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An Application of a Self Tuning Regulator

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1973

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Report 7337 November 1973
Lund Institute of Technology
Division of Automatic Control

MOISTURE CONTENT CONTROL ON A PAPER MACHINE - AN APPLICATION OF A SELF-TUNING REGULATOR†

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ABSTRACT

Results from experiments with self-tuning control of moisture content on a paper machine are reported. The experiments were carried out at the Gruvön Mill in Grums, belonging to Billerud AB. Different regulator structures are discussed. The experiments on the paper machine were done under different operating conditions, including great process disturbances. Process variables and regulator parameters have been plotted to a large extent, and they are shown in this report.

The experiences of the self-tuning control were good. The experiments showed that the self-tuning regulator is a useful tool in process control.

†This work has been supported by the Swedish Board for Technical Development (Contract 72 - 1026/U833)

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1. INTRODUCTION

The feasibility of self-tuning regulators has been investigated in a joint project between Billerud AB and the Division of Automatic Control, Lund Institute of Technology. The results of the investigation are summarized in [1] and [4]. From the experiments it was concluded that the self-tuning regulators in many cases might be convenient to use on many industrial processes. The main advantages are that the algorithm can tune many parameters in the regulator without any difficulties and that the adaptation to new process conditions is fast. Further, the regulator is simple to implement and to use.

In this report it is discussed how the self-tuning regulator can be applied to an industrial process. The process under consideration is moisture control of a paper machine producing fluting at the Gruvön Mill in Grums, Sweden. The report is organized as follows. In section 2 the paper machine and the control problems are described in detail. The algorithms that are used are discussed in section 3 and listings of program heads are given in the Appendix. In section 4 it is discussed how the algorithm can be implemented on the IBM 1800 computer at the Gruvön Mill. A program package called PPCP (Process and Production Control Program) is available in the computer. The special features of this system are discussed, as well as general considerations, when self-tuning algorithms are included in DDC-packages. Some practical aspects on the regulator design are given in section 5. The experiments are described in section 6. Shorter, as well as longer experiments, are presented,and the performance of the process is evaluated.

The experiments have been possible to make thanks to financial support from STU (the Swedish Board for Technical Development, Contract 72 - 1026/U833) and the compliance of Billerud AB.

The authors want to express special thanks to O. Alsholm, L. E. Endresen and O. Stavnes at the Gruvön Mill in Grums for their help and support during the experiments.

2. DESCRIPTION OF THE PROCESS

The experiments were made on a machine producing fluting at the Gruvön Mill. The production is approximately 130 000 ton per year. The basis weight of the fluting is 112 - 150 g/m^2. The paper machine, as well as the refiners and digesters, are controlled from an IBM 1800 computer.

2.1 The refiners

The refiners split groups of fibres by pressing and rotating them. In this way the free fibre surface is increased, and the surface tensions get stronger.

The refiners have great influence on the moisture control. Disturbances in the refiners generally influence the couch vacuum. Variations in the quality of the pulp or in the fibre flow may also affect the couch vacuum. If there is no compensation in the drying sections for these changes, the moisture of the paper will show similar variations.

On PM6 there are special control loops to keep the specific energy of the refiners constant. The energy is computed by dividing the refiner power by the flow of pulp. By the refiner control it is possible to eliminate some of the disturbances originating from the variations in the quality of the pulp.

It might be possible to improve the refiner control by including a feedback loop from the couch vacuum. As the time delay between the refiners and the couch vacuum pit is comparatively long, such a feedback loop should primarily be used to remove variations in a long time range.

2.2 The drying sections

The moisture content of the paper is primarily controlled with a feedback loop from a fixed capacitive moisture gauge to the steam pressure in the drying cylinders in the two last drying sections, fig. 2.1. There is also a feedforward loop from the couch vacuum. It is desirable to have a certain drying profile, i.e. to have a certain relationship between the pressures in the different drying sections. Therefore, a special program which is able to adjust the drying profile is included in the system.

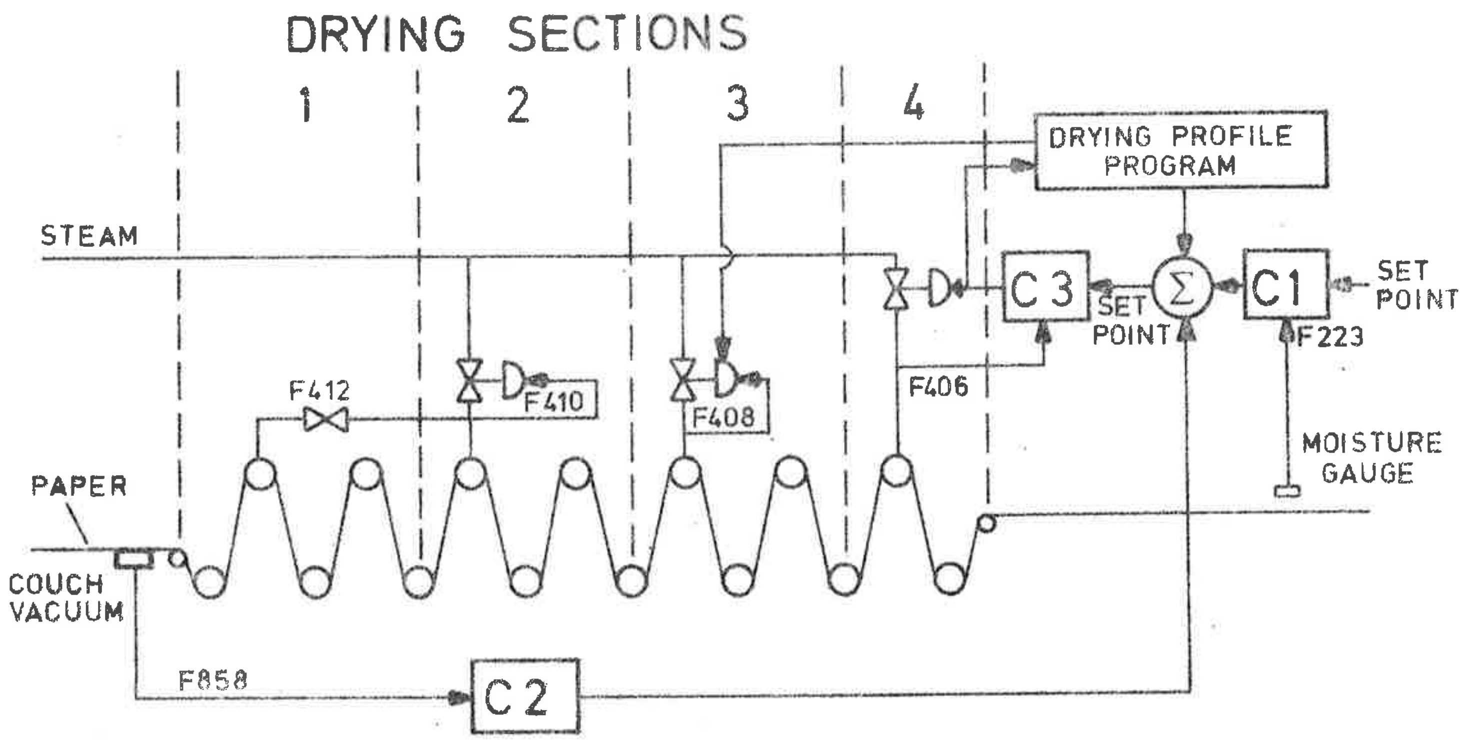

Fig. 2.1. Schematic figure of the drying sections and the control loops.

The reference value of the steam pressure F406 can thus be altered in three different ways. The moisture signal is sampled and filtered every 8:th second. A sampling interval of 16 seconds is used for the control of the feedback loop. The signal F223 is compared with the reference value of the moisture content. If there is a difference, the set point of the controller C3 is changed. The controller C1 is basically a PI-regulator with dead time compensation. The controller C2 is of proportional type. It is used for feedforward compensation from the couch vacuum. Every 8:th second the couch vacuum is sampled and filtered, and the signal from C2 alters the set point of C3 with the same time interval. C3 is a PI-regulator controlling the steam pressure F406 in the last drying section. A new control signal is computed every 8:th second. The pressure F406 is allowed to vary in the interval is 0-1 kp/cm^2 below the pressure F408. If the regulator requires a lower pressure, the reference value of F408 is changed. This change is made by a program that is called when the limits of F406 are violated.

The basis weight control loop of the considered paper machine was not in use. For a machine having control of the basis weight it is favourable to have a feedforward loop from the fibre flow. One advantage of this is that information of changes in basis weight is obtained early. However, the basis weight fluctuations are also taken into consideration with a feedforward loop from the couch vacuum.

3. A FORTRAN ALGORITHM OF THE SELF-TUNING REGULATOR.

Assume that the process can be described by

$$y(t) + a_1y(t-1) + \dots + a_ny(t-n) = b_1u(t-k-1) + \dots + b_nu(t-k-n) + \sigma[e(t) + c_1e(t-1) + \dots + c_ne(t-n)] + d_1v(t-k-1) + \dots + d_nv(t-k-n) \tag{3.1}$$

where y(t) is the output at time t, u(t) is the input at time t, v(t) is a known signal at time t, $\{e(t),\ t = 0, \pm 1, \pm 2, \dots\}$ is a sequence of independent normal N(0,1) random variables and k is the number of time delays.

In the self-tuning regulator the computation of the control signal basically consists of two steps, [2]. First the parameters of the model

$$y(t+k+1) + \alpha_1y(t) + \dots + \alpha_my(t-m+1) = \beta_0[u(t) + \beta_1u(t-1) + \dots \beta_\ell u(t-\ell)] + \gamma_1v(t) + \dots + \gamma_pv(t-p+1) + \varepsilon(t+k+1) \tag{3.2}$$

are determined with a recursive least-squares method. It is assumed that β_0 is known.

The new control signal is then computed from

$$u(t) = \frac{1}{\beta_0}[\alpha_1y(t) + \dots + \alpha_my(t-m+1)] - \beta_1u(t-1) - \dots - \beta_\ell u(t-\ell) - \frac{1}{\beta_0}[\gamma_1v(t) + \dots + \gamma_pv(t-p+1)] \tag{3.3}$$

When the regulator parameters have converged, the following covariances are zero

$r_y(\tau) = 0, \quad \tau = k + 1, \ldots, k + m$

$r_{yu}(\tau) = 0, \quad \tau = k + 1, \ldots, k + \ell + 1$

$r_{yv}(\tau) = 0, \quad \tau = k + 1, \ldots, k + p$

where k is the number of pure time delays. If the least-squares estimation converges and if

$m = n, \; l = n + k - 1, \text{ and } p = n + k,$

then the algorithm will give the optimal minimum variance control law that can be obtained if the parameters of the process (3.1) are known, [7]. In this case

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

The properties of the self-tuning algorithm is analysed in detail in [3] and [7].

The FORTRAN algorithm for the self-tuning regulator presented here consists of two subroutines, TUNE and REG. These correspond to the two steps discussed above. The program heads are given in Appendix.

3.1 The subroutine TUNE.

TUNE is a subroutine for recursive least-squares estimation. In every sample point it "tunes" the regulator parameters.

Consider the system (3.2). Introducing the vectors φ and θ

defined by

$$\varphi(t) = [-y(t) \ \ldots \ -y(t-m+1) \ \beta_o u(t-1) \ \ldots \ \beta_o u(t-\ell) \ v(t) \ \ldots \ v(t-p+1)]$$

$$\theta = [\alpha_1 \ \ldots \ \alpha_m \quad \beta_1 \ \ldots \ \beta_\ell \quad \gamma_1 \ \ldots \ \gamma_p]^T$$

we get

$$y(t+k+1) = \beta_o u(t) + \varphi(t)\theta + \varepsilon(t+k+1)$$

The parameters are determined by minimizing the loss function

$$V(N) = \sum_{t=n}^{N} \lambda^{N-t} e(t)^2 \qquad \lambda \leq 1$$

For time invariant systems the parameter λ should be equal to one. By giving λ a smaller value, it is possible to decrease the influence of early observations. For instance, this can be done if the process is slowly time varying.

An algorithm performing the minimization is, [6]

$$\hat{\theta}(t+1) = \hat{\theta}(t) + K(t)[y(t) - \beta_o u(t-k-1) - \varphi(t-k-1)\hat{\theta}(t)]$$

$$K(t) = P(t)\varphi^T(t-k-1)[1 + \varphi(t-k-1)P(t)\varphi^T(t-k-1)]^{-1}$$

$$P(t+1) = \frac{1}{\lambda} [P(t) - K(t)[1 + \varphi(t-k-1)P(t)\varphi^T(t-k-1)]K^T(t)]$$

In the subroutine TUNE the above computation is done. The subroutine call is

```
CALL TUNE(YS,U,VS,T,P,RL,NA,NB,NC,K,NSTEP)
```

where YS is a vector containing $(y-y_{ref})/\beta_o$

U is a vector containing the process input
VS is a vector containing the known signal $v(t)/\beta_o$
T is a vector containing the estimated parameters
P is the covariance matrix of the estimated parameters
RL is the base of the exponential weighting function (RL=λ)
NA is the number of α-parameters
NB is the number of β-parameters
NC is the number of γ-parameters
K is the number of time delays
NSTEP is the number of sample events between the tunings.

If the process is not changing, the value of RL should be one. On the other hand, if the process is varying, RL should have a smaller value. If RL = 0.99 the two hundred latest sample points approximately will influence the result. If RL = 0.95, only the forty latest sample points will be of importance.

NA, NB, NC, and K are determined using knowledge of the process or simply by testing different values.

The parameter NSTEP makes it possible to change the tuning frequency.

3.2 The subroutine REG.

The subroutine REG uses the parameters that have been calculated by TUNE. It computes the control signal according to eq. (3.3). REG must be executed at every sample event. The regulator parameters in the T-vector are updated by TUNE with a frequency of NSTEP sampling intervals.

The subroutine call is

```
CALL REG(YS,U,VS,T,NA,NB,NC,K,MSTEP)
```

where MSTEP is the maximum value allowed for NSTEP. The other parameters have been defined above.

4. COMPUTER IMPLEMENTATION

At the Gruvön Mill there are two IBM 1800 computers controlling different parts of the paper mill. They use a process and production control program, PPCP, which is a system of many different programs running under the real time operating system, MPX.

4.1 The process and production control program PPCP.

PPCP is a "fill-in-the-form" programming system. It is written partly in FORTRAN and partly in Assembler. There are many standard routines available:

periodic functions

- o reading of process inputs
- o filtering
- o conversion to engineering units
- o limit checking
- o data collection and reduction
- o regulation
- o generation of output signals

non-periodic functions

- o process operator console communication
- o action in case of limit violation
- o switching off of the output of a digital regulator
- o change of a set-point.

The periodic functions are executed with certain time intervals. The non-periodic functions are executed only when they are requested.

It is possible to integrate user-written programs in PPCP. These programs may be written in FORTRAN or Assembler. There are also certain subroutines making it possible for user to get access to the data base. Process variables, i.e. flows, temperatures, etc. are described in, "Main Table variable specification forms." Such a form contains all information about the type of processing that a variable is subject to.

There are special "system tables" storing data from the system specification, from certain computations in PPCP programs, etc. There are routines available to user giving access to some of these system tables and making it possible to modify them. It is also possible to reach them via the process operator console.

The following types of signals are used in executing the control commands:

- o pulse train
- o pulse duration
- o full analog
- o incremental analog.

4.2 Main Table variables.

Data concerning the process variables needing periodic processing are stored in the Main Table. These variables are called Main Table variables.

A process variable is said to be "measured," if its value is determined from the readings of only one process input. It is said to be "calculated," if its value is determined from the readings of two or more process inputs or from the values of other measured or calculated variables.

4.2.1. Execution periods.

The periodic functions in PPCP are divided into three groups with execution periods called P1, P2, and P3. With "fast scan" P1 is 1 second. With "normal scan" P1 is 4 seconds or multiples of 4 seconds. P2, as well as P3, is equal to or a multiple of P1. P3 is available only with "normal scan."

The group executed with period P1 includes input reading, validity check, and digital filtering. The group executed with period P2 includes conversion to engineering units, operational limit check, regulation, storage, and averaging. The last group, executed with period P3, includes filing of calculated values on disk.

4.2.2 Main Table records.

Each Main Table variable has a record in the Main Table. One part of the Main Table is subject to "fast scan," where the records are scanned at a period of 1 second. The other part is subject to "normal scan," where the scanning period is 4 seconds.

The Main Table records may have different lengths. They are stored one after the other without any empty space in between. They have the same order as the cards used in generating the table.

A Main Table record stores information of certain constants, type of filtering, type of regulation, process inputs, process outputs, etc.

4.2.3 Address Table.

A special Address Table is used in locating a certain Main Table record. Each Address Table word contains the absolute address of the first word of a Main Table record.

Each Main Table variable has an identification number which is defined by the position of the corresponding word in the Address Table. Thus the number is independent of the order of the cards used in generating the Main Table.

4.2.4 Regulation routines.

A process variable has in its Main Table record three bits indicating the type of regulation algorithm it is submitted to. There are seven different algorithms including general PID-regulators and a special PI-regulator, which also uses the two latest inputs. Generally, incremental control signals are computed.

A digital regulator is either a master or a slave. A slave sends its signals to an analog regulator in the process. A signal from a master is directed to one or more other digital regulators.

4.3 Integration of the self-tuning algorithm in PPCP.

The priority and execution frequency of a routine determine the way of implementation.

4.3.1. Principal ways of implementation.

If the priority is high, the routine must be core resident or included in an interrupt core load. In the latter case the highest frequency allowed is 32 seconds.

If the routine has low priority and frequency, it is suitable to include it in a "main line core load." This is executed periodically. The timing with the scanning of other Main Table records must not be important for this type of core load.

This way of implementation is easy to do, as it does not demand any modification of the operating PPCP system.

If the structure of the self-tuning regulator can be chosen to be the same as in one of the standard regulators in PPCP, the subroutine REG need not be used. In this case the regulator parameters stored in the Main Table are tuned by user. The subroutine TUNE delivers the resulting regulator parameters directly to the Main Table. At every sample event the control signal is then calculated by the PPCP standard routine.

4.3.2 Implementation during the preliminary investigations.

A main line core load was used during the preliminary investigations. This way of implementation was the most flexible one with respect to testing of different regulator structures. When the program was executed, it requested a new execution at a time corresponding one sampling interval later.

In the beginning of the program the latest process output was fetched. The subroutines TUNE and REG were then called. Before the calculated control signal was placed in the Main Table, it was checked that neither the incremental value nor the absolute value was too high. In case of limit violation the calculated input was decreased so that the specified limits were not exceeded.

A special area of the disk was reserved, where temporary results were stored. Another area was reserved for logging of regulator parameters and process variables relevant for the experiment.

A separate program was written to handle the data. Mean values and standard deviations could be calculated, and the data could be listed on line-printer and punched on cards.

As the program was not included in the PPCP system on interrupt level among the other regulation routines, the time between two executions was not always exactly the same. However, the small deviations that occurred did not seem to cause any problem.

5. PRACTICAL ASPECTS ON THE REGULATOR DESIGN

When the regulator structure is chosen, the properties of the process must be taken into consideration. Here some comments will be given on the regulator design for PM6.

In fig. 5.1 it is schematically shown how the self-tuning regulator was connected to the process. The self-tuning regulator replaced the two controllers C1 and C2 in fig. 2.1.

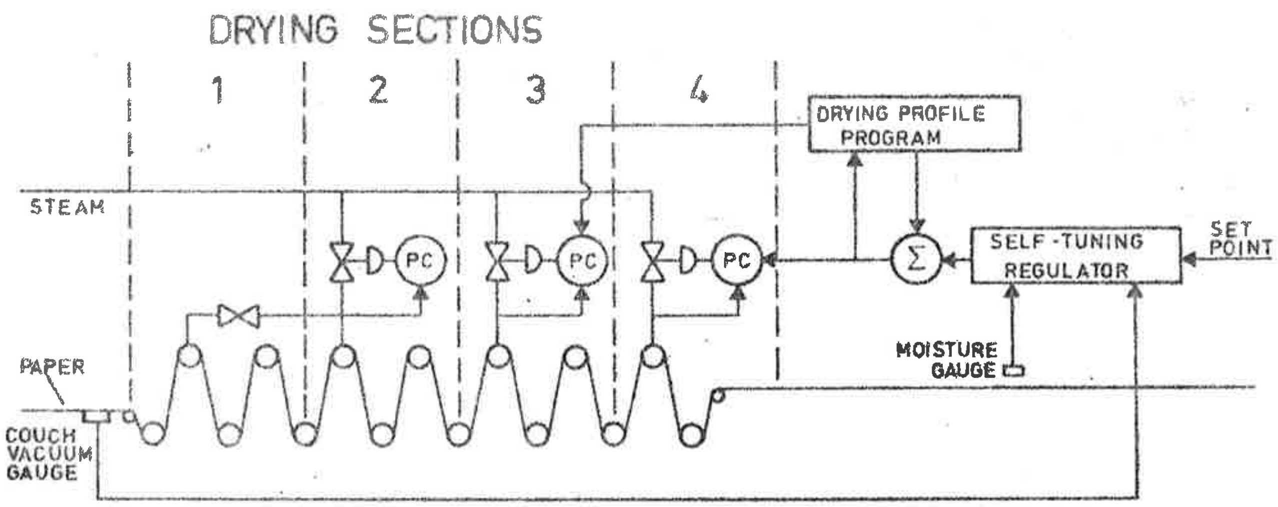

Fig. 5.1. Connection of the self-tuning regulator to the process.

The control signal was delivered via the Main Table record of the PPCP controller in the feedback loop (controller C1 in fig. 2.1)

5.1 The regulator structure.

Time delays and time constants of the process play an important role at the choice of regulator structure. On PM6 the transport time between the couch vacuum pit and the last drying section was 60 - 80 seconds. The time constant of the steam system was somewhat longer.

The sampling interval of the self-tuning regulator was 16 seconds. Experiments were made with 3 - 5 pure time delays in the subroutines TUNE and REG. In the regulator structure the time delay of the feedforward signal from the couch vacuum was assumed to be the same as for the control signal.

The control signal computed in the subroutine REG was

$$\Delta u(t) = \frac{1}{\beta_o}[\alpha_1 y(t) + \dots + \alpha_m y(t-m)] - \beta_1 \Delta u(t-1) - \dots - \beta_\ell \Delta u(t-\ell) -$$

$$- \frac{1}{\beta_o}[\gamma_1 \Delta v(t) + \dots + \gamma_p \Delta v(t-p+1)] \qquad (5.1)$$

where

Δu = incremental control signal

y = difference between the set point of the moisture content and the measured value

Δv = incremental couch vacuum signal.

5.2 Parameters in the subroutine TUNE.

Preliminary experiments had shown that

$\beta_o = 10$

was a good value. The tuning also worked well with $\beta_o = 5$ or $\beta_o = 20$.

Generally, the initial value of the covariance matrix was $P = 10\,I$ or $P = I$, where I is the unit matrix. As the regulator parameters were tuned at every sample event, the parameter NSTEP of the subroutine TUNE was NSTEP = 1.

5.3 The start-up procedure.

If there are α- and β-parameters available from earlier experiments, these may often be good as initial values for the algorithm. An appropriate value of the covariance matrix must also be provided.

If nothing is known in advance, the start-up procedure will work well with e.g. zeroes as initial parameters. In this case it is suitable to have a limit on the control signal. On PM6 the limit was

$|\Delta u| \leq 0.5$ engineering units.

If there is already some kind of regulator controlling the process, it is often advantageous to use this during the start up. On PM6 a standard regulator was used in the beginning of the tuning. The subroutine TUNE was then updated with the inputs that were sent to the process by the standard regulator. The parameters resulting from this tuning worked well as start values when the self-tuning regulator took over the control.

5.4 Tests during normal process operation.

Regulator installations must often be made during normal process operation. This may give special problems and precautions should be taken. The computed control signals should be tested so that they are reasonable. Process adjustments that are made by the operators should be registered.

On PM6 the drying sections limited the capacity of the machine. The maximum steam pressure was about 8 kp/cm^2. On some occasions a higher pressure was required to keep the moisture content at the desired level. During the experiments the total control signal u was checked, and it was never allowed to exceed 7.7 kp/cm^2.

At the evaluation of the experiments it is good to have registrations of relevant process variables. The following variables were generally registered:

- moisture content [%]
- incremental control signal (Δu) [engineering units]
- steam pressure in the fourth drying section (u) [kp/cm^2]
- steam pressure in the third drying section [kp/cm^2]
- couch vacuum (v) [m H_2O]

When the process operator altered the set point of the specific energy of the refiners, it was often possible to notice this in the couch vacuum registration.

If the control signal, i.e. the steam pressure, is to be studied the pressure F408 (ref. value) in the third drying section gives a good understanding of the control action. As the actual control signal, F406 in the fourth drying section gets its reference level changed by the drying profile program, no information about long trends in the steam pressure is obtained from this signal.

During the normal operation of the process there are sometimes interrupts in the moisture registration. These may depend on cleaning of the moisture gauge (occurs about every half-hour) on paper break, etc. When a paper break has occurred, a special system program starts decreasing the steam pressure. When the process is ready to start up again, the same program increases the steam pressure to the value it had before the paper break.

6. EXPERIMENTS

In this section some experiments with different regulator structures will be discussed. The process was subject to varying operating conditions during these experiments, and machine speed changes, as well as basis weight changes, have been studied.

In the figures showing moisture content the set point has been indicated with a line.

6.1 Control experiment on October 23, 1972.

In this experiment the following regulator structure was used:

Number of α-papameters	2
Number of β-parameters	2
Number of γ-parameters	2
Number of time delays	4
Base of weighting function	0.99
Scale factor β_o	10

The length of the experiment was 24 hours.

Figure 6.1 shows registrations from the first part. The basis weight was 127 g/m^2. At 21.12 the ordinary regulators were disconnected, and the self-tuning regulator started to control.

At 21.42 the specific energy of the refiners was decreased from 20 kW/ton to 18 kW/ton. This change influenced the couch vacuum, which was getting smaller, fig. 6.1.e. To keep the moisture content at a constant level the regulator had to decrease

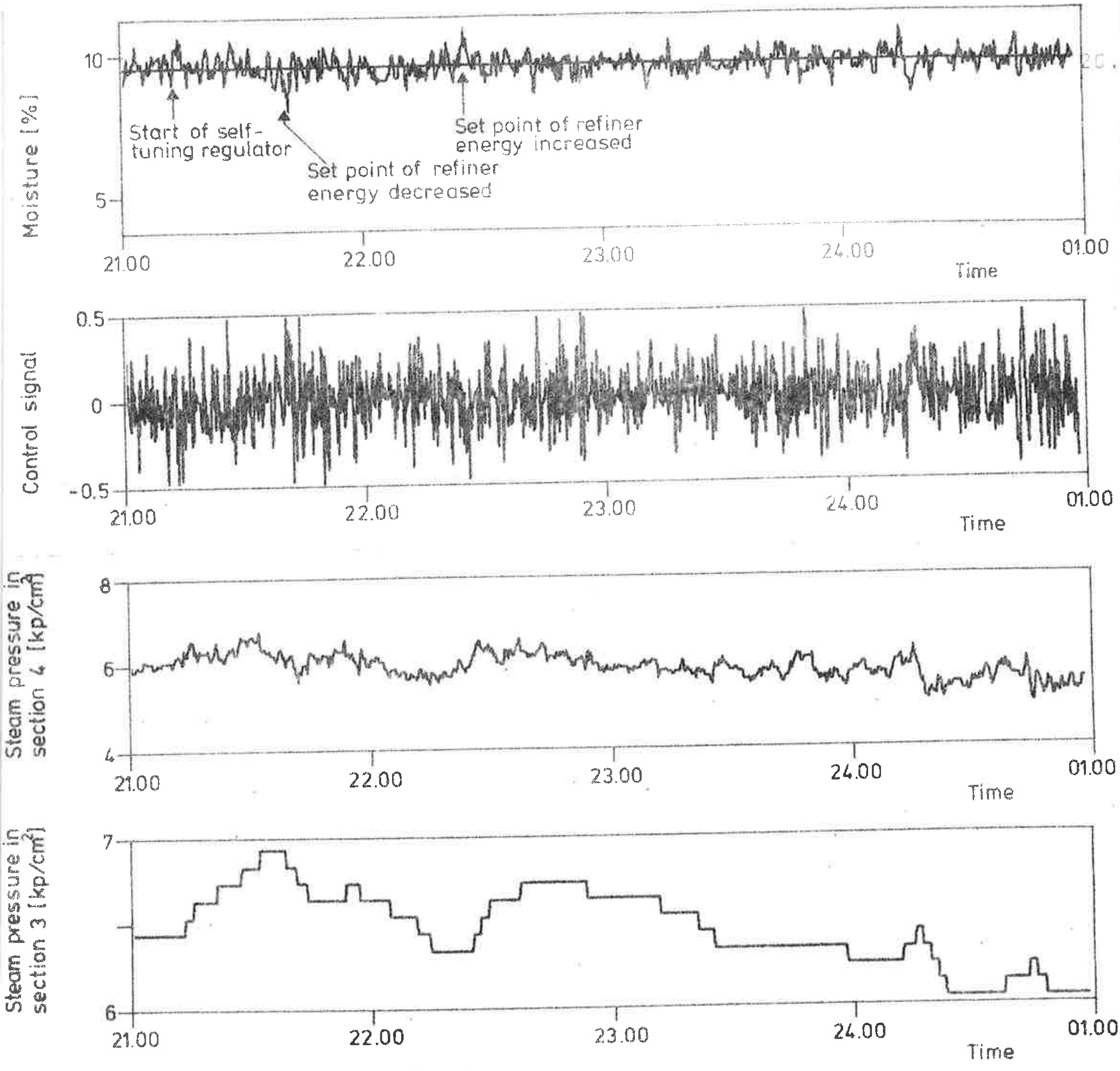

Fig. 6.1. Control experiment on October 23, 1972, between 21.00 and 01.00.

a. Moisture content
b. Control signal
c. Steam pressure in section 4
d. Steam pressure in section 3

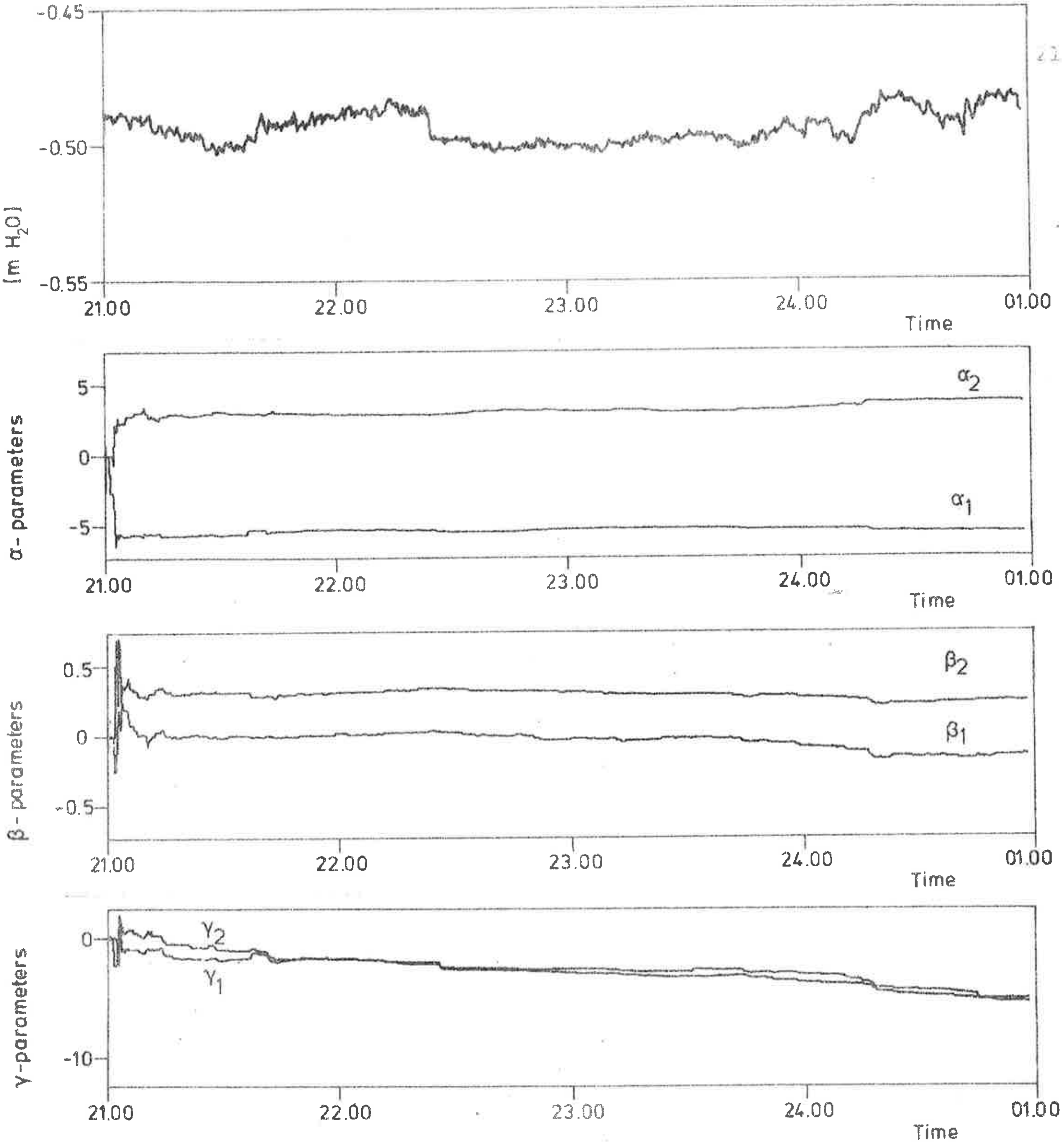

Fig. 6.1 (cont'd)

e. Couch vacuum

f. α-parameters

g. β-parameters

h. γ-parameters

the steam pressure, fig. 6.1.d. Fig. 6.1.a shows that there was a sudden disturbance in the moisture content at the time of the energy change of the refiners.

At 22.28 the specific energy was increased and fig. 6.1.a shows that the moisture content suddenly got high. In fig. 6.1.e a corresponding change in the couch vacuum can be seen. The self-tuning regulator managed to increase the steam pressure quickly, fig. 6.1.d, and the moisture content returned to the ordinary level.

At 24.18 and at 24.47 there were also significant disturbances in the moisture content, fig. 6.1.a. From fig. 6.1.e it appears that there were great disturbances in the couch vacuum at the same point of times. However, the self-tuning regulator managed to change the steam flow quickly enough to eliminate the disturbances.

The regulator parameters did not vary much. The disturbances in the moisture content at 21.42, 22.28, 24.18, and 24.47 were however noticeable, especially in the registration of the γ-parameters.

Fig. 6.2 shows the same experiment between 2.40 and 6.40 on October 24. The trend of the couch vacuum changed during this period, fig. 6.2.e. The self-tuning regulator compensated for this by increasing the steam pressure at about 03.40, fig. 6.2.d. Except for some sudden disturbances, the moisture content is then satisfactory, fig. 6.2.a.

The dip of the moisture content at 03.31 was caused by a small change in machine speed. The regulator parameters were also influenced. At 06.06 the specific energy of the refiners was

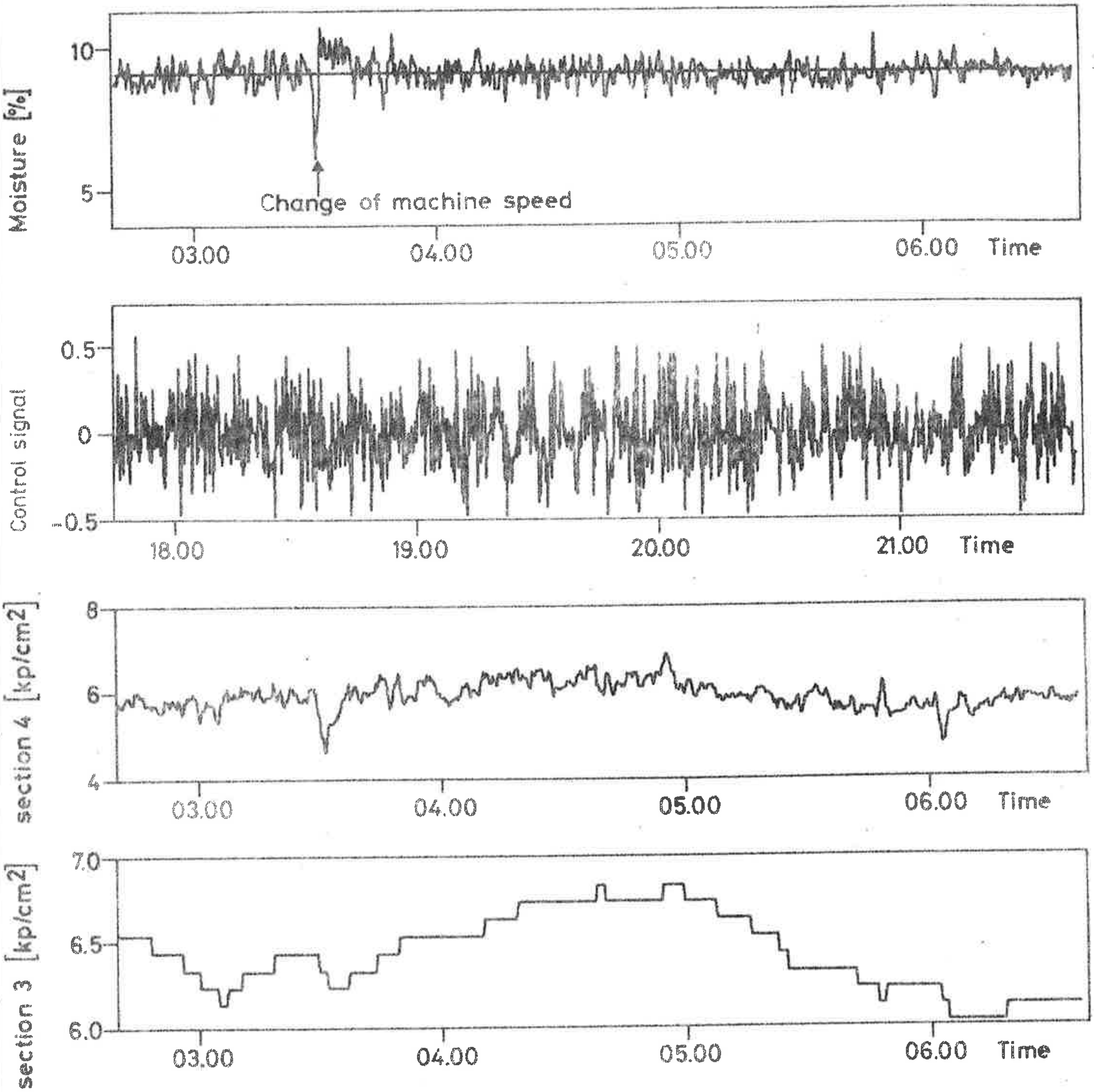

Fig. 6.2. Control experiment on October 24, 1972, between 02.40 and 06.40 (continuation of the experiment in fig. 6.1)

a. Moisture content
b. Control signal
c. Steam pressure in section 4
d. Steam pressure in section 3

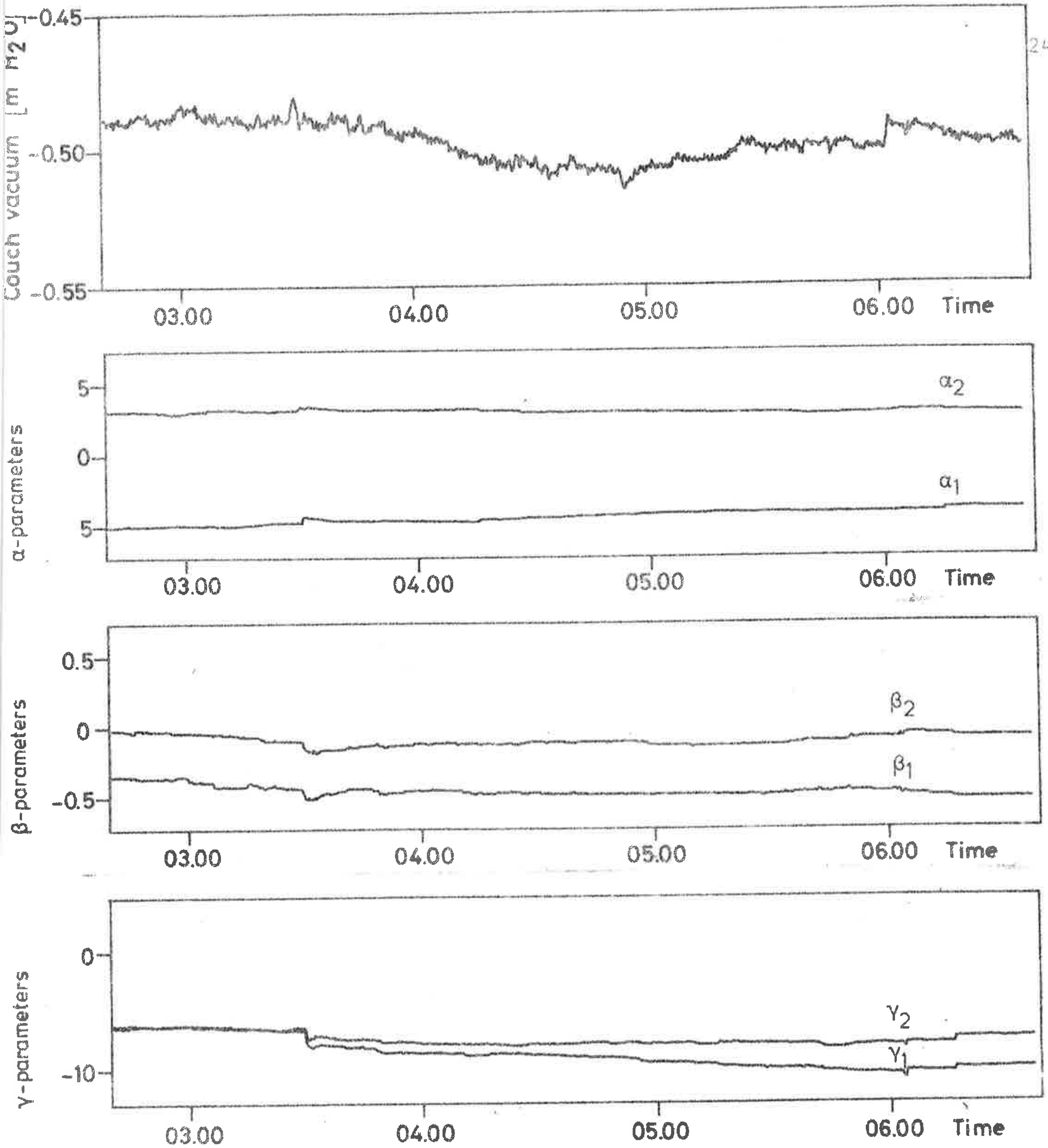

Fig. 6.2 (cont'd)

e. Couch vacuum

f. α-parameters

g. β-parameters

h. γ-parameters

changed by the operator. This introduced a disturbance in the moisture content and in the regulator parameters.

The standard deviation of the moisture content is 0.37% for fig. 6.1.a and 0.44% for fig. 6.2.a.

In fig. 6.3.a the estimated covariance for the moisture content, $\hat{r}_y(\tau)$, has been plotted for the first part of the experiment. Fig. 6.3.b shows the cross covariance between the moisture content and the incremental control signal, $\hat{r}_{yu}(\tau)$. For a minimum variance regulator

$$\hat{r}_y(\tau) = 0, \quad \tau \geq 5$$

$$\hat{r}_{yu}(\tau) = 0, \quad \tau \geq 5$$

if the disturbances are gaussian. The dashed lines in the figures indicate a 95% confidence interval for $\tau \neq 0$.

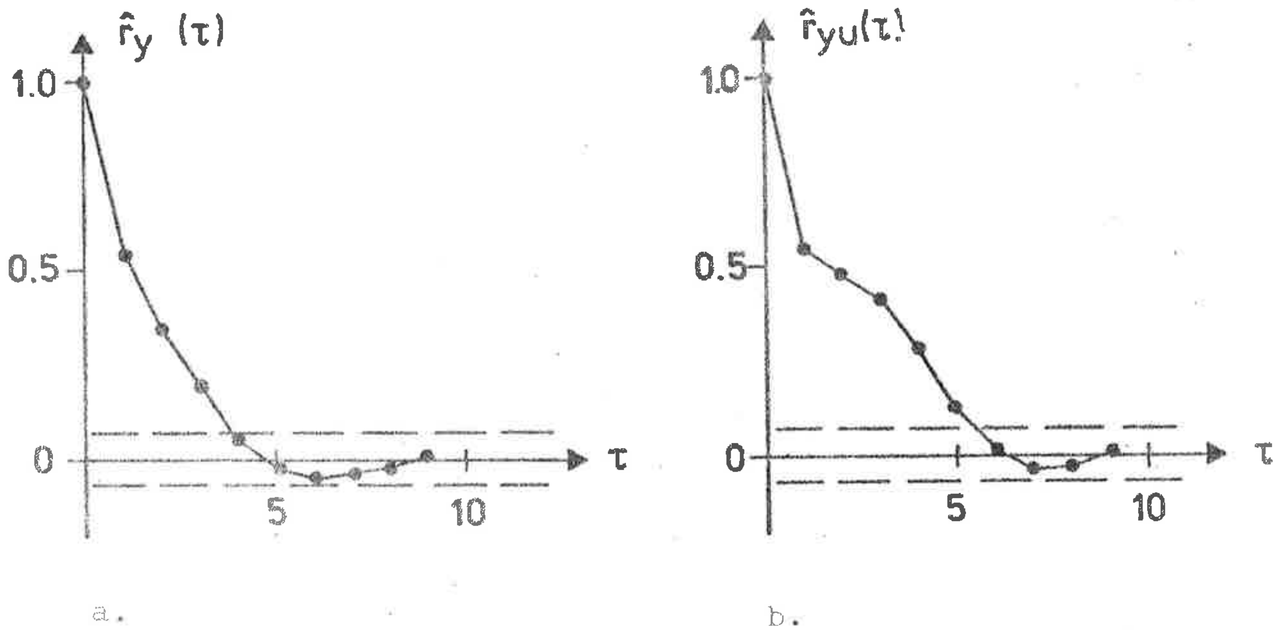

Fig. 6.3. The estimated covariances $\hat{r}_y(\tau)$ and $\hat{r}_{yu}(\tau)$ computed for the first part of the experiment (fig. 6.1). The covariances have been normalized. There were four time delays in the regulator.

In fig. 6.5 the estimated covariances $\hat{r}_y(\tau)$ and $\hat{r}_{yu}(\tau)$ for the data in fig. 6.4 have been plotted.

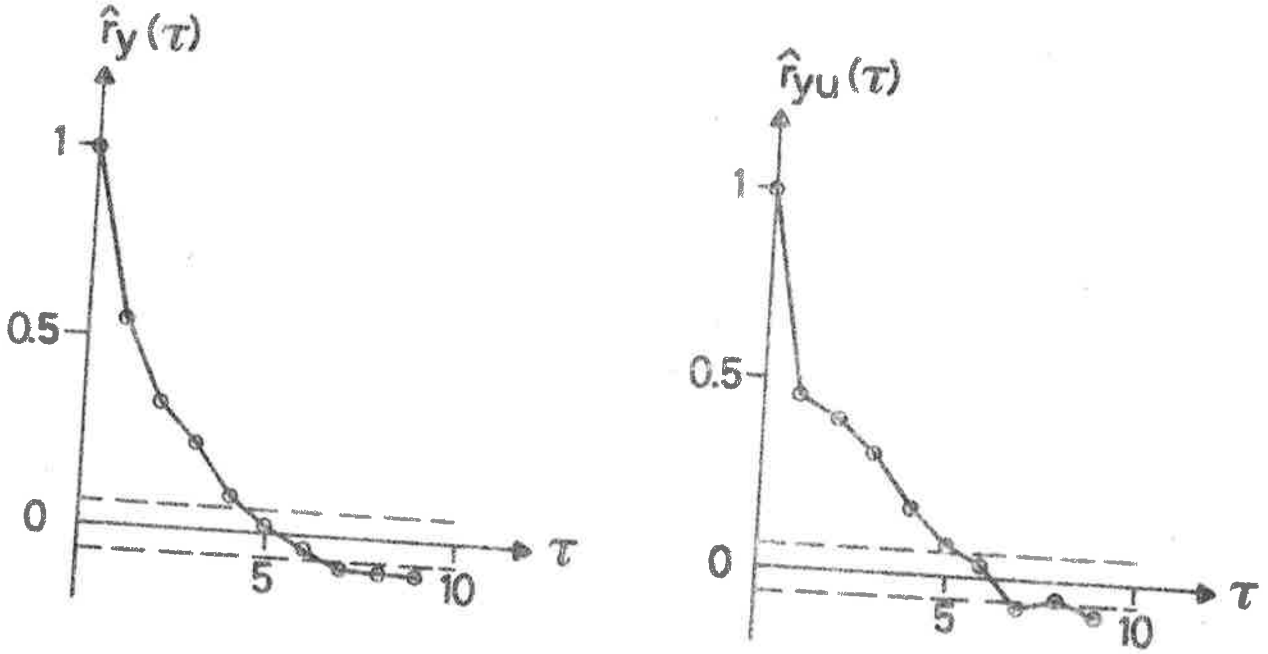

Fig. 6.5. The estimated covariances $\hat{r}_y(\tau)$ and $\hat{r}_{yu}(\tau)$. They have been normalized. In this experiment there were three time delays in the regulator.

In fig. 6.6 there is a registration of the moisture content from the whole experiment, about 20 hours.

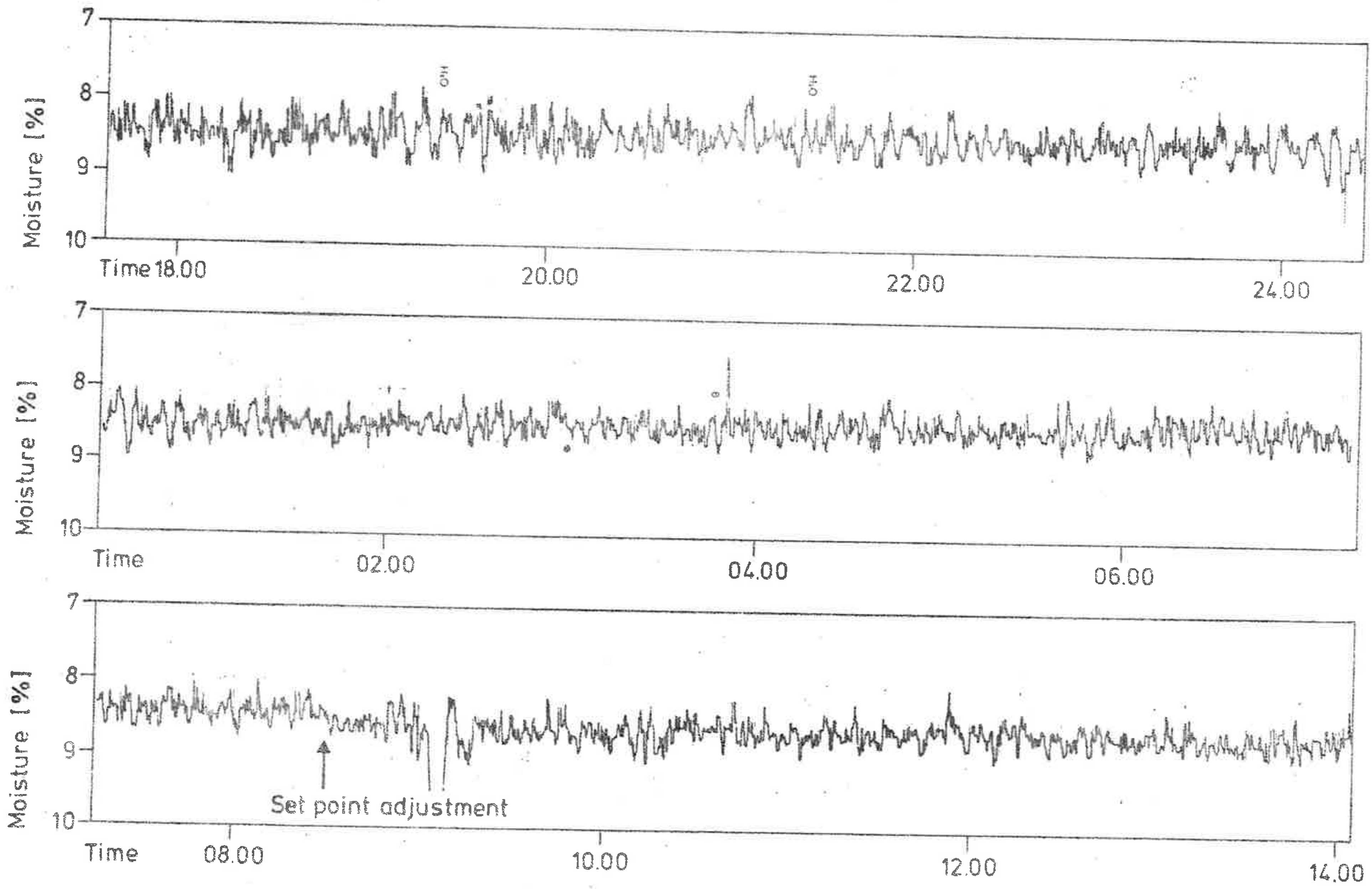

Fig. 6.6. Control experiment on October 25, 1972. Registration of the moisture content for about 20 hours.

6.3 Control experiment on October 27, 1972.

Compared with the previous experiment the number of γ-parameters was now decreased to one, and the base of the weighting function was increased to 0.999.

Number of α-parameters	3
Number of β-parameters	4
Number of γ-parameters	1
Number of time delays	3
Base of weighting function	0.999
Scale factor β_o	10.

The experiment, which was 14 hours long, includes a basis weight adjustment, from 150 g/m^2 to 112 g/m^2, which was made at 12.50.

The results from the first part of the experiment are given in fig. 6.7. The self-tuning regulator was connected at 00.30. The registration of the couch vacuum, fig. 6.7.e, indicates that there were rather great disturbances in the process at the time of the experiment. The plot of the moisture content, fig. 6.7.a, shows that the difference between the actual moisture content and the reference value was sometimes great, although the mean value seemed to be satisfactory.

The registrations are continued in fig. 6.8. At 05.52 the couch vacuum decreased, fig. 6.8.e. Therefore, the self-tuning regulator decreased the steam pressure, fig. 6.8.d, to keep the moisture at a constant level.

At 07.20 the machine speed was changed from 308 m/min to 320 m/min by the operator. This speed change introduced a sudden disturbance in the moisture content, fig. 6.8.a. About ten minutes after the speed change the moisture level was satisfactory again.

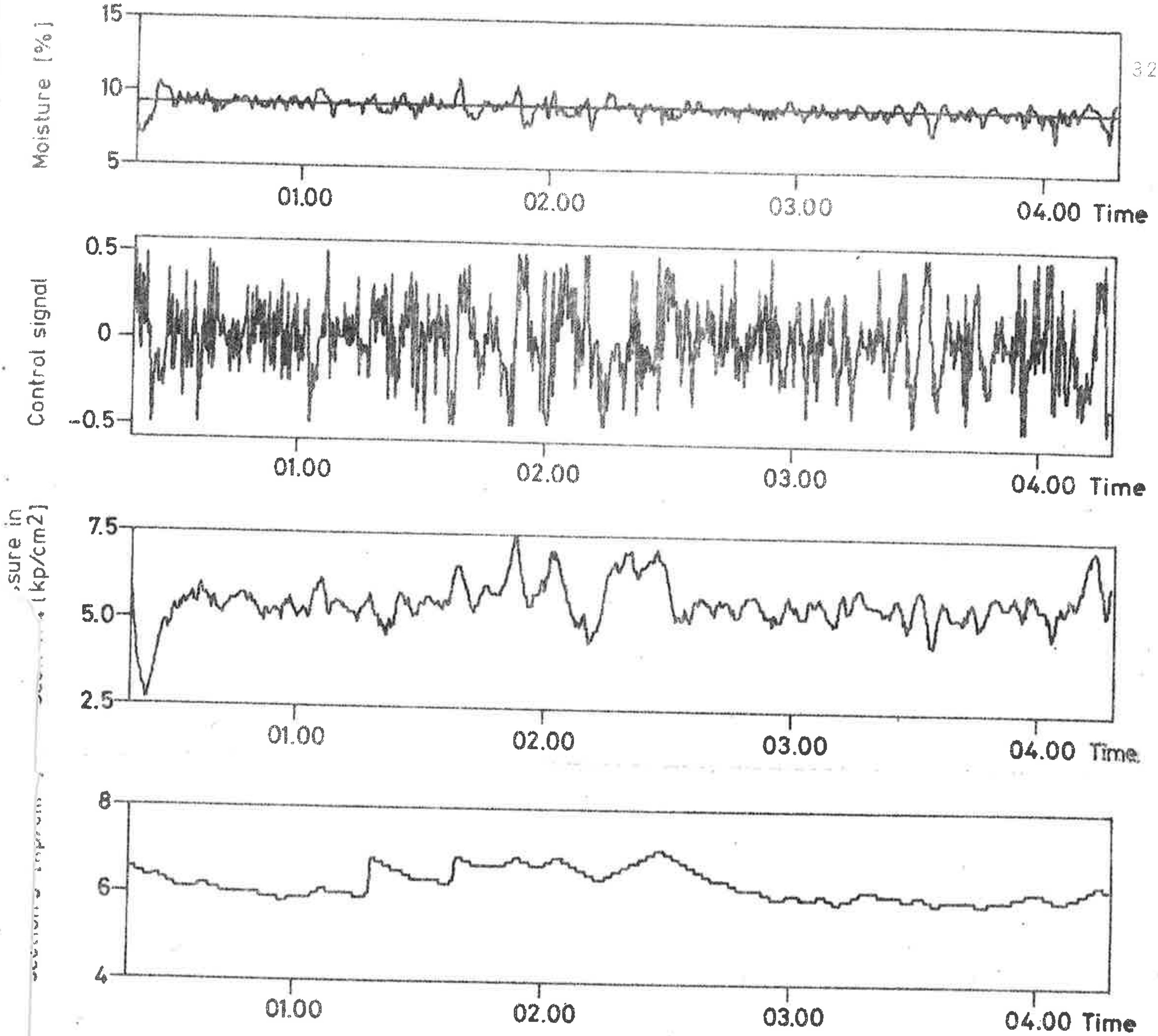

Fig. 6.7. First part of the control experiment on October 27, 1972.

a. Moisture content
b. Control signal
c. Steam pressure in section 4
d. Steam pressure in section 3

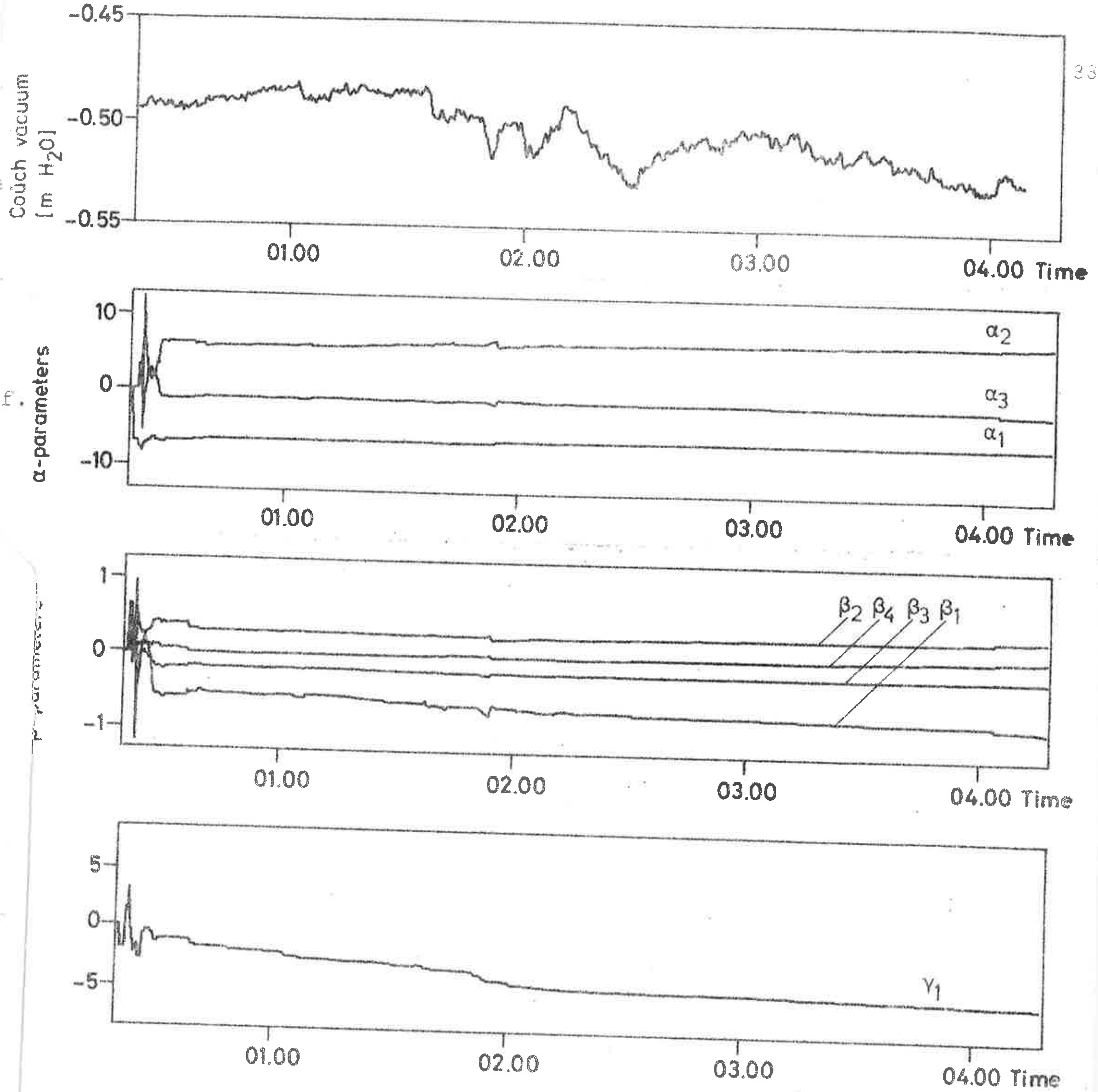

Fig. 6.7 (cont'd)

e. Couch vacuum

f. α-parameters

g. β-parameters

h. γ-parameters

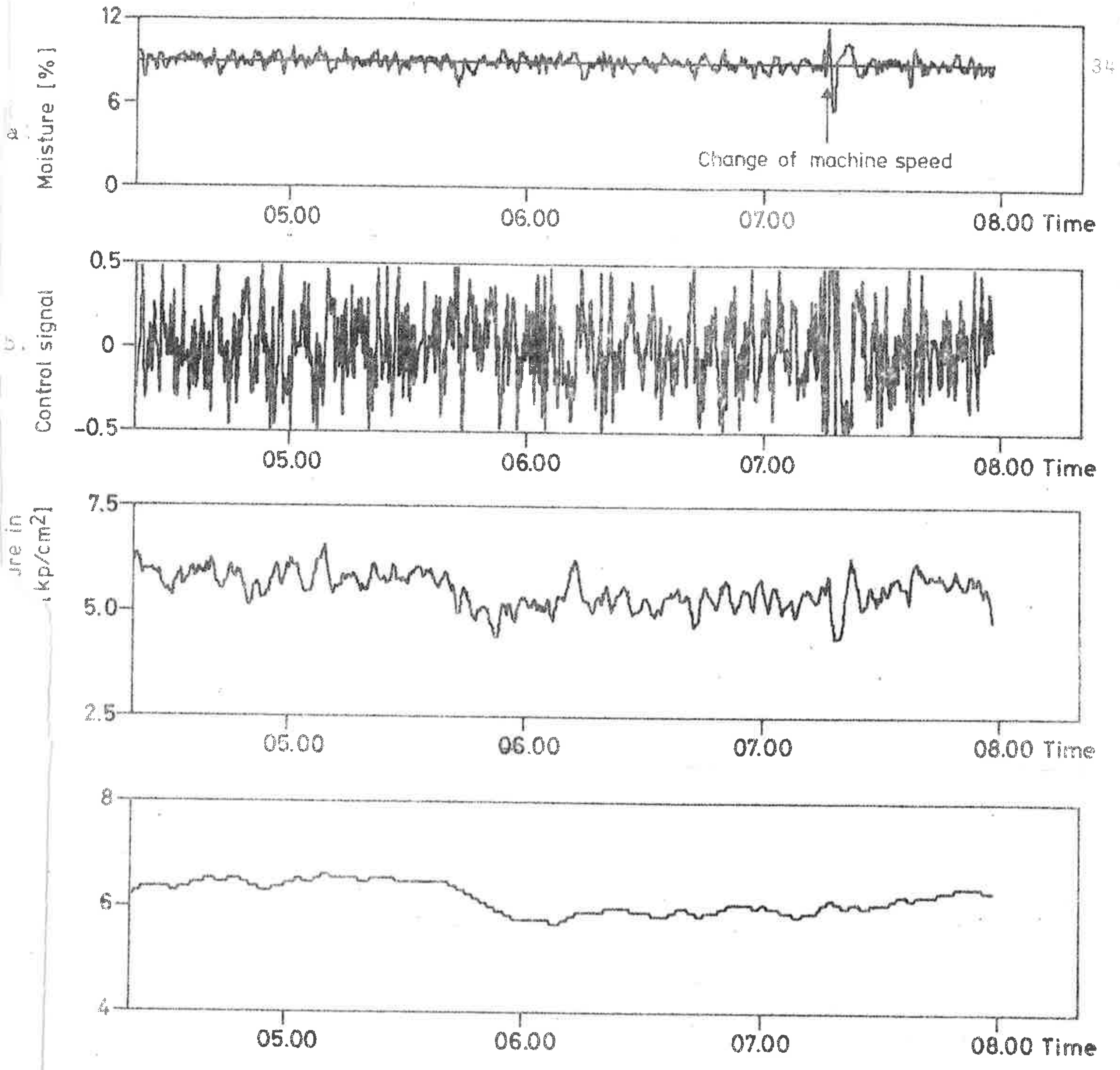

Fig. 6.8. Second part of the control experiment on October 27, 1972.

a. Moisture content
b. Control signal
c. Steam pressure in section 4
d. Steam pressure in section 3

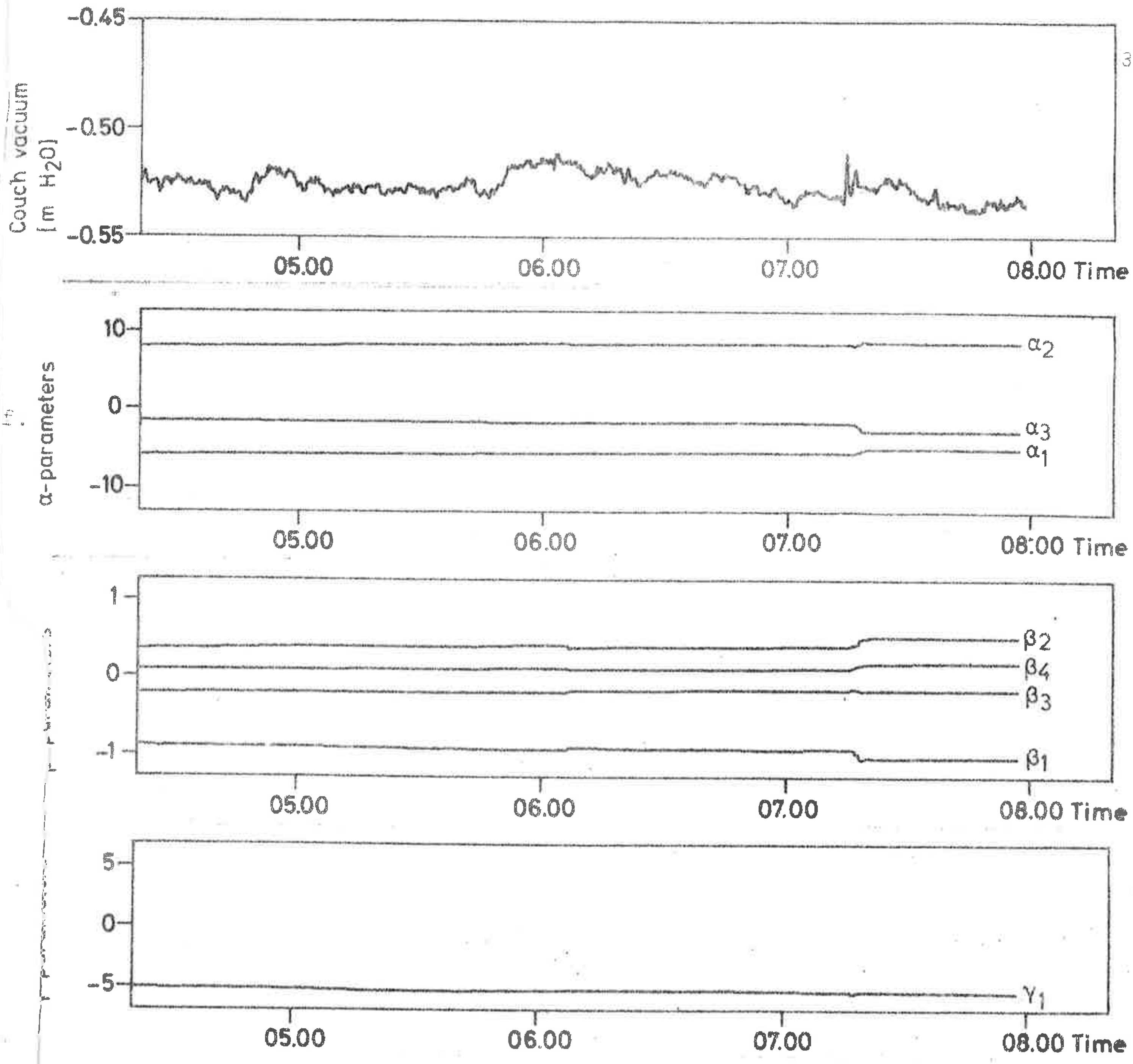

Fig. 6.8 (cont'd)

e. Couch vacuum

f. α-parameters

g. β-parameters

h. γ-parameters

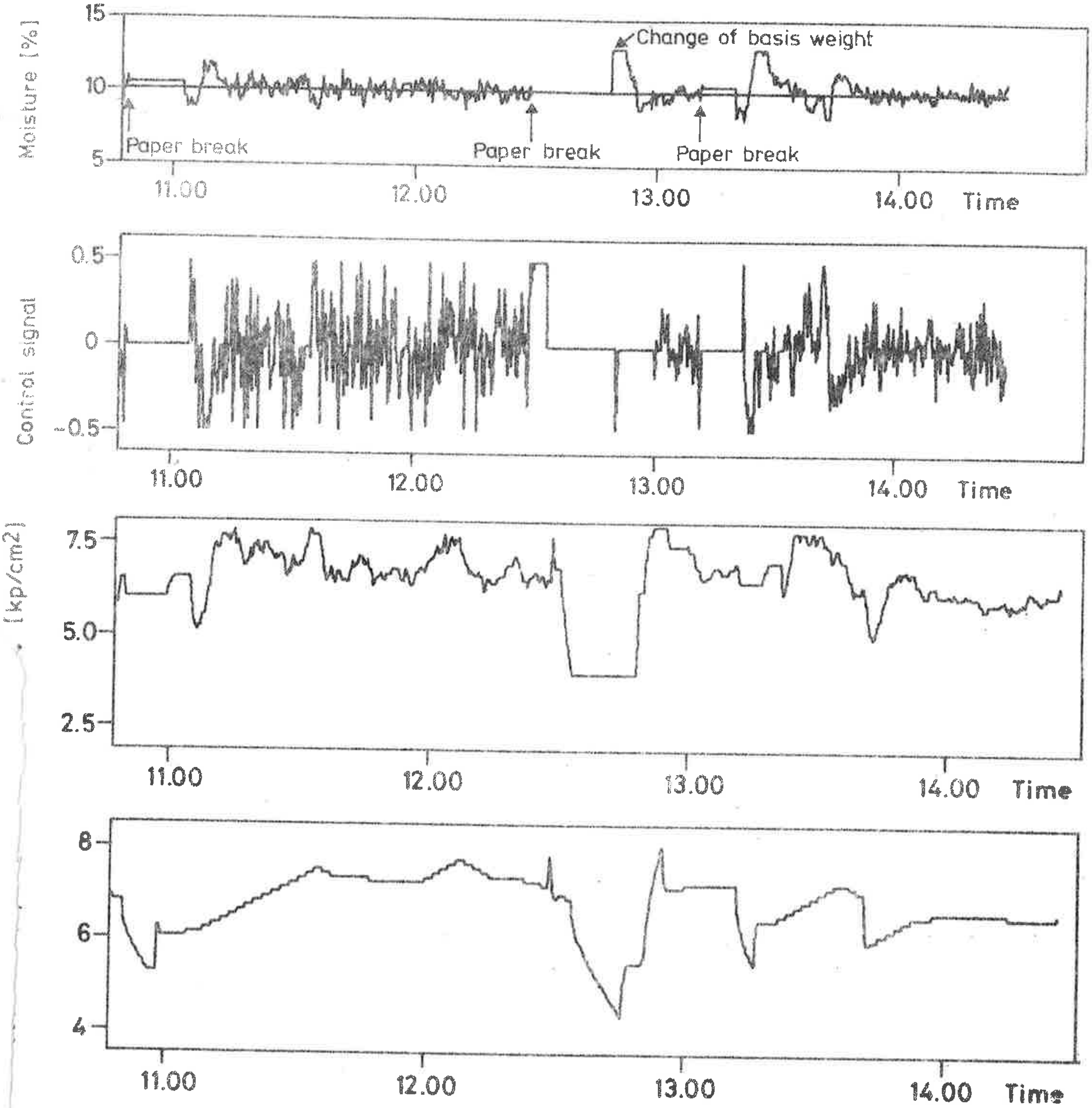

Fig. 6.9. Third part of the control experiment on October 27, 1972.

a. Moisture content

b. Control signal

c. Steam pressure in section 4

d. Steam pressure in section 3

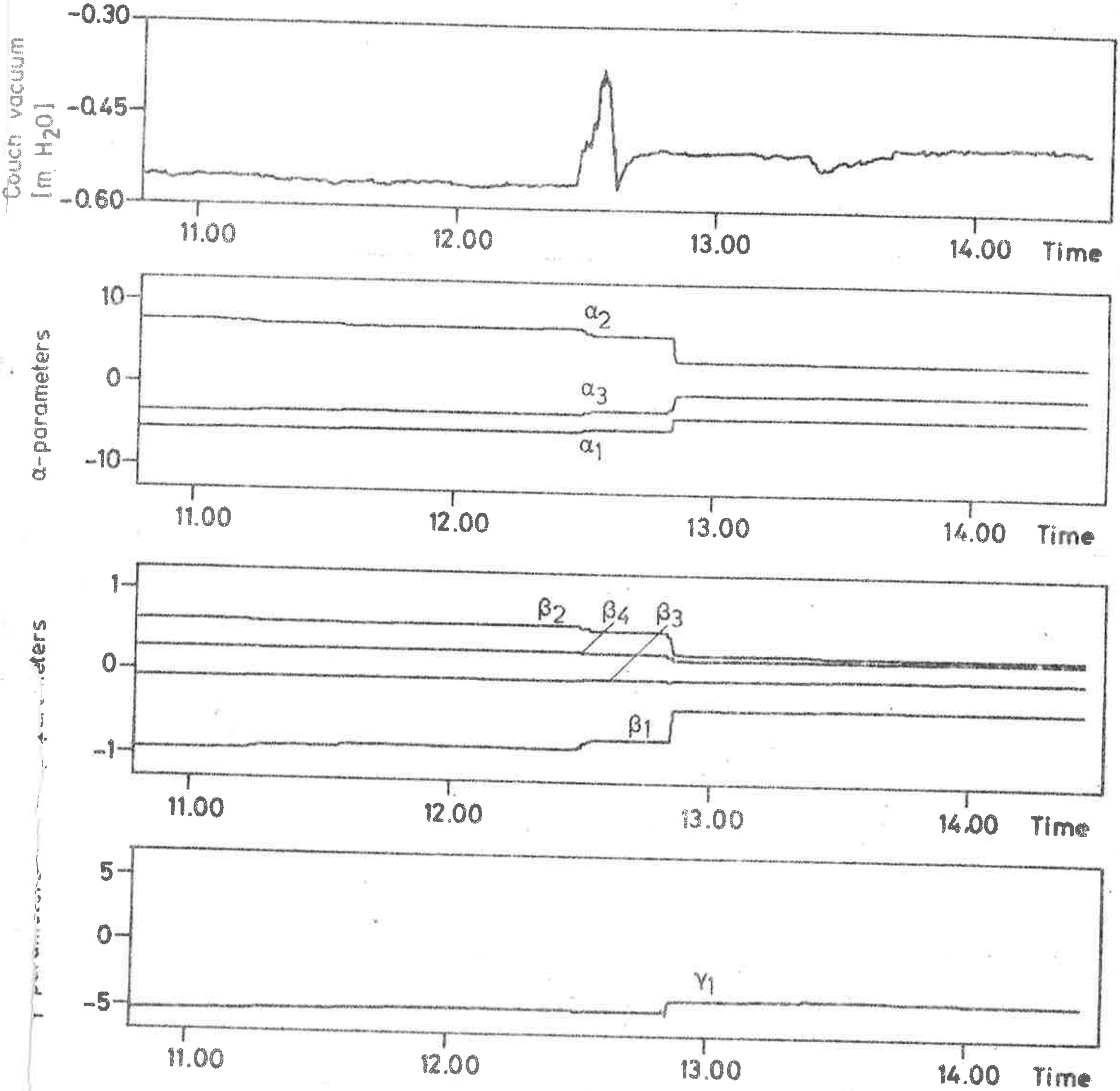

Fig. 6.9 (cont'd)

e. Couch vacuum

f. α-parameters

g. β-parameters

h. γ-parameters

The results from the last part of the experiment are shown in fig. 6.9. Three paper breaks occurred during this period, namely at 10.50, 12.33, and 13.16.

The second paper break was caused by an unsuccessful attempt to change the basis weight. At 12.50 the basis weight had been successfully adjusted to 112 g/m^2. During the change the machine speed had been increased from 320 m/min to 430 m/min, and the lip opening had been decreased from 29 mm to 25 mm. The fibre flow and the head box pressure had also been changed.

The process dynamics seemed to change at the basis weight adjustment, and the parameter estimates obtained new values in a short time. After the third paper break the operating conditions seemed to be normal again, and the moisture content control worked well.

This experiment included great process disturbances, machine speed changes, and a basis weight adjustment. The self-tuning regulator was connected to the process all the time without any troubles. The standard deviation of the moisture content in fig. 6.7.a and 6.8.a is 0.52% and 0.54% respectively.

In the figures 6.10 and 6.11 the estimated covariances for the data in the figures 6.7 and 6.8 have been plotted. For a minimum variance regulator

$$\hat{r}_y(\tau) = 0, \qquad \tau \geq 4$$

$$\hat{r}_{yu}(\tau) = 0, \qquad \tau \geq 4$$

if the disturbances are gaussian. The dashed lines indicate a 95% confidence interval.

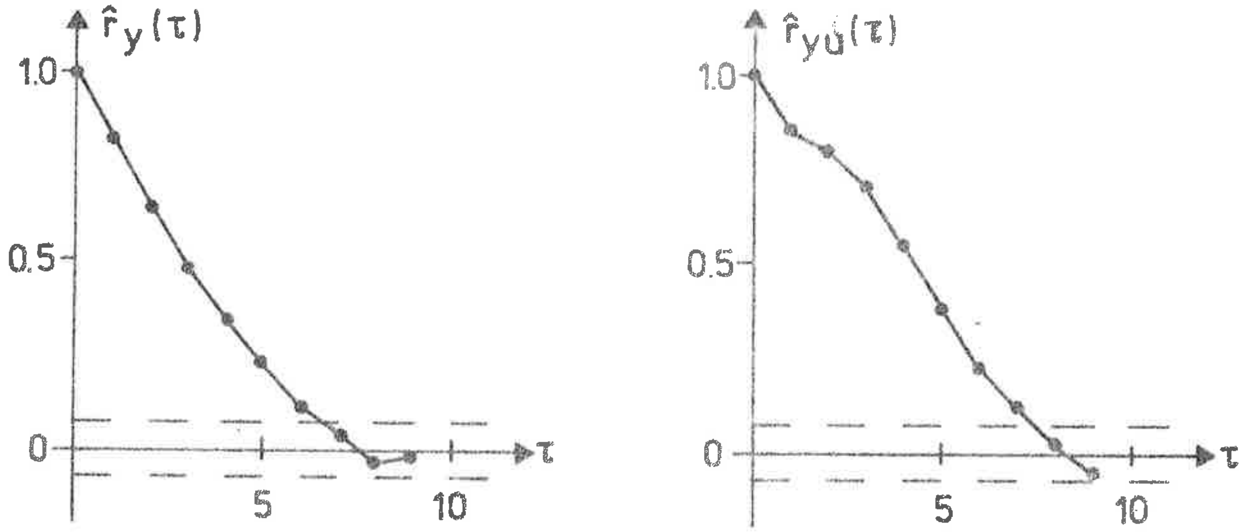

Fig. 6.10. The estimated covariances $\hat{r}_y(\tau)$ and $\hat{r}_{yu}(\tau)$ computed for the first part of the experiment (fig. 6.7). The covariances have been normalized. There were three time delays in the regulator.

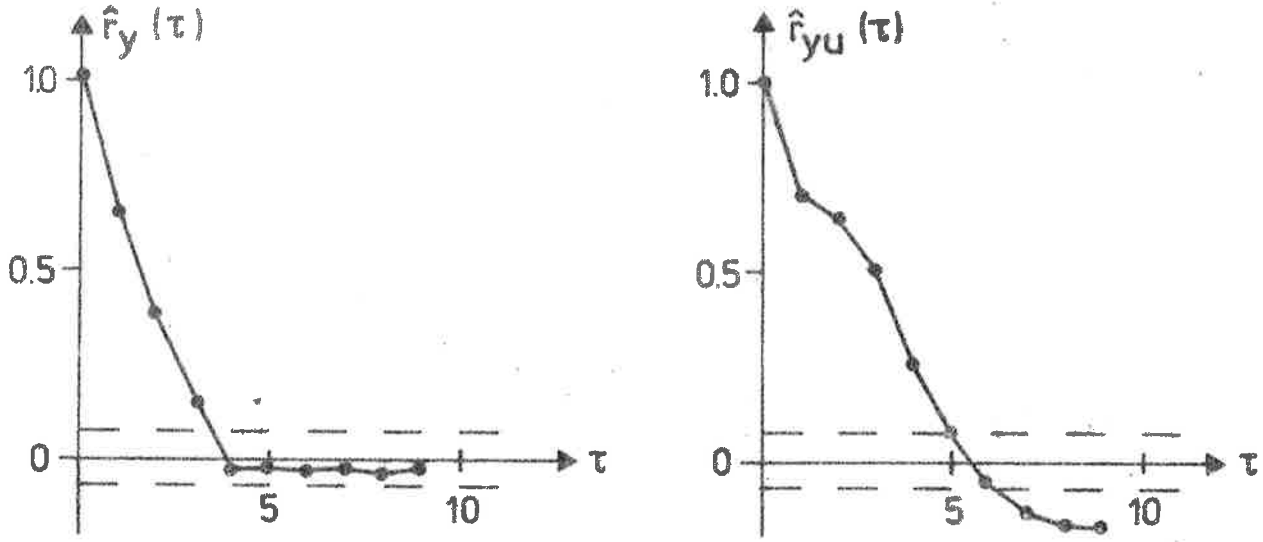

Fig. 6.11. The estimated covariances $\hat{r}_y(\tau)$ and $\hat{r}_{yu}(\tau)$ computed for the second part of the experiment (fig. 6.8). The covariances have been normalized.

The couch vacuum registration for the first part of the experiment, fig. 6.7.e, shows that the disturbances were unusually great. In fig. 6.10 it is seen that the resulting covariances tend to zero more slowly than expected. During the second part of the experiment the disturbances seemed to be more normal, fig. 6.8.e. Consequently, the covariances tend to zero faster in this case, fig. 6.11. Better regulator parameter estimates may also have improved the result.

6.4 Control experiment on February 21, 1973.

The following type of regulator was used:

Number of α-parameters	2
Number of β-parameters	2
Number of γ-parameters	1
Number of time delays	5
Base of weighting function	0.98
Scale factor β_o	10.

The self-tuning regulator was connected to the process from the beginning of the experiment. The initial values of the parameters were

$$\alpha_1 = -6, \quad \alpha_2 = 3, \quad \beta_1 = 0, \quad \beta_2 = 0.4$$

and the covariance matrix was $0.5I$.

Fig. 6.12 shows the process variables registered at the experiment. In the beginning there were great disturbances in the process. This can be seen e.g. in the couch vacuum or the moisture content, fig. 6.12.e and 6.12.a respectively. At about 12.00 the couch vacuum had stabilized at a higher level. This required a higher steam pressure, fig. 6.12.d. The regulator parameters were influenced by the change in the pulp that made the couch vacuum decrease at about 11.30. This can be seen especially in the β- and γ-parameters, fig. 6.12.g and h.

The standard deviation of the moisture content in fig. 6.12.a is 0.28%.

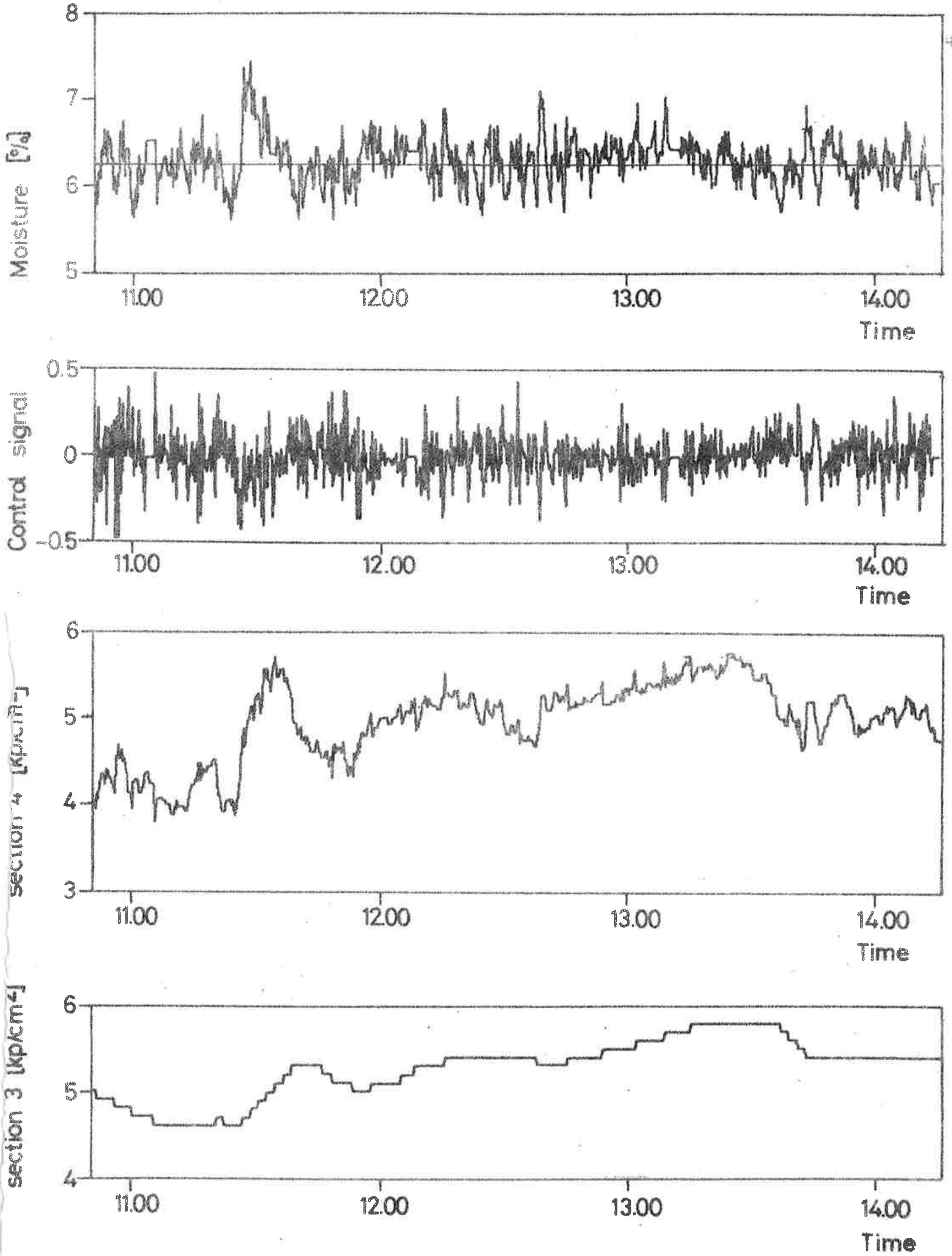

Fig. 6.12. Control experiment on February 21, 1972.

a. Moisture content   c. Steam pressure in section 4

b. Control signal   d. Steam pressure in section 3

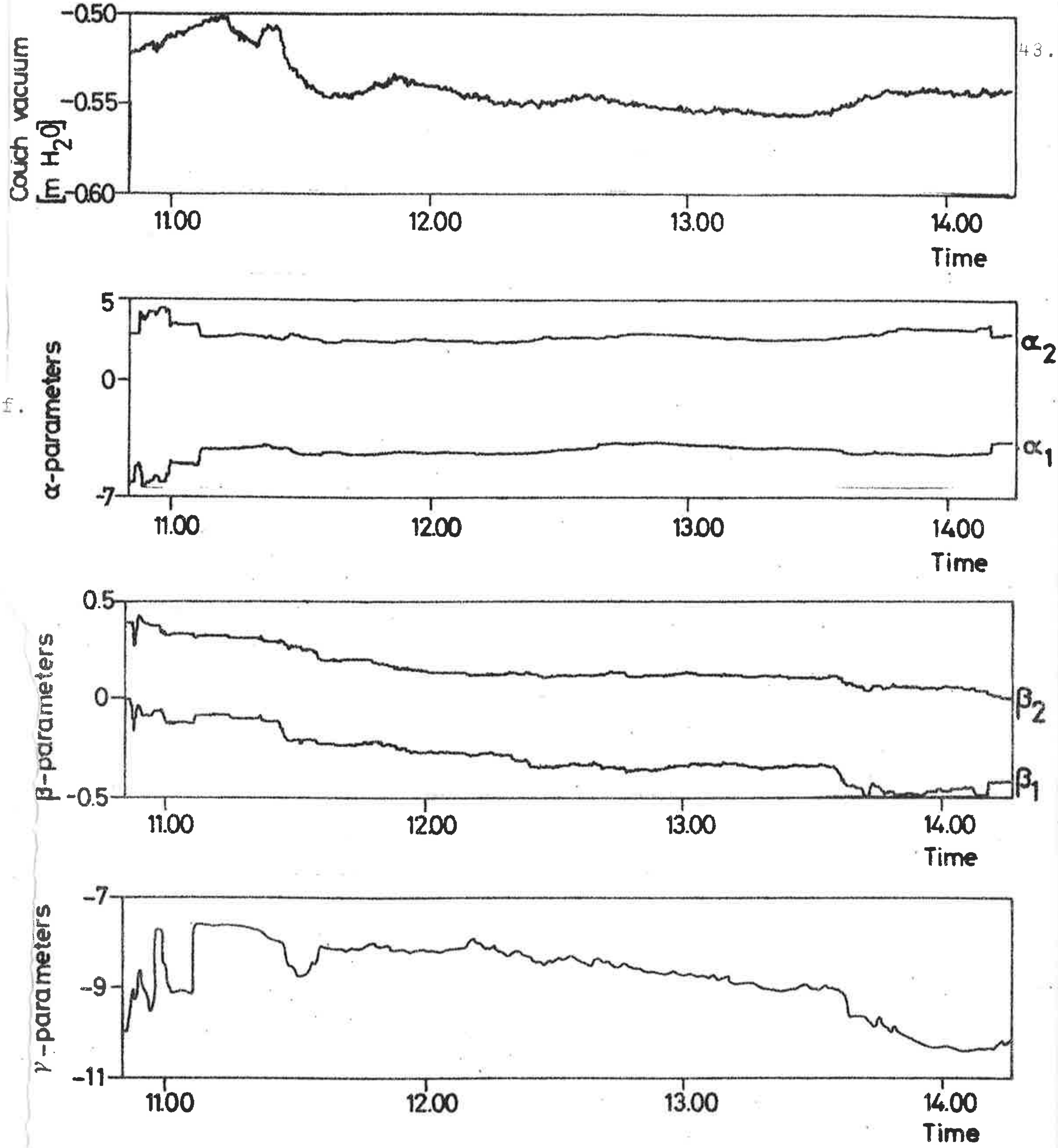

Fig. 6.12 (cont'd)

e. Couch vacuum

f. α-parameters

g. β-parameters

h. γ-parameters

The estimated covariances $\hat{r}_y(\tau)$ and $\hat{r}_{yu}(\tau)$ have been plotted in fig. 6.13.

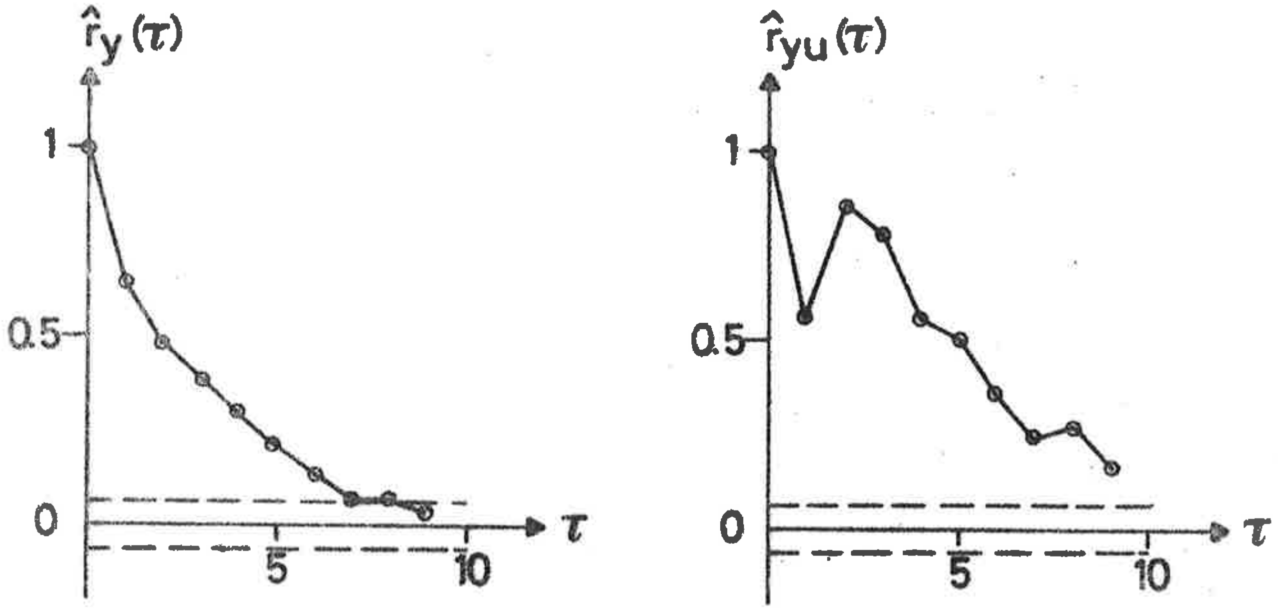

Fig. 6.13. The estimated covariances $\hat{r}_y(\tau)$ and $\hat{r}_{yu}(\tau)$. They have been normalized. In this experiment there were five time delays in the regulator.

7. REFERENCES

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[2] Arvidsson, B., Ericsson, B., Morsk, B., Mäkipää, V., Pinna, A., Sangregorio, G., Save, B., and Strandberger, R.: Process and Production Control Program, IBM European Programming Library, Type III No. 1800-23.5.703, June 18, 1970

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[4] Borisson, U., and Wittenmark, B.: An Industrial Application of a Self-Tuning Regulator, Report 7310, Lund Institute of Technology, Division of Automatic Control.

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[6] Wieslander, J.: Real Time Identification - Part I, Report 6908, November 1969, Lund Institute of Technology, Division of Automatic Control.

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APPENDIX

Programs

```
      SUBROUTINE TUNE(YS,U,VS,T,P,RL,NA,NB,NC,K,NSTEP)
C
C     PERFORMS THE TUNING IN THE SELF TUNING REGULATOR
C
C     AUTHOR    U. BORISSON 1972-05-02
C
C     REFERENCE   ASTROM,K.J., WITTENMARK,B.: ON SELF TUNING REGULATORS
C     REPORT 7209(B), MAY 72, LUND INSTITUTE OF TECHNOLOGY
C     DIVISION OF AUTOMATIC CONTROL
C
C     THE ALGORITHM IS BASED ON THE MODEL
C
C     Y(T+K+1)-Y0+A(1)*(Y(T)-Y0)+...+A(NA)*(Y(T-NA+1)-Y0)=
C     =B0*(U(T)+B(1)*U(T-1)+...+B(NB)*U(T-NB))+
C     +C(1)*V(T)+...+C(NC)*V(T-NC+1)+E(T)    (*)
C
C     WHERE Y0 IS THE REFERENCE VALUE OF Y
C
C     THE TUNING IS DONE WITH A REPEATED LEAST SQUARES ESTIMATION OF THE
C     MODEL PARAMETERS
C
C     THE NUMBER OF SAMPLE INTERVALS BETWEEN THE TUNINGS IS DENOTED BY
C     NSTEP.   THE MAXIMUM VALUE OF NSTEP IS DENOTED BY MSTEP.
C
C     YS-VECTOR OF SCALED PROCESS OUTPUTS OF DIMENSION NA+K+MSTEP+1
C        YS IS NOT CHANGED IN TUNE AND IS ORGANIZED AS FOLLOWS
C        YS(1)=(Y(T)-Y0)/B0
C        YS(2)=(Y(T-1)-Y0)/B0
C        .
C        .
C     U-VECTOR OF PROCESS INPUTS OF DIMENSION NB+K+MSTEP+1
C       U IS NOT CHANGED IN TUNE AND IS ORGANIZED AS FOLLOWS
C       U(1)=U(T-1)
C       U(2)=U(T-2)
C        .
C        .
C     VS-SCALED VECTOR OF KNOWN PROCESS DISTURBANCES OF DIMENSION NB+K+
C        +MSTEP+1. VS IS NOT CHANGED IN TUNE AND IS ORGANIZED AS FOLLOWS
C        VS(1)=V(T)/B0
C        VS(2)=V(T-1)/B0
C        .
C        .
C     T-VECTOR OF ESTIMATED PARAMETERS OF DIMENSION NA+NB+NC AND ORGA-
C       NIZED AS FOLLOWS (AE(I) DENOTES THE ESTIMATED VALUE OF A(I),ETC.)
C       T(1)=AE(1)
C       T(2)=AE(2)
C        .
C        .
C       T(NA)=AE(NA)
C       T(NA+1)=BE(1)
C        .
C        .
C       T(NA+NB)=BE(NB)
C       T(NA+NB+1)=CE(1)
C        .
C        .
C       T(NA+NB+NC)=CE(NC)
C     P-COVARIANCE MATRIX OF THE PARAMETER ESTIMATES OF ORDER (NA+NB+NC)*
C       *(NA+NB+NC)
C     RL-THE BASE OF THE EXPONENTIAL FORGETTING FUNCTION
C     NA-NUMBER OF A-PARAMETERS IN (*)
C     NB-NUMBER OF B-PARAMETERS IN (*)
C     NC-NUMBER OF C-PARAMETERS IN (*)
C     K-NUMBER OF PURE TIME DELAYS IN THE PROCESS
C
C     SUBROUTINE REQUIRED
C           NONE
C
```

```
      SUBROUTINE REG(YS,U,VS,T,NA,NB,NC,K,MSTEP)
C
C     COMPUTES THE CONTROL SIGNAL OF THE SELF TUNING REGULATOR
C
C     AUTHOR    J. BORISSON 1972-05-02
C
C     REFERENCE    ASTROM,K.J., WITTENMARK,B.: ON SELF TUNING REGULATORS
C     REPORT 7209(B), MAY 72, LUND INSTITUTE OF TECHNOLOGY
C     DIVISION OF AUTOMATIC CONTROL
C
C     THE CONTROL SIGNAL TO BE APPLIED AT TIME T IS COMPUTED FROM
C
C     U(T)=(AE(1)*(Y(T)-Y0)+...+AE(NA)*(Y(T-NA+1)-Y0))/B0-BE(1)*U(T-1)-...
C          -BE(NB)*U(T-NB)-(CE(1)*V(T)+...+CE(NC)*V(T-NC+1))/B0         (*)
C
C     WHERE Y0 IS THE REFERENCE VALUE OF Y. AE(I),BE(I) AND CE(I) ARE THE
C     LEAST SQUARES ESTIMATES FROM THE SUBROUTINE TUNE
C
C     YS-VECTOR OF SCALED PROCESS OUTPUTS OF DIMENSION NA+K+MSTEP+1
C        YS IS SHIFTED ONE STEP IN REG AND IS BEFORE THE SHIFT ORGANIZED
C        AS FOLLOWS
C        YS(1)=(Y(T)-Y0)/B0
C        YS(2)=(Y(T-1)-Y0)/B0
C        .
C        .
C     U-VECTOR OF PROCESS INPUTS OF DIMENSION NB+K+MSTEP+1
C       U IS SHIFTED ONE STEP IN REG AND IS BEFORE THE SHIFT ORGANIZED
C       AS FOLLOWS
C       U(1)=U(T-1)
C       U(2)=U(T-2)
C       .
C       .
C     VS-SCALED VECTOR OF KNOWN PROCESS DISTURBANCES OF DIMENSION NB+K+
C        +MSTEP+1. VS IS SHIFTED ONE STEP IN REG AND IS BEFORE THE SHIFT
C        ORGANIZED AS FOLLOWS
C        VS(1)=V(T)/B0
C        VS(2)=V(T-1)/B0
C        .
C        .
C     T-VECTOR OF ESTIMATED PARAMETERS OF DIMENSION NA+NB+NC AND ORGA-
C       NIZED AS FOLLOWS (AE(I) DENOTES THE ESTIMATED VALUE OF A(I),ETC.)
C       T(1)=AE(1)
C       T(2)=AE(2)
C       .
C       .
C       T(NA)=AE(NA)
C       T(NA+1)=BE(1)
C       .
C       .
C       T(NA+NB)=BE(NB)
C       T(NA+NB+1)=CE(1)
C       .
C       .
C       T(NA+NB+NC)=CE(NC)
C     NA-NUMBER OF A-PARAMETERS IN (*)
C     NB-NUMBER OF B-PARAMETERS IN (*)
C     NC-NUMBER OF C-PARAMETERS IN (*)
C     K-NUMBER OF PURE TIME DELAYS IN THE PROCESS
C
C     SUBROUTINE REQUIRED
C           NONE
C
```

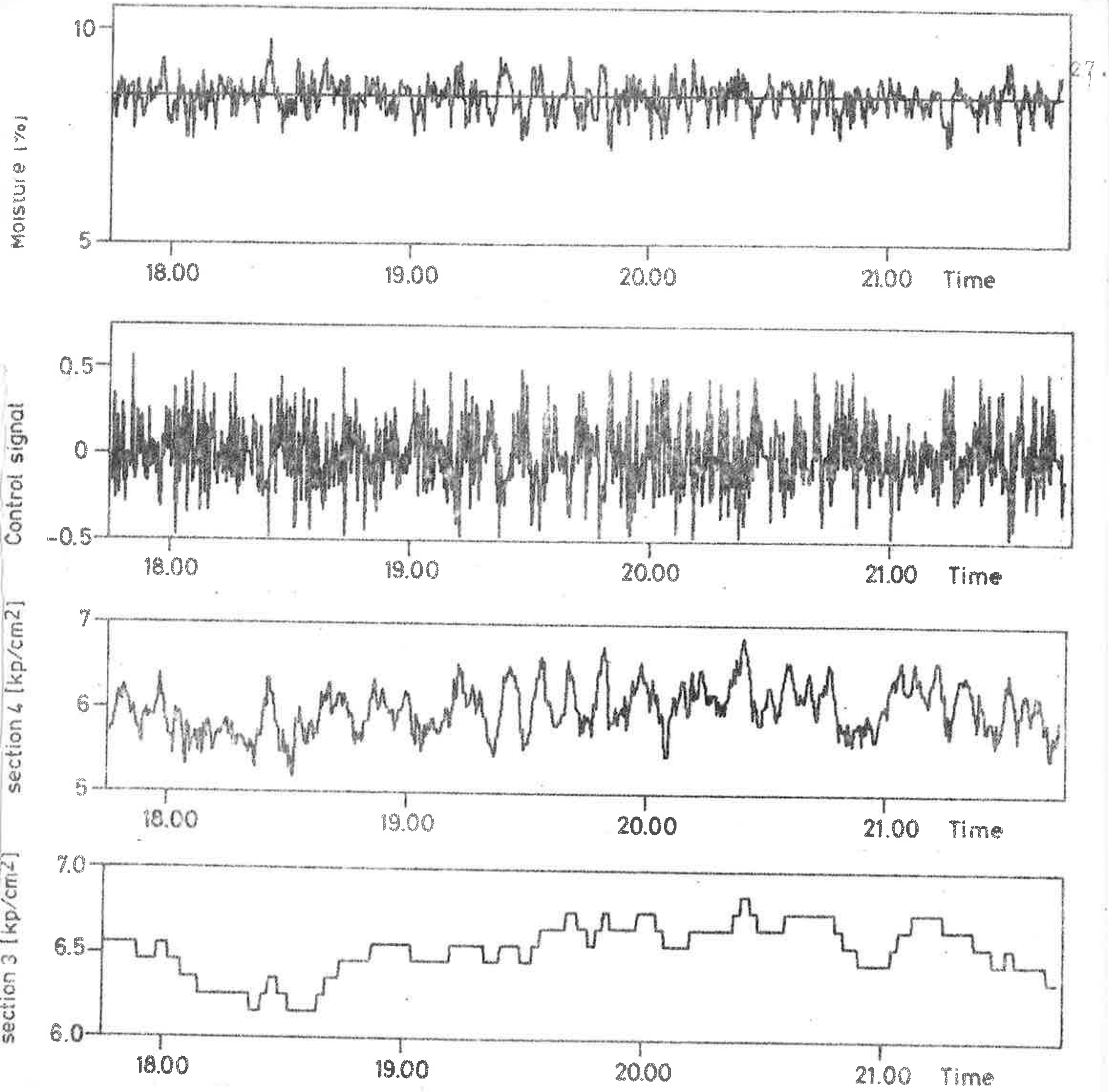

Fig. 6.4. Control experiment on October 25, 1972, the first four hours

a. Moisture content

b. Control signal

c. Steam pressure in section 4

d. Steam pressure in section 3

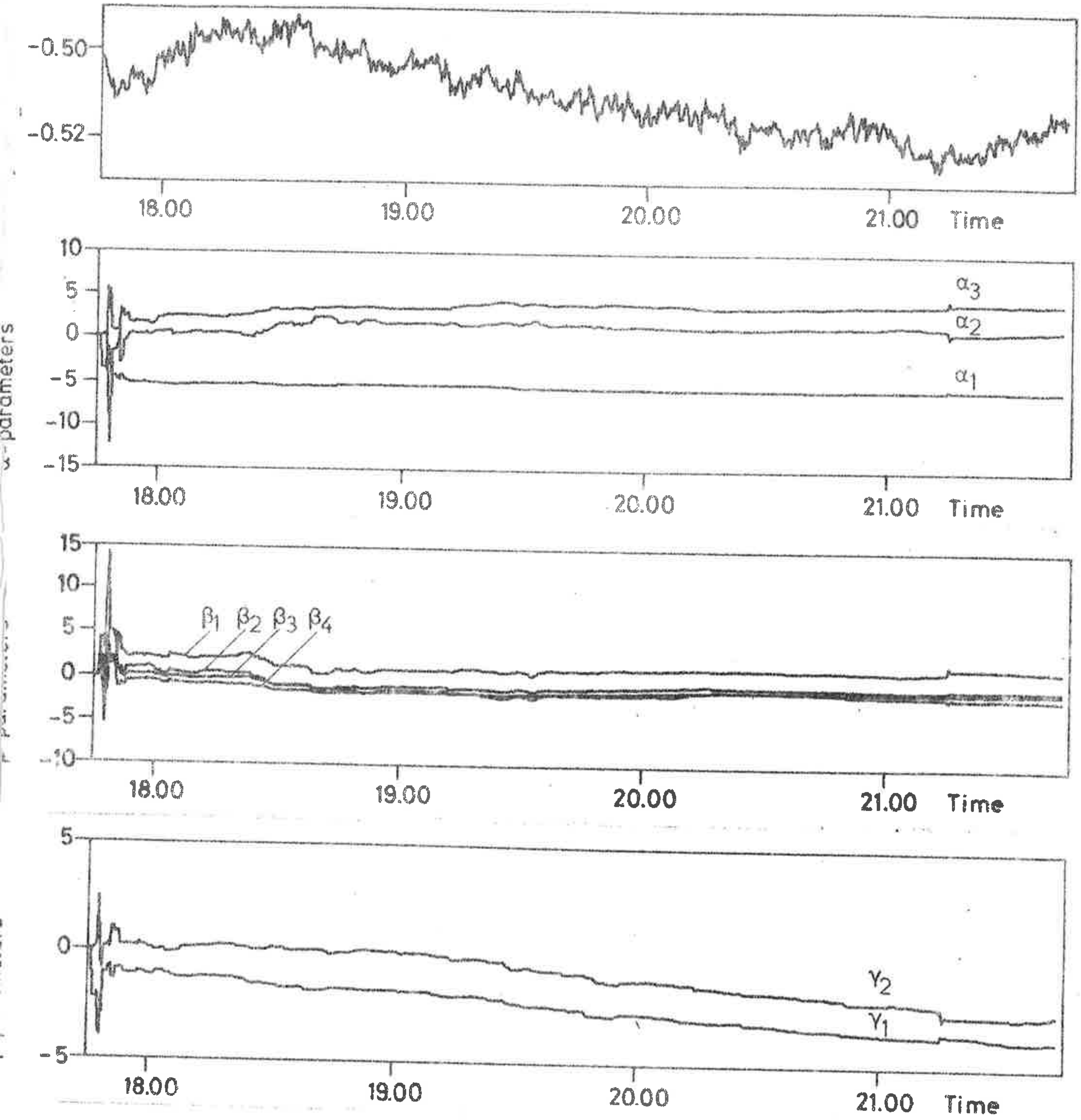

Fig. 6.4 (cont'd)

e. Couch vacuum

f. α-parameters

g. β-parameters

h. γ-parameters

6.2 Control experiment on October 25, 1972.

This experiment was made with an increased number of regulator parameters and three time delays.

Number of α-parameters	3
Number of β-parameters	4
Number of γ-parameters	2
Number of time delays	3
Base of weighting function	0.99
Scale factor β_0	10.

The length of the experiment was 20 hours. Registrations from the first part are shown in Fig. 6.4. The basis weight was still 127 g/m^2. After about eight minutes the self-tuning regulator started to control.

At about 18.40 the quality of the paper was changing. This can be seen in the couch vacuum registration, fig. 6.4.e. The self-tuning regulator compensated by increasing the steam pressure, fig. 6.4.d.

At the end of the registration in fig. 6.4.f - h the parameters were

$\alpha_1 = 4.04$ $\alpha_2 = 1.06$ $\alpha_3 = -6.03$

$\beta_1 = 0.22$ $\beta_2 = -0.40$ $\beta_3 = -0.18$ $\beta_4 = -0.24$

$\gamma_1 = -3.93$ $\gamma_2 = -5.82$

The standard deviation of the moisture content in fig. 6.4.a is 0.39%.