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AUTOMATION OF A PAPERMACHINE AND ITS ANCILLARIES*

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Synopsis A digital computer was installed on the Centre Technique du Papier's experimental machine in order to study the problems involved in the automation of a papermachine.

After a short description of the installation, this paper summarises the work done during the installation phase, in particular, control of the basis weight was designed to go into service as soon as the computer was installed. It uses a control algorithm compensating for the dead time from the point of view of loop stability. The initial results are encouraging.

The same principles will be extended to the control of the dryer section after development of an appropriate model.

Introduction

AN AGREEMENT on participation in a programme of research (No. 67.00.911) made it possible to install an Automateur MAT 01 computer built by the Automation Division of Télémécanique Electrique on the experimental papermachine at the Centre Technique du Papier.

This paper gives an account of the study up to the time when the computer was installed on site.

Aims of the study

THE general aim of the study was to investigate all the possibilities offered by the use of a digital computer in the control of a papermachine.

We feel it is necessary to emphasise the fact that the objective was not to automate the Centre's experimental machine, but to develop a general approach to the problem of papermachine automation.

We also intend to show that part of the programming can be done in

* This study was carried out by the Centre Technique du Papier under the terms of agreement for participation in a research programme (No. 67.00.911) with the Délégation Générale à la Recherche Scientifique et Technique with the participation of the firm Télémécanique Electrique, which supplied the computer and software

Under the chairmanship of P. E. Wrist

advance by means of approximate models so as to be able to put the computer to work on some jobs as soon as it is installed and thus reap some economic return almost immediately.

In this paper, we shall deal at any length only with the points already achieved or due to be achieved in the near future, the more long-term projects being merely roughly outlined.

Description of the pilot unit

THE investigation was carried out on the experimental machine at the Centre Technique du Papier at Gières.

Experimental machine

This machine was built by Ets. Neyrpic under licence to SICMA. Its main features (as far as this paper is concerned) are as follows—

Maximum speed	100 m/min
Trimmed width	50 cm

The stock prepared in the machine chest is sent to a constant level stuff box. The circuit includes a consistency regulation system.

Dilution takes place in a mixing chest combined with the centrifugal strainer. The stock and recirculated water are controlled by valves, the head on the valves being supplied by controlled level tanks.

The mixing chest is connected to a conventional head box, but is higher to provide a head. This box is placed under vacuum in order to keep the stock level higher than it would normally be for the pressure at the slice.

The Fourdrinier machine is equipped with wet boxes, table rolls, suction boxes and a suction couch roll. The water from the wet boxes and table rolls on the one hand and from the suction boxes and suction couch on the other hand is collected in two separate chests working as communicating vessels, which enables the wet boxes and table rolls water to be taken first for dilution purposes.

The press section has two plain presses—a couch press and a reversed press. The dryer part, which is equipped throughout with pocket ventilators, is split into two sections supplied by separate manifolds. All 12 sections of the machine are driven from a main shaft through tapered pulleys.

Instrumentation

It was planned from the start to provide quite comprehensive instrumentation so as to be able to meet all the requirements of the study as a whole and, if necessary, to investigate problems of paper technology not directly connected with the control machine.

Hence, it was planned to link up some 80 analog measurements to the computer. Among these, the items concerning us directly are the following—

Stock and dilution water flows and wire drainage flows (electro-magnetic flow meters).
Consistency at the above flows (consistency pick-ups and turbidity meters).
Head and level in the head box (differential pressure pick-ups).
Slice opening (potentiometer pick-ups).
Dry end and wet end basis weight and moisture content (beta-gauge and capacitance pick-up).
Steam pressure in the post-dryer section.

The dilute stock and whitewater consistencies and the value of the dry basis weight at the wet end will be taken into account for control purposes as soon as the pick-ups are correctly adjusted, which is proving difficult.

Seven separate controls are provided, with the possibility of future extension. They work through digital/analog converters, consisting of an inching control motor receiving the impulses from the computer and a force balance, which converts the position of the motor into a standardised 4·20 mA dc current. This signal is then transformed into a pressure of 0·2–1 bar actuating the control mechanisms.

The physical quantities controlled are—

Stock and whitewater flow rates.
Steam pressure at the post-dryer.
Slice opening.
Papermachine speed.
Degree of vacuum in head box.

In addition, the machine is equipped with a number of conventional pneumatically operated control systems—

The levels in the stuff boxes, which will probably remain as they are.
The consistency control, for which computer control is also being contemplated.

Computer and data input systems

Computer—The computer's main characteristics are—

8 K words of 21 bits (18 value bits).
Base cycle 5 μs.
Six interrupt levels.
Programming in machine or assembly languages.

The link with the operator is through a DDC console handling requests for display, print-out or modification of the parameters in the control loops. The messages are printed and punched by teleprinter. The teleprinter can be used also for program input from punched tape.

The link with the control process is either through relays (simple on/off relays) or a selector switch and analog/digital converter for the analog signals. All signals have been standardised at 50 mV and are amplified to 10 V before conversion.

The control operations are performed by relays in the case of on/off operations and by impulses in the case of the analog quantities, conversion being by means of the digital/analog converters described above.

Dry basis weight control

THE first regulation of the dry basis weight has been prepared before installation of the computer to enable it to be used as soon as the system is operational. This involved the development of a theoretical mathematical model of the papermachine.

Mathematical model

We need not go into a detailed description of the static model consisting of the steady state water balance and solids balance, which are expressed in the Sankey diagram well-known in the paper industry. The use of this model is nevertheless indispensable in order to establish the operating point on which the dynamic model will be based.

Development of the dynamic model—The development of models representing the dynamic behaviour of the papermachine is also well-known.[1–3] The method consists in breaking down the machine into separate parts, which can be represented by simple equations, then linking up the equations. In our case, we are basically dealing with volumes involving mixtures and piped transport.

There is no question of working on a model that describes the behaviour of the machine in response to all possible working conditions. We have confined ourselves to building up a model that can express mathematically the relationships between the control quantities and the output quantities under certain operating assumptions.

In the present case, the control quantities are the stock and recirculation water flow rates. The output is the dry basis weight calculated from the data provided by the dry end combined metering system (basis weight and moisture content measurements).

The operating assumptions are essentially as follows—

1. Proportionality between the dry basis weight and the quantity of solids leaving the wet end. This hypothesis enables the presses and dryers to be replaced by a dead time.

2. Constant total flow in the head box—the first model developed in fact showed (and practical tests confirmed) that possible variations in stock flow rate with respect to total flow rate cannot be ignored in an open head box from either hydraulic operating characteristics or response in dry basis weight points of view and it was therefore decided to control both flow rates simultaneously so as to work at a constant total rate of flow.
3. Constant volumes—this hypothesis is justified in view of the constant rate of flow in the head box and mixing box and the constant levels in the other tanks.
4. Retention varying linearly with the quantity of solids on the wire. (This latter assumption, although at first sight questionable, checks fairly satisfactorily in the case of small variations; an increase in the solids content on the wire is accompanied by a decrease in the solids content in the table roll water and that of the suction box water rises as a result of the transfer of part of the drainage from the table rolls to the suction boxes.)

On these assumptions, the wet end diagram shown in Fig. 1 may be expressed in the form of the block diagram in Fig. 2, which describes the dynamic behaviour of the quantiites of matter θ on the machine in the case of small variations.

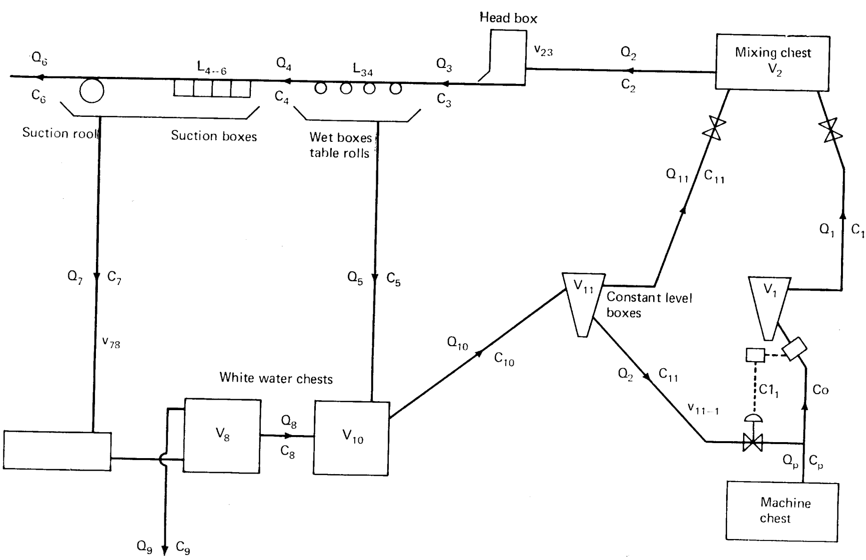

Fig. 1—Wet end diagram of the papermachine

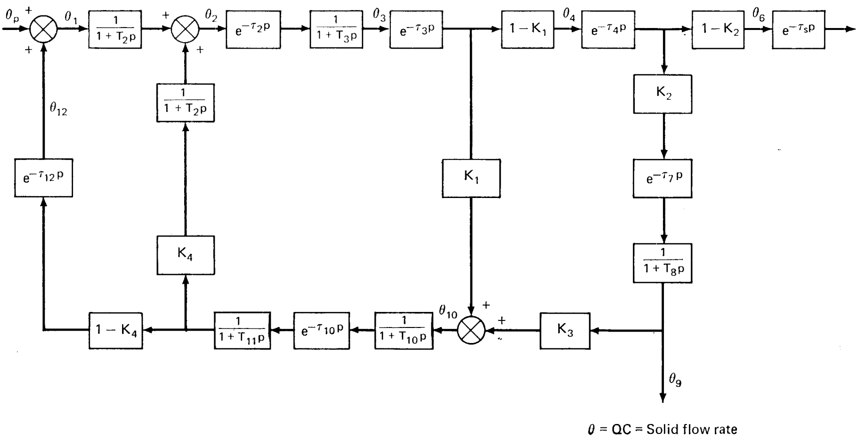

Fig. 2—Block diagram of the wet end

Using the following notation, we have in the case of the mixing chest, for example—

Q_1, C_1, θ_1	Stock flow rate, consistency and solids throughout, respectively.
Q_{11}, C_{11}, θ_{11}	Ditto for the whitewater flow.
Q_2, C_2, θ_2	Ditto for the diluted stock flow.
V_2	Volume of the mixing chest.

We then have the following in the mixing chest—

$$Q_1C_1+Q_{11}C_{11} = Q_2C_2+V_2\frac{dC_2}{dt}$$

If we introduce a variation (small letter)—

$$q_1 = -q_{11} = q$$

it becomes—

$$q(C_1-C_{11}) = Q_2C_2+V_2\frac{dC_2}{dt}$$

or in Laplacian notation—

$$q(C_1-C_{11}) = (Q_2+V_2p)C_2 = \left(1+\frac{V_2}{Q_2}p\right)Q_2C_2$$

and by putting $\theta_2 = Q_2C_2$

$$\frac{\theta_2}{q} = (C_1-C_{11})\Big/\left(1+\frac{V_2}{Q_2}p\right)$$

and, if in addition, we make—

$$\theta_1 = C_1 q \text{ and put } V_2/Q_2 = T_2$$

we get—

$$\frac{\theta_2}{\theta_1} = \frac{C_1 - C_{11}}{C_1} \cdot \frac{1}{1+T_2 p}$$

We thus replace the mixing chest by an in-line mixing followed by a time constant.

The model assembled from the various elements was studied using two different approaches.

Frequency aspects—We calculated the transmittance of this model in gain and in phase and compared it to the transmittance of the direct flow circuit (without recirculation).

These two transmittances are shown in graphical form in Fig. 3 in the Bode diagram (ignoring the dead time in the dryers). The curves are slightly different at very low frequencies and practically identical above 2×10^{-3} cycles.

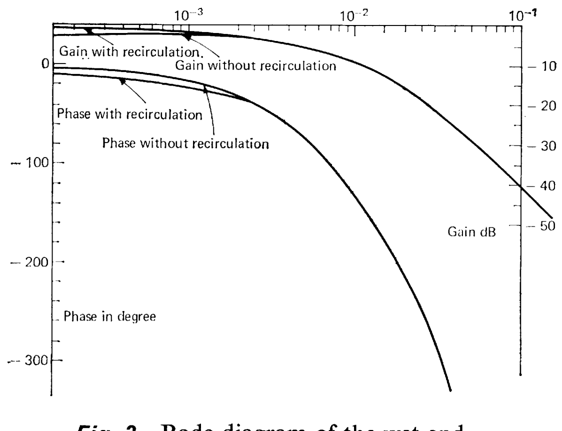

Fig. 3—Bode diagram of the wet end

As an example, Fig. 4 gives the comparison between the theoretical response (three time constants) and the response actually recorded on the unit. These tests were done before simultaneous valve control was installed and provide a good illustration of the effects of variations in total flow rate (first part of the curve). From this, it was concluded that the process may be fairly approximated by a system involving three time constants and a dead time.

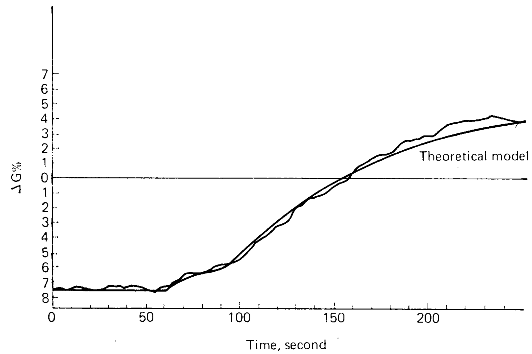

Fig. 4—Basic weight response to a step of stock flow rate

The orders of magnitude of these parameters are—

Mixing chest V_2 = 250 litre, T_2 = 40–130 s
Head box V_3 = 40 litre, T_3 ≃ 6–20 s
Filter on measuring instrument T_s = 3 or 10 s
Dead time in pipe 6–20 s; on machine 40–120 s.

Allowing for the fact that T_2 is quite a good deal larger than T_3 and T_s, it is even possible to envisage a model with one time constant and one dead time; this case has also been examined, as will be seen later.

Time aspect—Chronologically, this study was in fact done before the frequency study.

The first model developed was intended to be of a more general character than the one described above. In particular, it was desired to find out the stabilisation time for the various chests at the start of a manufacturing run, but before the machine was actually started.

In view of the complexity of the phenomena involved, also for reasons of convenience, it was decided right from the start to use a numerical simulation approach.

To do this, the equations for the mixtures in the stock chests were put in finite difference form and the dead times taken as simple time decrements.

In addition, numerical simulation makes it possible to account for non-linearities, which are difficult to deal with using a frequency approach. Thus, the first program, written in ALGOL for processing on an IBM 7044, allowed for flow and level variations and the separations on the wire were represented by various sets of fairly complex equations taken from the literature on the subject.

The stabilisation times derived from simulation were found to give good agreement with practical results. The response of this model to small variations showed on the one hand the all-important role of the direct flow circuit (without recirculation) and, on the other, the need for simultaneous control of both head flow rates to maintain a constant total discharge. These two observations led us to simplify the original model. This program was transposed into FORTRAN for processing on an IBM 360 computer and it is being used for an initial verification of the control algorithms (with adaptation of the coefficients, if necessary) before they are applied on the machine.

Feedback control

Originally, we asked the supplier to provide the software for logging and for classical three-mode control (proportional, integral and derivative), as well as the computer hardware. In particular, we intended to obtain exact performance data on the three-mode control in the difficult case of basis weight in order to compare it with the performance of any other control of better design.

Since the frequency study and simulation test showed that this type of control system could not be expected to work well, it was abandoned in favour of a study of a regulation system enabling stability to be maintained despite dead time.

Dead time compensation principle—There are now many publications available on control systems using dead time compensation, which should not be confused with predictive control. In the first case, the dead time is compensated for as far as the stability of the loop is concerned, but the dead time remains in the actual process. The principle is shown schematically in Fig. 5. A control algorithm $C(p)$ is designed such that, the transmittance of the process being $G(p)e^{-\tau p}$, scheme No. 1 is equivalent to scheme No. 2, in which $H(p)$ is chosen such that the response has a predetermined form.

Identification of the two transfer functions—

$$\frac{C(p)G(p)e^{-\tau p}}{1+C(p)G(p)\text{-}e^{-\tau p}} \text{ and } \frac{H(p)e^{-\tau p}}{1+H(p)}$$

enables $C(p)$ to be computed by identification—

$$C(p) = \frac{H(p)}{G(p)}[1+H(1-e)^{-\tau p})]^{-1}$$

A control algorithm of this type, involving the dead time in a process, can easily be applied on a digital computer. On the other hand, the use of this computer involves sampling and it is better to study the system using the z-transform.

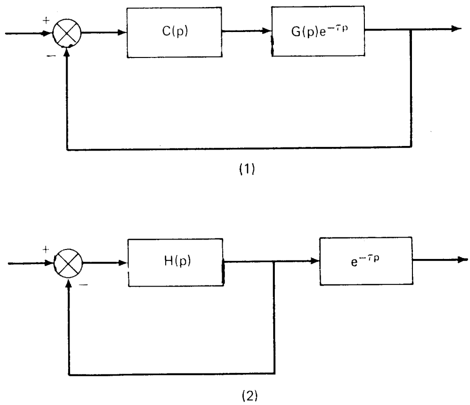

Fig. 5—Principle of dead time compensation

Numerical correction of dry basis weight—This is a cascade control system: the stock and whitewater flow rates are held to given settings that can themselves be modified by the main loop from the output of the end of machine combined metering unit (Fig. 6).

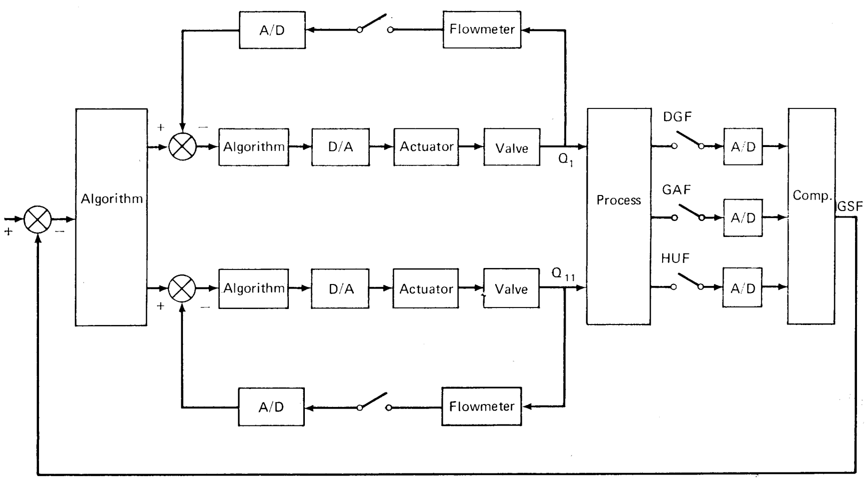

Fig. 6—Numerical correction for dry basis weight

A 5 s sampling period was adopted for the measurements and control operations.

For the theoretical aspect, the reader is referred to Volgnine.[5]

Automatic flow control—The computer controls the valves from the indications given by the flow meters. Since the set points of these loops are to be driven by the computer, it is advisable to take a minimum prototype whose response is complete by the time the next sample is taken.

Furthermore, since the digital analog converter/current pressure transducer/control valve/flow meter system, considered as a whole, has a response much shorter than the sampling period (less than 1 s) we have a controller of the single mode type.

The problem is thus reduced to determining the gain and the whole control system may be considered as a clamp.

Main control loop—In view of the results obtained when designing the model, we are trying to develop a control strategy for a process involving three time constants and dead time. Considering the values of these time constants, the 5 s sampling period satisfies, at least approximately, Shannon's theorem.

For the first application, we have chosen a control algorithm that is a good compromise between a very good response to a one-step change in set point and a wave-free response.

The expression for the control algorithm defined by the above method, but using the z-transform gives—

$$S_i = v_o S_{i-(n+1)} + v_1 S_{i-(n+2)} + v_2 S_{i-(n+3)} + \frac{a_o}{K}[\varepsilon_i - \lambda_1 \varepsilon_{i-1} + \lambda_2 \varepsilon_{i-2} - \lambda_3 \varepsilon_{i-3}]$$

in which S_i is the output at time i,
ε_i is the deviation at time i,
n is process dead time expressed in number of sampling periods,
a_o, v, λ are coefficients determined from time constants for the process,
K is process gain.

For the regulation study, we decided to start by investigating the response to a single thick stock consistency control step.

In theory, the output z-transform can be obtained in terms of the input z-transform, the actual output values being obtained by means of a polynomial division program.

Furthermore, we have applied this type of control algorithm on a simulation on the full model in order to ascertain the effect of the whitewater return line.

Fig. 7 shows the two responses obtained. An explanation has not yet been found for the fact that the response of the full model appears at first sight to be better than the theoretical response. The practical tests are in progress and will be presented at the conference.

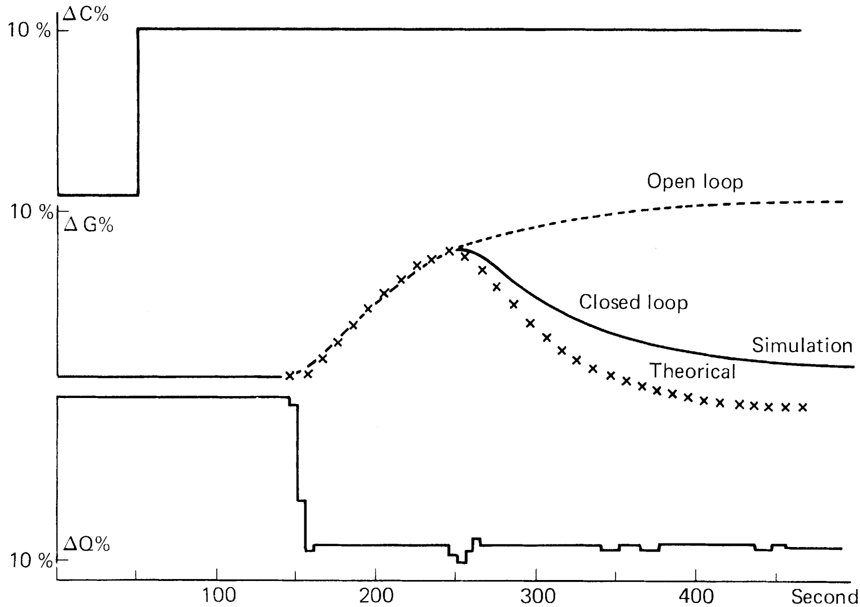

Fig. 7—Basis weight response to a step consistency (three time constants model)

If the process is approximated to one time constant plus a dead time, the control algorithm is simpler—

$$S_i = S_{i-(n+1)} + a_1 \varepsilon_i - a_2 \varepsilon_{i-1}$$

The responses are given in Fig. 8.

It is this control algorithm that was programmed at first, but, since adjustment of the coefficients was found to be a tricky business, it has been discarded in practice—at least for the time being—in favour of the earlier one. Anyhow, the use of a more complex algorithm is no problem when a computer is available.

A few practical considerations

Automatic flow control—Owing to the non-linearity of the valves, the optimum gain of the control system is variable, depending on gate opening. This problem is fairly easily solved. The computer selects the gain itself from the actual flow rate and the valve calibration curve stored in the memory.

The slack in the valves corresponds to about 10 control impulses (for a total travel of 1 000 impulses). This problem has not yet been fully solved, since the compensation tests carried out up to now have yielded poorer results than with no compensation at all. As a result, the response in certain cases is obtained only in the second sampling period, instead of in the first.

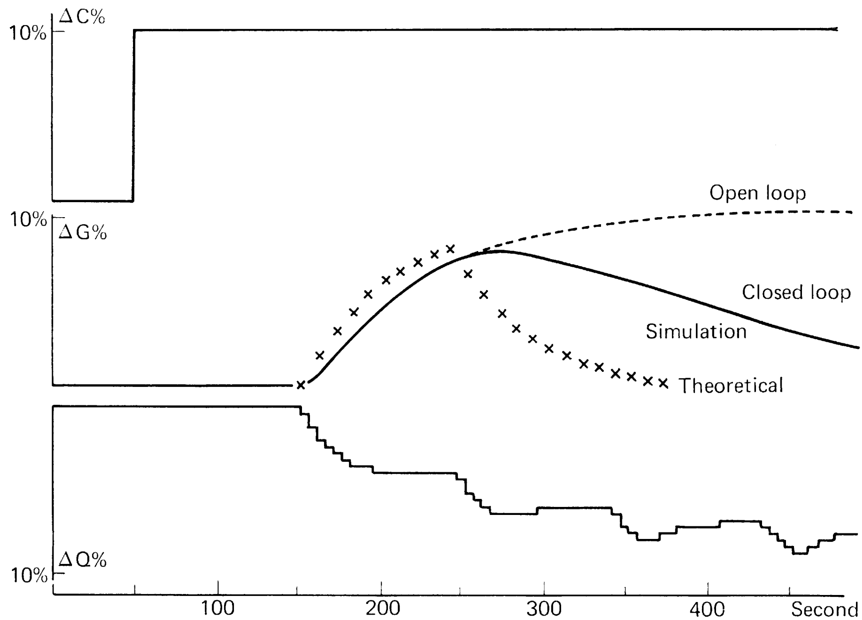

Fig. 8—Basis weight response to a step consistency (one time constant model)

Dry basis weight—An industrial pick-up is used, which sends out three signals—

GAF Total basis weight setting.
DGF Percentage deviations on the above.
HUF Moisture content related to the indicated basis weight (the maker assumes that the capacitance pick-up gives a picture of the basis weight in water and divides this signal by the indicated basis weight).

A 20 points linearisation is applied to GAF, which has a logarithmic variation law and the dry basis weight is then computed—

$$\text{GSF} = \text{GAF}\left(1+\frac{\text{DGF}}{100}-\frac{\text{HUF}}{100}\right)$$

The accuracy of this computed value governs the whole regulation system, which is thus highly dependent on the correct operation and calibration of the combined metering unit, in particular the moisture content meter.

Case of an industrial machine—In the case of a laboratory papermachine with a width of 50 cm, the combined metering unit works in a set position and measurements are continuously available.

On an industrial papermachine, it is debatable whether the pick-up should be kept in one position or whether it should scan the sheet in order to give an average reading. In the latter case, the signal is available only at much longer intervals (of the order of a minute). In this instance, a correction of the type used in the flow control system must be used, which is much less efficient with relatively rapid perturbations. The final choice between the two solutions—a single scanner type pick-up or one fixed pick-up for control purposes and a scanner for monitoring across the sheet—depends on the operating characteristics of the machine.

Short-term projects

THESE include simultaneously the progress of a simulation study and of experiences on the machine.

The work is now oriented towards a study with a control algorithm of the type defined above for a certain number of products (grades) so as to be able to check performance in the face of various perturbations (retention, adjustment of suction pressure in the wet end, for example), also towards a study of the dryers, in which it is intended to use basically the identification method.

In the corresponding experiments, we expect to be able to achieve—

1. Finer calibration of the wet end and dry end moisture and basis weight combined metering units, as well as turbidity meters.
2. A basis weight control system that, in a first stage during the first half of 1969, will take into account the indications from the wet end metering unit, with further refinements later in the form of flow and consistency measurements around the wire.

We have also started investigating changes in machine operating conditions, the practical application of the theoretical results being due during the second half of the year.

Conclusions

THE first part of this study, lasting over some 18 months, has been mainly preparation—definition of the problems, installation of the equipment and familiarisation with it.

The theoretical study carried on concurrently with the practical installation work has enabled a sound foundation to be laid for a satisfactory start when the computer was brought in.

In particular, the model study of the wet end showed that the effect of whitewater recirculation may be ignored, around an operating point. This simplification enabled a type of dry basis weight control to be devised, which was applied right from the start.

We are now entering a new phase of the study, the addition of a computer enabling our working methods to be modified.

We are in fact going to put into practice the first control systems considered and make any necessary additions. The powerful instrumentation facilities now at our command will enable us to deepen our knowledge of the unit with a view ultimately of developing more sophisticated control systems and procedures for production changes.

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Discussion

The Chairman It seems that the day of the overflowing head box on grade change or start-up has gone for ever.

Mr J. Mardon First of all, I am very grateful for your courtesy. I suppose Dr Sanborn that you took the total head by a dp cell, converted it to digital form and matched in the digital form.

Dr I. B. Sanborn Yes.

Mr H. B. Carter Please clarify if the fan pump runs at the same speed with all these various grades?

Dr Sanborn Yes, it does. We have not experimented in terms of variable speed fan pumps to achieve total head control. Admittedly, this is a definite possibility, but we have no experience.

Mr P. A. A. Talvio Dr Sanborn's model includes the constants C_2 and C_3, but they are not in fact constants, as they depend on time and frequency. The simplification you made causes quite a large error at low total head values.

All parts of the head box model can be readily calculated on paper by hand. The equations are given, for instance, in Dr B. W. Smith's paper at this symposium and in the paper I presented at the IFAC conference, London 1966.

Did you Dr Sanborn ever try to calculate the complete transfer functions instead of making identification tests?

Dr Sanborn Yes, we did try to calculate some equations analytically. Initially, reasonable agreement was found between measured and actual values, but the trouble is that it is almost impossible to predict what the dynamics of valves, etc. will be. Since we have implemented this control, we have eliminated identification in terms of actual operation. Now, we usually identify when we first start a system up at some specific set of operating conditions. We are then able to calculate how the systems parameter will change with operating conditions. As a result, we have what might be called an adaptive controller.

On C_2 and C_3, all I can say is that we have had no difficulty with controllability. This may be because we have never run our machines below about 600 ft/min.

Dr D. B. Brewster In the grade you showed, I was not clear whether the total head set point was being determined by the speed set point or by the actual speed.

Dr Sanborn The total head set point is determined by the actual speed. The way that we have head box control set up is that the operator enters the drag at which he wants to operate; we then measure wire speed, calculate the total head required and set the total head set point accordingly.

Mr E. Justus In controlling total head box head on these particular installations, do you have to show the difference between head and set head—setting the valve in a fixed position mechanically, then trying to identify what the variables are?

Dr Sanborn The only information we have is the performance in terms of drag variations for constant speed with the total head controller loop closed and open. With it closed, the standard deviation of the drag was $\pm 2{\cdot}5$ ft/min. About half of that variation is due to wire speed fluctuations. Hence, only half of it can be ascribed to the total head controller. Without total head control, a standard deviation of ± 5 ft/min was noted. This shows that we had a well-behaved system before we implemented the controller.

Mr B. W. Wells (written comment) This comment refers to the problems of the need for different flow box control constants during different paper grade conditions. Surely, when using a computer there would be no more difficulties involved in using a supervisory program during grade changes to change the control constants of a DDC three-term control algorithm than changing the control constants in a digital compensator (as mentioned under *Control design—part 3*)?

Regarding the problem of 8 s dead times associated with the flow box, in our experience, such dead times would inevitably impair the response characteristics of any control system and would justify effort to remove them before serious thought could be given to designing a sophisticated control system.