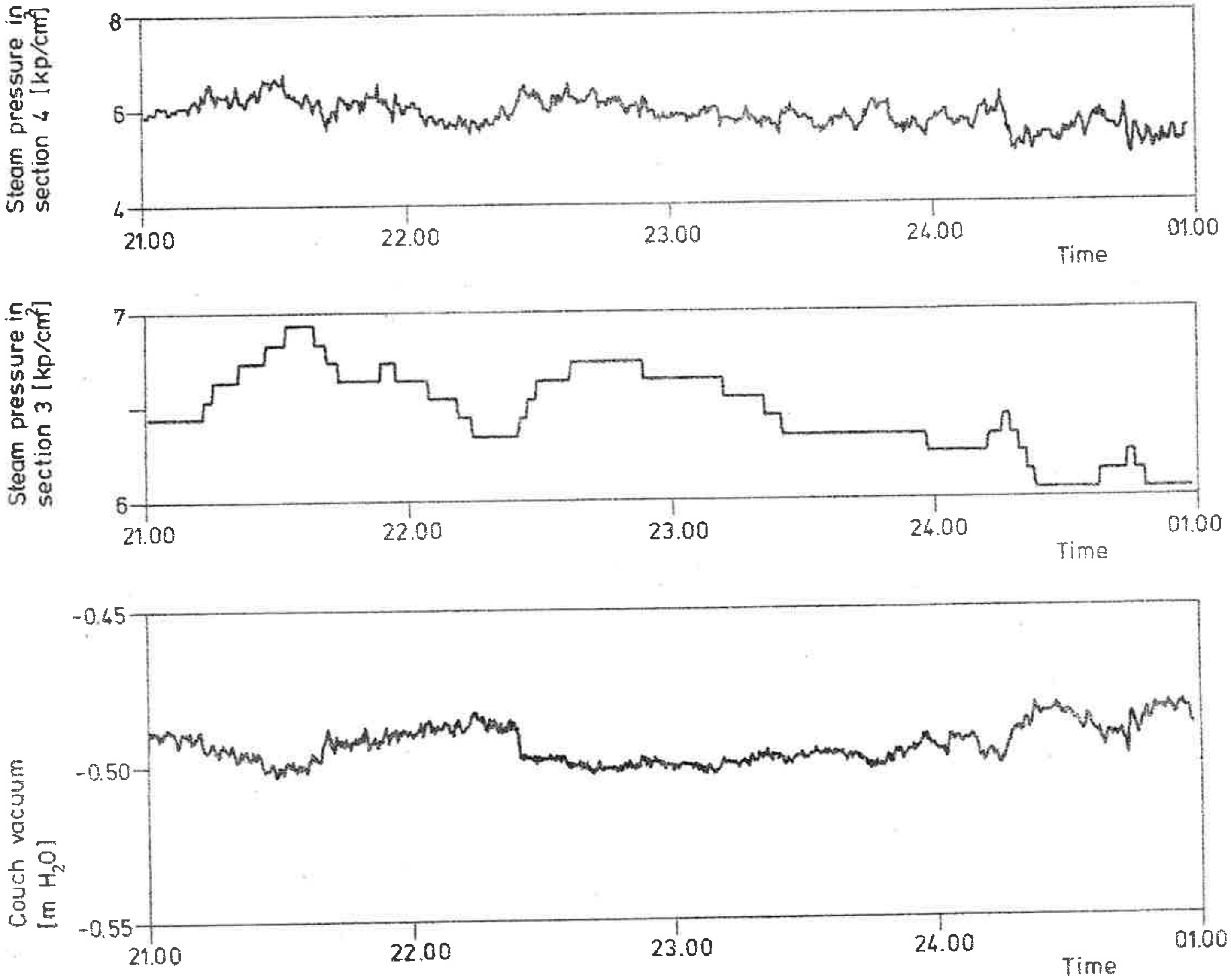


Fig. 4.3 - 4.5 - Steam pressure in the last drying section, reference value of steam pressure in the third drying section and couch vacuum from the experiment in Example 1.

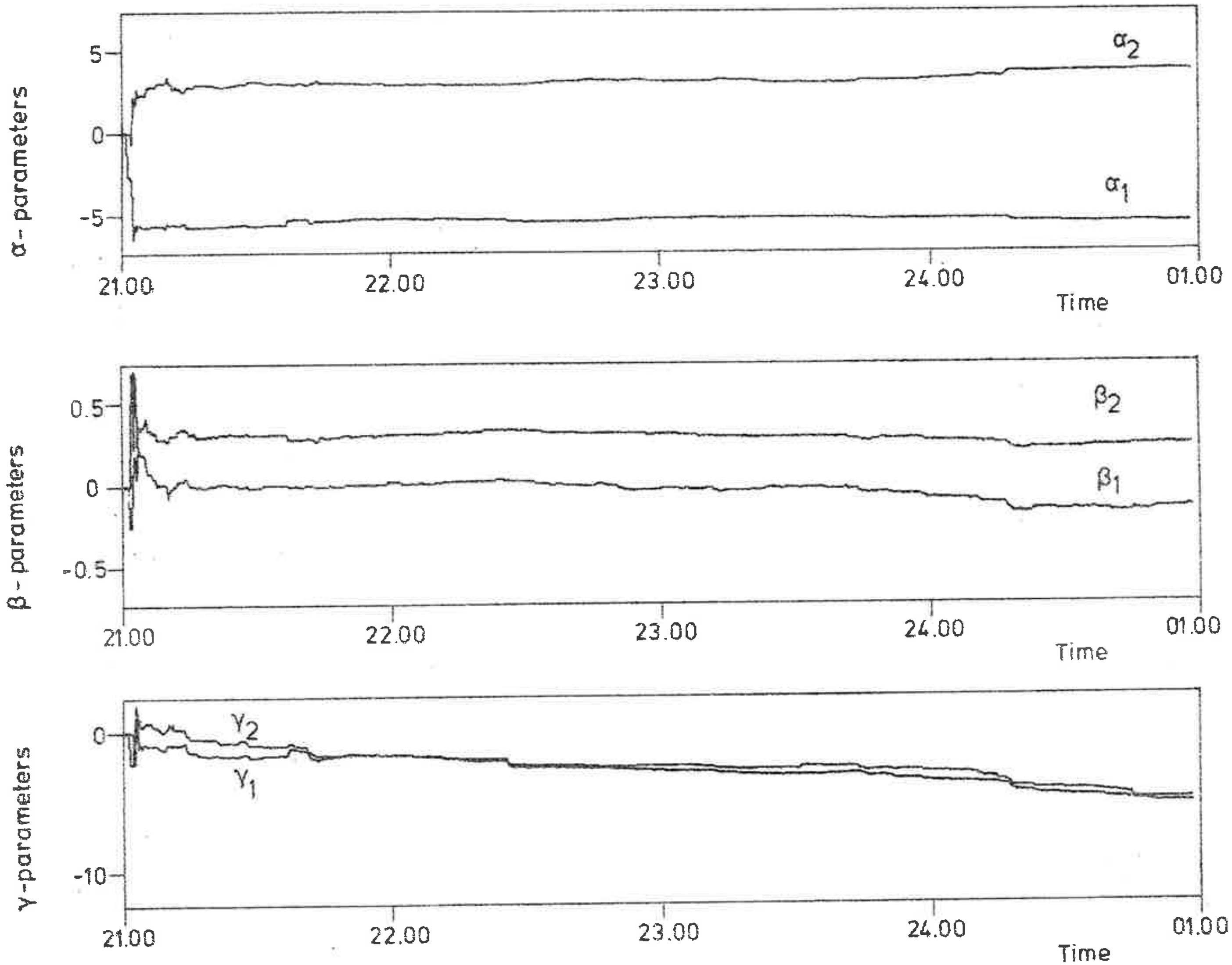


Fig. 4.6 - 4.8 - Parameter estimates from the experiment in Example 1.

4.1 is about 0.37%. This result is quite good when using a moisture gauge kept in a fixed position and without averaging over the machine width. In the Figures 4.6 - - 4.8 the regulator parameters are shown.

When the parameters have converged, and if the structure of the regulator is the same as of the minimum variance regulator of the system, then [2]

$$r_y(\tau) = 0 \qquad \tau \geq k+1$$

$$r_{yu}(\tau) = 0 \qquad \tau \geq k+1$$

where k is the number of time-delays. In Fig. 4.9 the estimated covariances $\hat{r}_y(\tau)$ and $\hat{r}_{yu}(\tau)$ have been plotted. The dashed lines indicate a 95% confidence interval for $\tau \neq 0$.

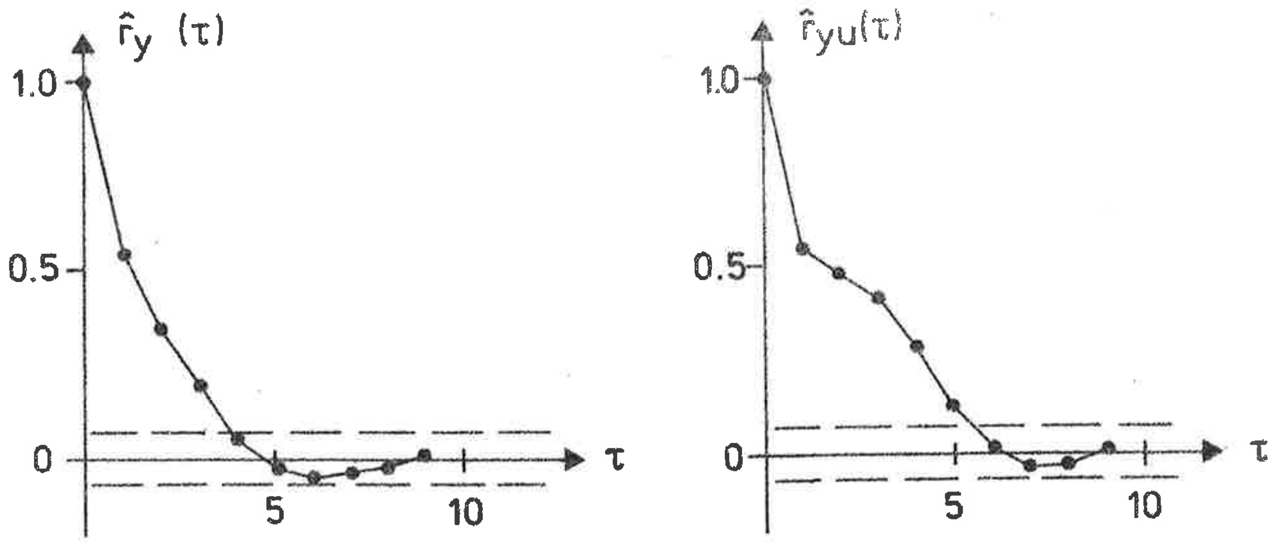


Fig. 4.9 - The estimated covariances of the data in Fig. 4.1 and 4.2. The covariances have been normalized.

In this example the covariances are expected to be zero for $\tau \geq 5$. In Fig. 4.9 there is only one point, $\hat{r}_{yu}(5)$, that is outside the 95% confidence interval.

<u>Example 2</u>. In this case the regulator contained nine parameters. The regulator had the structure

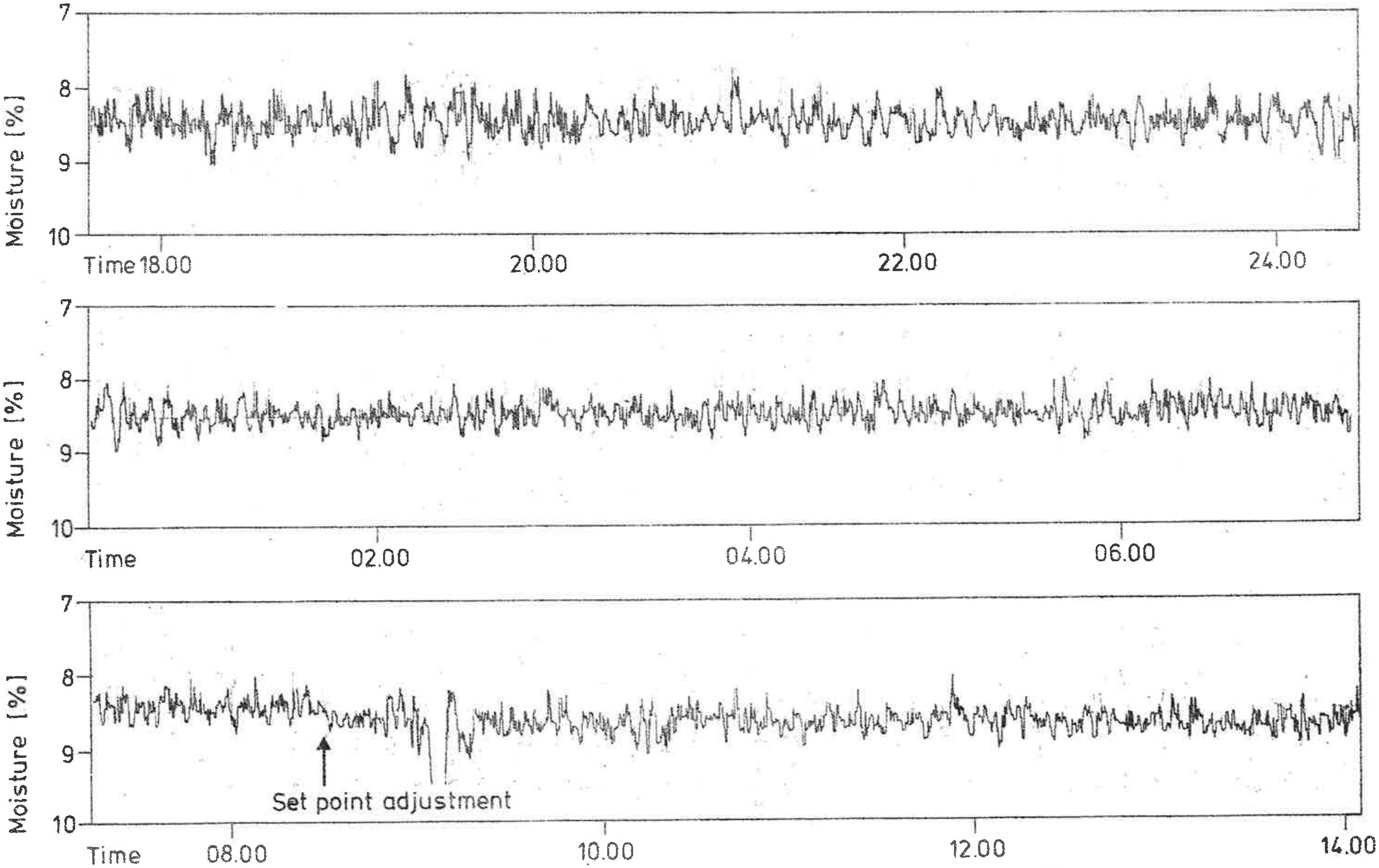
$$\nabla u(t) = \alpha_1 y(t) + \alpha_2 y(t-1) + \alpha_3 y(t-2) -$$

$$- \beta_1 \nabla u(t-1) - \beta_2 \nabla u(t-2) - \beta_3 \nabla u(t-3) - \beta_4 \nabla u(t-4) +$$

$$+ \gamma_1 \nabla v(t) + \gamma_2 \nabla v(t-1)$$

The parameter k was given the value 3.

In Fig. 4.10 there is a registration of the moisture content for about 20 hours. The set point was 8.5% until 08.30. Then it was increased to 8.7%. The self-tuning regulator managed to keep the moisture content near the set point all the time. The estimated standard deviation of the first four hours is 0.39%. Later in the experiment it was even smaller.



<u>Fig. 4.10</u> - Moisture content from the experiment in Example 2. The length of the experiment is about 20 hours.

5. EXPERIENCES.

The self-tuning regulator has been used in experiments of different lengths to control the moisture content of paper. The experiences are very good both concerning the start-up phase and the steady state control.

In the experiments on the paper machine it turned out that the choice of parameters in the regulator was not crucial. The number of parameters in the regulator could be chosen in different ways without influencing the steady state performance drastically.

When the disturbances acting on the process were small, the experimental results were in accordance with the theoretical results. See for instance the estimated covariances in Figure 4.9. At paper breaks the self-tuning routine was stopped and a special program was started to decrease the steam pressure of the drying sections. When the process was started up again the same program increased the steam pressure. Then the self-tuning regulator took over the control using the same parameters as before the paper break. Generally the parameters were not influenced very much by the paper breaks.

In most experiments a start-up procedure with an identification phase was used as described in Section 2. In the registrations of the parameters it can be seen that the transient period of the parameters has been about 10 minutes, which corresponds to about 40 sampling intervals. There may be a slow trend after the first transient before the stationary values are reached. Since it is desired that the stationary values should be reached as quickly as possible it can be convenient to use an exponential weighting factor, λ, which is time-varying. The weighting factor also makes it possible to follow slowly varying parameters. When the value of λ is determined there is a conflict between the demands on the ability of parameter tracking and the quality of steady state control. This is the dilemma that always exists when designing adaptive controllers.

From the registrations of the moisture content and the couch vacuum it can be seen that the disturbances do not always seem to be stationary. The disturbances can be small for a long period of time but suddenly large disturbances may occur in the process. However, the self-tuning regulator does not seem to have any difficulty to handle this type of disturbances in practice.

The self-tuning regulator had the same structure as the moisture controller used on the paper machine, i.e. a feedback loop from the moisture gauge and a feedforward loop from the couch vacuum gauge. The ordinary controller sometimes had difficulties to compensate for drift in the couch vacuum which originated mainly from variations in pulp quality and the degree of refining. Using the self-tuning regulator it was possible to follow the reference value better. The balance between the feedback and feedforward loops was improved by the self-tuning regulator. The performance of the ordinary controller was then improved by adjusting the parameters in accordance with the estimates obtained from the self-tuning regulator.

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