Preferred citation: A.R. Farmer. Analog computing techniques applied to papermaking. In **Papermaking Systems and their Control**, *Trans. of the IVth Fund. Res. Symp. Oxford, 1969*, (F. Bolam, ed.), pp 269–282, FRC, Manchester, 2018. DOI: 10.15376/frc.1969.1.269.

ANALOG COMPUTING TECHNIQUES APPLIED TO PAPERMAKING

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Synopsis An examination of papermachine wet end fibre balance and stock flow equations reveals the interdependence of important papermaking parameters and the control strategy required to make changes in machine running conditions. To avoid breaks during any adjustment, the fibre and water balance of the wire must be controlled closely and any controlling device must incorporate some 'built in' knowledge or mathematical model of the process. It is shown how analog computing elements can fulfil this requirement and thus provide a low cost alternative to a digital computer installation.

An analog computer control system has been in operation for 18 months on the No. 2 papermachine at the Grove Mill Paper Co. of New Mills. During this period, a 15 per cent increase in production can be attributed directly to the use of the computer. Results given include a typical beta-gauge chart, showing the close control of basis weight and the sequence of events that occur during a grade change.

Introduction

THIS paper outlines the theory behind the analog papermachine control system that has been operating successfully for the past 18 months at the Grove Mill Paper Co. of New Mills near Stockport, Ches. Development work on the system started in May 1965, when the mill management indicated an interest in automating No. 2 machine to improve product uniformity and production efficiency. The mill makes a wide range of papers used for packaging and display of consumer goods, in addition to base papers for further converting processes. A significant proportion of the business consists of small orders of various grades of paper made to agreed specifications.

During initial studies on the problems of papermachine control, it was

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Under the chairmanship of Dr N. K. Bridge rapidly appreciated that the operator's skill is required not so much in maintaining a particular grade of paper as in manipulating the machine controls to achieve that grade of paper and adjusting for formation and speed during the change from one grade of paper to another. Adjustments on the machine must be made in the correct time sequence to avoid transient disturbances in basis weight that could weaken the sheet and cause it to break. The computer system is designed to assist in performing these critical adjustments, acting as an interface between the operator and the machine.

Control objectives

THESE may be summarised as follows—

1. To maintain by means of closed loop control the basis weight of a given grade of paper within the limits of $\pm 1{\cdot}5$ per cent.
2. To provide the operator with facilities for independent control of machine speed, basis weight, breast box consistency and efflux ratio.
3. Automatic grade change—that is, the ability to change from some initial speed, basis weight, breast box consistency and efflux ratio to a completely new set of conditions demanded by the operator.

Objective *2* allows the operator to obtain near optimum machine performance for any grade of paper.

Theory

THE control strategy required to achieve the above objectives becomes apparent once relevant material balance equations have been derived for fibre flows in the wet end system. The mathematical model so formed must be adequate to account with sufficient accuracy for both the steady state and dynamic behaviour of the papermachine.

Steady state material balance equations

Fibre balance on the wire—Referring to Fig. 1, when stock flows from the slice on to the wire, a proportion of the fibres form into paper to be drawn off the couch, but the remainder drop through the wire into the trays and the backwater silo. If the flow from the slice is F_s and the consistency (amount of fibres per unit volume) is C_s, then the fibres flowing on to the wire is F_sC_s. The through factor t is defined as the proportion of fibres lost through the wire; therefore, the quantity of fibres leaving the wire as paper is given by $F_sC_s\,(1-t)$. This equals basis weight × machine width × wire speed, that is—

$$S \times \text{width} \times V_w = F_sC_s(1-t)$$

where V_w = wire speed
and S = substance or basis weight.
But F_s = effective slice gap $G_{sa} \times$ machine width $\times$ slice jet velocity V_s.
Thus, $S \times \text{width} \times V_w = G_{sa} \times \text{width} \times V_s \times C_s(1-t)$.
Therefore,

$$S = \rho G_{sa} C_s(1-t) \qquad (1)$$

where ρ, the efflux ratio $= \dfrac{\text{Slice jet velocity } V_s}{\text{Wire speed } V_w}$

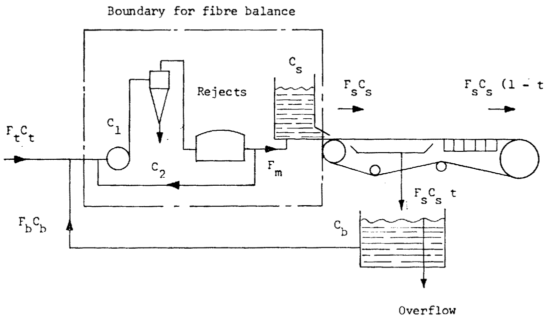

Fig. 1—Fibre and flow balance in wet end

Fibre and flow balance in the wet end—For the values—

F_t = thick stock flow
C_t = thick stock consistency
F_b = backwater flow
C_b = backwater consistency

Fibre flow into the wet end = Fibre flow from slice
that is, $F_tC_t + F_bC_b = F_sC_s$, but $F_t + F_b = F_s$.
Elimination of the flow terms is possible if the thick stock flow is made proportional to slice flow, that is—

$$F_t = rF_s.$$

Then $F_b = F_s - F_t = F_s(1-r)$
and $rF_sC_t + (1-r)F_sC_b = F_sC_s$.
To a very close approximation the backwater consistency $C_b = tC_s$.

$$\left.\begin{aligned} &\text{Therefore } C_s = \frac{rC_t}{1-t+rt} \\ &\text{or} \quad C_s(1-t) = rC_t - rtC_s \end{aligned}\right\} \qquad (2)$$

The term rtC_s is small compared with rC_t and is a correction for fibre loss in the backwater system. For increased accuracy, further coefficients may be added to account for stock loss from the cleaners or screen or for the effects of spray water in the breast bow. The value of t may be set by the operator for each grade of paper or preset for all papers, if (as at Grove mill) t is low for all papers made.

Machine throughput—Equations (*1*) and (*2*) may be combined to give the machine throughput relationship—

Thick stock fibre flow in = fibre made into paper+losses.

Eliminating $C_t(1-t)$ from equations (*1*) and (*2*)—

$$\frac{S}{\rho G_{sa}} = rC_t - rtC_s$$

therefore

$$C_t = \frac{S}{r\rho G_{sa}} + \frac{S}{\rho G_{sa}} \cdot \frac{t}{(1-t)} \qquad (3)$$

This equation may be used to calculate (in retrospect) the incoming thick stock consistency.

Control strategy

Closed loop control of basis weight—Holding steady basis weight depends not only on maintaining a constant incoming mass flow of thick stock relative to machine speed, but in correcting for transient disturbances that occur within the system. Referring to equation (*1*), S the substance or basis weight can be influenced by variations in efflux ratio (that is, in the pressure head at the slice) or by variations in through factor t, which also affect breast box consistency C_s. Through factor is influenced by temperature, refining, furnish (recipe for the stock) and many other variables.

The concept of thick stock mass flow control is attractive. F_tC_t may be kept constant and equal to the mass flow required by making use of the signal from a consistency transmitter placed in the thick stock pipeline just before the thick stock valve. In practice, unfortunately, signal drift occurs. Most consistency transmitters do not respond to clay variations and they are to some extent sensitive to pipeline conditions, temperature and changes in refining. It is possible to overcome the problem of drift by calculating thick stock consistency from equation (*3*) for machine throughput, then using this value to update the calibration of the transmitter. This technique is used at Grove mill.

Auxiliary control loops operate as follows.

The pressure head at the slice h is controlled as a function of wire speed. Slice jet velocity—

$$V_s = c_v\sqrt{2gh} = \rho V_w$$

therefore $h = \rho^2 V_w^2/2g$

if c_v, the coefficient of discharge at the slice, is assumed to be unity. Values V_w and ρ are set by the operator.

The effective slice gap G_{sa} is determined from the measurement of h and the main flow to the breast box F_m. In the steady state—

$$F_m = F_s = \rho V_w G_{sa} \times \text{machine width} \quad . \quad . \quad . \quad (4)$$

$$\text{therefore } G_{sa} = F_m/(\text{width} \times \sqrt{2gh})$$

Thick stock flow $\quad F_t = rF_m = rF_m . C_t/C'_t,$

where C_t represents the value of thick stock consistency obtained from equation (*3*) using the values of S, ρ, G_{sa} and r, as well as $C_t' = C_t$ modified by the signal from the thick stock consistency sensor.

Basis weight is measured by a beta-gauge located just before the reeler. At Grove mill, the basis weight error signal is integrated and fed back to modify the slice gap and thus thick stock flow via control of efflux ratio and the ratio of thick stock flow to main flow. Slice gap, main flow and thick stock fibre flow change in synchronism as a total flow control system. This technique minimises process dead time, allowing a faster correction of substance error and eliminates the need to compensate for the dynamic effects of consistency changes in the wet end. The disadvantages of moving the slice are those associated with changing the drainage conditions on the wire, possibly the profile of the sheet. Practical experience has shown, however, that excursions of slice gap seldom exceed ± 2 per cent of mean value.

The value of C_t is updated condintuously from G_{sa}.

Change of machine speed without affecting basis weight, breast box consistency or efflux ratio—This is inherent because of the closed loop controls for efflux ratio and the ratio of thick stock flow to main flow.

Change of breast box consistency without affecting basis weight or efflux ratio—Consider what would happen to breast box consistency if the flow of thick stock were suddenly increased; the effect is illustrated in Fig. 2*a*. The breast box consistency response may be approximated to the sum of three exponential lags with associated delay times. As T_1 corresponds to the process delay time of thick stock valve to slice and T_{11} to a lag due to the mixing effect in the pipelines, screen and breast box, $T_2 = T_1$ plus the time taken for recirculation of stock via the balance pipe. Therefore, $T_3 = T_1$ plus the time taken for recirculation of stock via the backwater silo. With suitable adjustment of thick stock flow as shown in Fig. 2*b*, the breast box consistency itself could have been made to increase suddenly and, assuming steady values of ρ, G_{sa} and t, by equation (*1*) this would have given rise to a similar rapid change in basis weight.

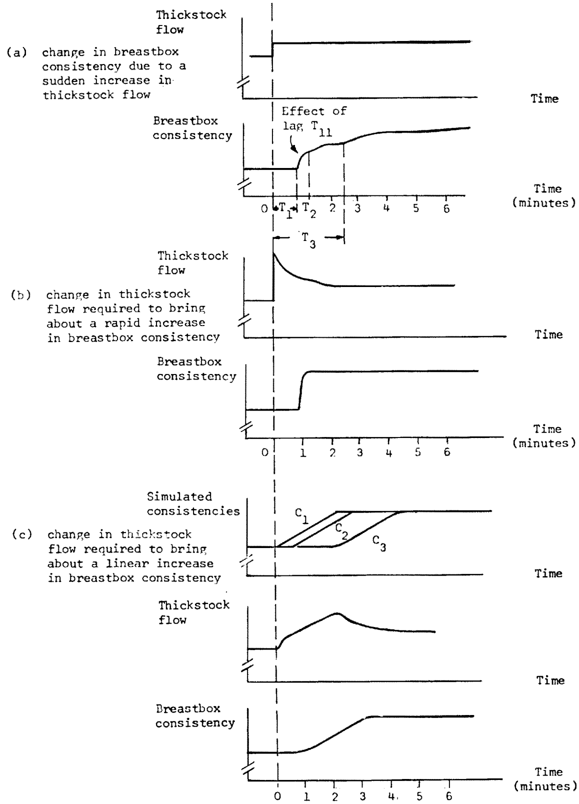

Fig. 2—Papermachine responses

In order to maintain basis weight constant, however, it is clear, also from equation (*1*), that the slice gap G_{sa} must be changed while the change is occurring in C_s; furthermore, during the transient C_s, G_{sa} must be kept constant. During a rapid change in breast box consistency, this requirement is virtually impossible to achieve. It is necessary therefore to slow down the rate of consistency change to such an extent that the timing of the slice movement is no longer critical.

The computer calculates the adjustments to thick stock flow required to bring about a linear in the consistency of the stock entering the breast box.

A dynamic model is used, which is again based upon material balance relationships.

Referring again to Fig. 1—

C_1 is the stock consistency at the outlet of the main pump,

C_2 is the consistency of the stock in the balance pipe.

Writing down an equation for fibre balance at the main pump—

$$F_tC_t+F_bC_b+(P-F_m)C_2 = PC_1$$

$$rC_t+(1-r)C_b+\left(\frac{P}{F_m}-1\right)C_2 = \frac{P}{F_m}C_1$$

$$r(C_t-C_b) = \frac{P}{F_m}(C_1-C_2)+C_2-C_b$$

Introducing C_3, a dummy variable—

$$r(C_t-C_b) = \frac{P}{F_m}(C_1-C_2)+(C_2-C_3)+(C_3-C_b) \quad . \quad (5)$$

$$\text{Now } C_2 = C_1e^{-(T_2-T_1)p}$$

$$\text{and } C_s = C_1\frac{e^{-T_1p}}{(1+T_{11}p)}$$

C_3 is defined by the equation $C_b = tC_3$

$$C_3 = C_1\frac{e^{-(T_3-T_1)p}}{(1+T_{11}p)(1+T_{33}p)}$$

The term T_{33} simulates the effect of stock mixing in the backwater silo.

As in equation (2), further terms may be added to account for stock loss from the cleaners or screen or for the effects of spray water in the breast box and to compensate for the effects of stock passing through secondary cleaners.

In the steady state, $C_1 = C_2 = C_3 = C_s$ and equation (5) reduces to equation (2)—

$$r(C_t-C_b) = C_s(1-t) \quad . \quad . \quad . \quad . \quad . \quad (2)$$

This means that the final value of rC_t (thick stock flow) may during consistency changes be predicted with good accuracy and the terms $\frac{P}{F_m}(C_1-C_2)$ and (C_2-C_3) occur only transiently to compensate for the dynamic response of the wet end.

Obtaining good representation for time delays is always difficult with analog equipment. At Grove mill, the consistencies C_1, C_2 and C_b or C_3 are simulated by analog integrators arranged to ramp between the initial and the final value of C_s set by the operator (Fig. 2*c*). These ramping signals are controlled by a timing unit that generates logic control signals dependent upon main flow. The integrator outputs are mixed to generate the correct signal for rC_t (thick stock flow). The time and rate of the resulting change in breast box consistency is predicted and the slice gap moved accordingly. When the adjustments are complete, any computational errors appear as a small error in basis weight, which is then automatically corrected by the feedback from the beta-gauge to the slice. The total effect of the change is a reduction in main flow corresponding to the change in slice gap with thick stock flow restored to more or less its previous value.

Change of efflux ratio without affecting basis weight or breast box consistency—Equation (*1*) shows that such a change is possible if the product ρG_{sa} is kept constant. After the change, the flow from slice F_s has the same value as before—equation (*4*)—but, if the machine has an open breast box as at Grove mill, a little more or less main flow F_m is required during the change while the level of stock changes. Any computational errors are automatically corrected by the feedback from the beta-gauge to the slice.

Change of basis weight without affecting breast box consistency or efflux ratio—Provided that the through factor remains steady, breast box consistency is determined by the ratio of thick stock flow to main flow—that is, if the main flow is varied because the operator wishes to change the machine throughput, C_s remains constant provided r is kept constant. Looking again at equation (*1*), for constant ρ, C_s and t, the basis weight S is proportional to G_{sa}. While moving the slice to change basis weight, machine speed is changed in sympathy. This allows the machine throughput to be controlled to a characteristic related to the performance of the drying cylinders and determined from previous running records for different weights of paper. This characteristic is shown in Fig. 3.

Change from some initial speed, basis weight, breast box consistency and efflux ratio to a completely new set of conditions demanded by the operator—The control required is a combination of the facilities already described and provision is made for the computer to make the necessary calculations simultaneously.

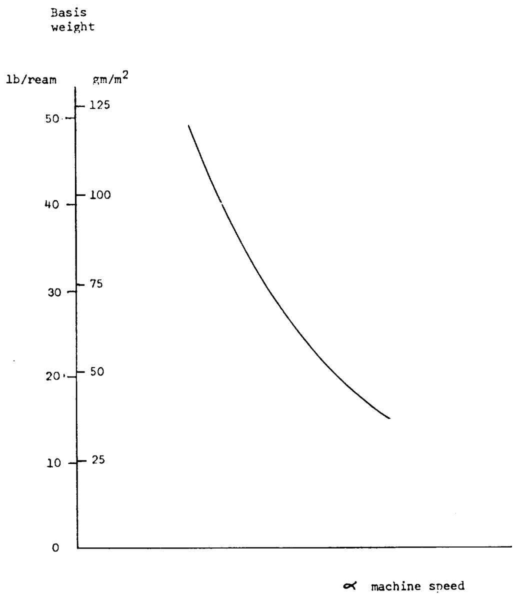

Fig. 3—Machine throughput characteristic

Instrumentation, the operator's controls and the computer

Communication between the operator, the computer and the plant is illustrated in Fig. 4.

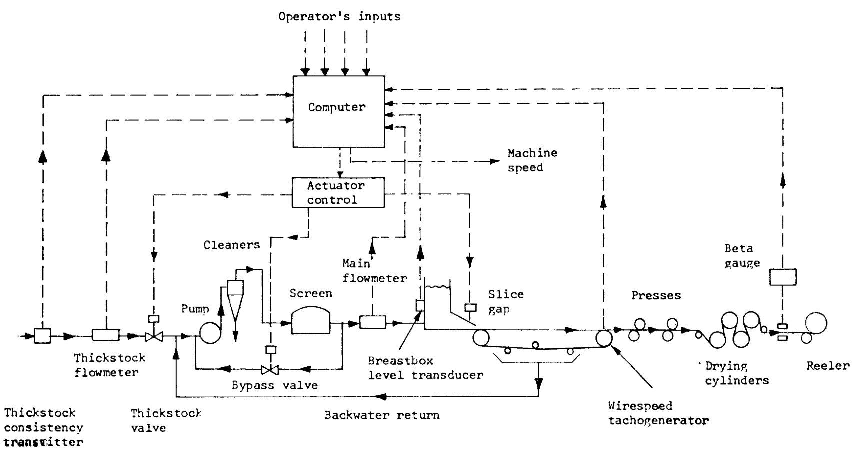

Fig. 4—Communications between the operator, computer and plant

Magnetic flow meters measure thick stock flow and the main flow to the breast box. The accuracy of these units is ±0·5 per cent. Stock level in the breast box is measured by a pressure transducer of the bellows type, again with an accuracy of ±0·5 per cent. A dc tachogenerator is coupled to the couch gearbox to measure wire speed. The remaining instrumentation comprises a beta-gauge and consistency transmitter.

The thick stock valve and main flow by-pass valve are 3 in and 10 in (7·6 cm and 25·4 cm) V-ball valves with motor-driven actuators. Positioning is achieved by control units with thyristor static switches in the ac supply lines to the actuator induction motors. Each actuator and control unit is rated to allow a maximum of two motor starts per second.

Another actuator provides for adjustment of the slice gap. A recirculating ball thread mechanism produces a linear output motion, which is transmitted to the slice via a simple lever attached to the cross-shaft supporting the profile adjustment handwheels. A total sensitivity of 0·1 per cent of stroke can be achieved in response to changes of demanded position.

On the operator's control desk are push-buttons for manual control of the actuators and the lineshaft drive. While on computer control, the operator sets up breast box consistency and efflux ratio by means of potentiometers and basis weight by the dial on the beta-gauge panel. There are lamps to inform the operator of the function being performed.

The analog computer is built up of analog control modules—84 modules in all, of 13 basic types that include potentiometers, scaling amplifiers, sample-hold integrators, multiplier/dividers, square-root extractors, comparators and three-state switches. These perform the functions required to solve the process equations. Typical computing accuracy per modules is ±10 mV or ±0·1 per cent of the 10 V standard signal level.

The logic system consists of approximately 180 elements that determine the set of equations currently being solved. There is a comprehensive test signal injection facility to assist with fault finding.

System operation and performance

System operation

The operator controls the machine manually until the paper is threaded through the machine before switching over to the computer. The changeover operation is performed by first balancing out the *set consistency* and *set efflux ratio* controls until associated deviation meters read zero. During this procedure, the computer calculates the value of the thick stock consistency and the settings so obtained correspond to the running conditions on the machine. Changeover is complete when the operator turns the *manual/auto* control switch and depresses the *reset beta-gauge* push-button to bring into operation the feedback control for basis weight. The changeover procedure causes no transient errors.

The computer continuously monitors the signals from the plant transducers and controls the settings of the valves and slice gap in accordance with the operator's instructions.

An increase in machine speed is simply performed by depressing the *raise speed* push-button. To maintain efflux ratio, the by-pass valve is closed and the resultant increase in main flow causes a proportional increase in thick stock flow.

For a change in breast box consistency, the operator adjusts the calibrated *set consistency* control potentiometer. Each potentiometer control is backed up with an analog memory and the adjustment by the operator is immediately detected. A warning lamp is lit while the system remains 'frozen' at the original setting. The change is allowed to proceed only when the *initiate*

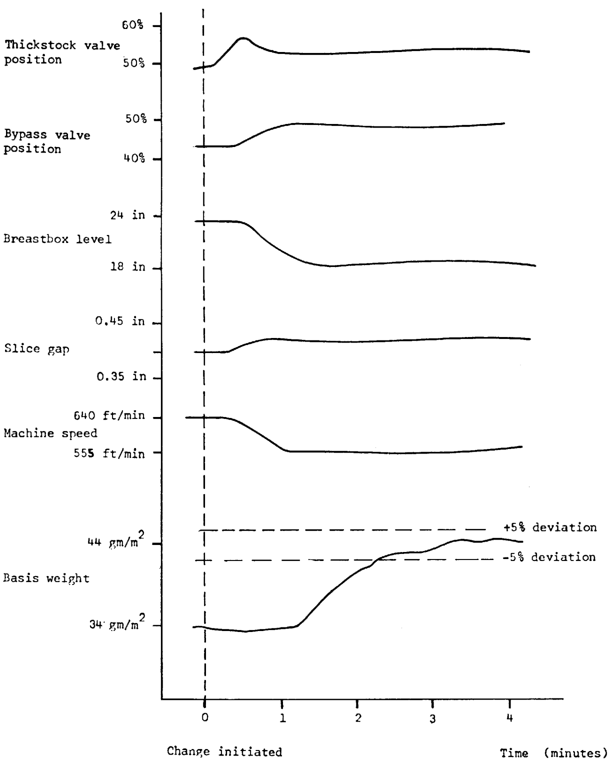

Fig. 5—Typical sequence of events during a grade change

push-button is depressed; the computer then solves the system equations and calculates a sequence of adjustments necessary to alter breast box consistency to the new value without affecting basis weight. Making use of analog memories in this way enables the operator to set all the controls before a multiple change and there is the added advantage that accidental movement of a control only causes the system to 'freeze'.

A typical sequence of events to occur during a grade change is shown in Fig. 5. The thick stock valve opens first to bring about an increase in breast box consistency. About 25 s later, the breast box consistency starts to change and the basis weight change is automatically initiated. Machine speed falls and the by-pass valve opens to reduce the flow of stock to the breast box. The level of stock in the breast box falls to maintain efflux ratio. After $1\frac{1}{2}$ min, the changes at the breast box are complete, but thicker paper has only just reached the beta-gauge. The paper becomes within ± 5 per cent of the new basis weight $2\frac{1}{4}$ min after the change was initiated.

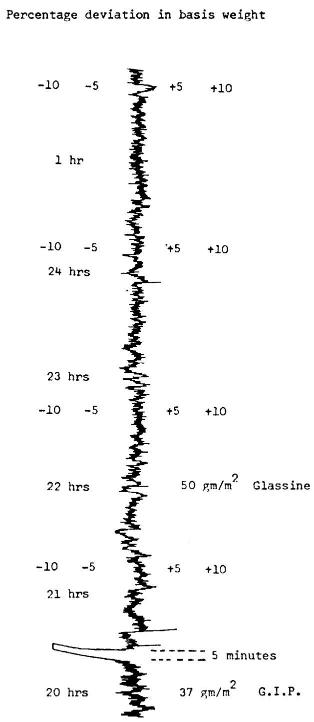

Fig. 6—Typical beta-gauge trace showing grade change

Installation and commissioning

The installation and commissioning of the equipment was effected in stages and with virtually no interruption of mill production. This approach proved to be very successful in that it gave the operators an opportunity to become familiar with each control facility as it was made available.

System performance

Results confirm that the control system is achieving its predicted performance. A typical beta-gauge trace of basis weight deviation may be seen in Fig. 6 and the accuracy of control is further illustrated by Fig. 7, which

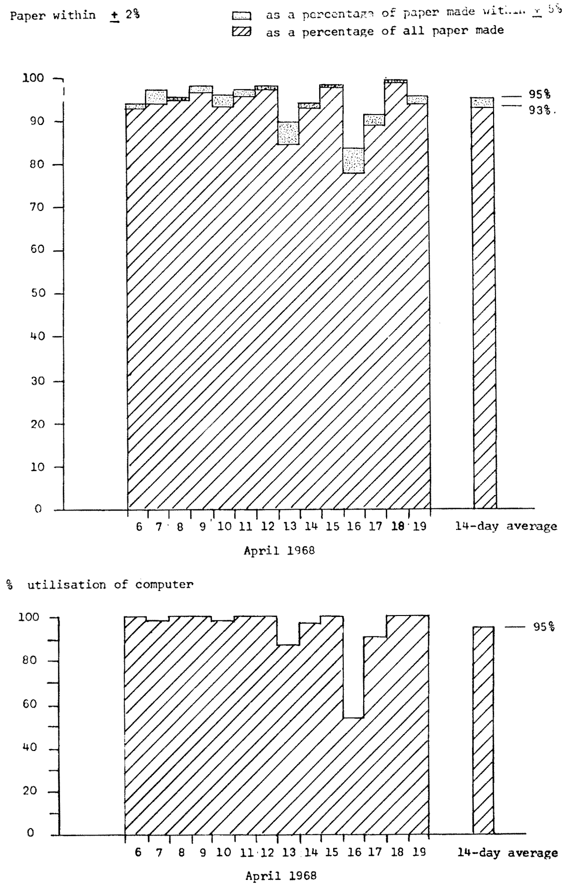

Fig. 7—System performance during the period 6–19 April 1968: the poor results on 13 April are attributable to malfunctions of the thick stock consistency transmitter and those on 16 April to repeated failures of the seal pit separator pump

presents an analysis of several consecutive days' running. The improvement in machine controllability enables the operator to obtain repeatable machine settings for any grade of paper; there are no shift-to-shift variations and wastage from off-specification paper has been significantly reduced. A 15 per cent increase in production arising from these factors can be attributed directly to the use of the computer.

Concluding remarks

THE system design experience gained at Grove Mill is applicable to either analog or digital papermachine control schemes, the same equations hold and only the method of implementation is different. The choice between analog and digital techniques usually depends on whether the papermachine is to be considered alone or as part of an integrated production control system. For a small papermill, however, the analog computer offers a cheap and realistic approach to the problem of papermachine automation.

The original scheme has now been standardised and the hardware arranged as a number of units that correspond to the control facilities available. Further work at Grove Mill will extend the area of control to include the drying cylinders and the refiners.

Discussion

Dr D. B. Brewster The author deserves congratulation on producing a good engineering solution to the problem. I am interested in the cost of digital computer implementation. Do you expect this to become markedly lower as circuit technology changes over the next five years?

Dr A. R. Farmer We are currently quoting for schemes that include moisture control and machine throughput maximisation in addition to the wet end control described in my paper. The approximate cost of the computer hardware and control desk is approximately £22 000. This price is likely to be reduced in the event of quantity production or by further utilisation of micro-electronic operational amplifiers and logic elements on the computing modules.

Mr B. W. Balls You include a motorised slice, but in your paper you say very little about cross-machine variations other than to admit their possibility. The same point arises from the paper by J. S. Harris and G. J. Mummery. Have you found that papermakers readily accept automatic slice movement? If only motorised slices would be acceptable in mills, a simple, improved form of wet end control would be immediately available.

Dr Farmer Cross-machine profile variations have not been troublesome on the 84 in machine at Grove Mill. Doubts were raised initially about moving the slice, but the papermakers soon took advantage of the extra degree of freedom provided by motorising the slice.

Mr N. C. Underwood In the graph, the speed and basis weight appear to be inversely related, so one would imply that the machine output was limited by drying capacity. Would you propose that the control strategy should be the same in this case as when the machine output is limited by the top speed of the dryer?

Dr Farmer The constraint of top speed limitation can easily be incorporated within the control strategy.

The Chairman This is quite an important point. It will show if there are any deficiencies in the control strategy, because when you are production limited (as appears to be the case at Grove Mill), your thick stock flow cannot be changed by a large amount, almost by definition.

Mr J. A. Bennett I would like to comment on the previous question about the movement of the slice. We had considerable misgivings about this in the initial stages, but it was considered a good philosophy to improve the flow to the slice rather than to worry about the effects of moving the slice lip. From a general papermaking point of view, this provided a tremendous improvement; then, as Dr Farmer said, the mere 2 per cent movement of the slice lip caused no noticeable profile problems.

The Chairman Has anyone else here any experience of controlling a papermachine by continually altering the slice?

Dr I. B. Sanborn We have the slices of two machines under control, but adjust them only to control flow through the head box. Basis weight control is achieved by manipulating the thick stock valve. We experience no particular difficulties with basis weight profiles varying, but the machines in question are only 150 in wide.

Mr J. Mardon To some extent, the participants have failed to appreciate that, with the new distribution systems, the basis weight variation across the machine is independent of the width of the machine.

The Chairman It is a good point, but not all of us have modern distribution systems.

A Speaker What was the discharge at the slice when the system was designed? Every time, when moving the slice, there must be a change in its coefficient. As an alternative, has increasing or changing the water quantity been considered? By raising the head in the slice or in the head box fractionally, a much closer change will occur, much more controlled.

Dr Farmer Coefficients of discharge at the slice that are significantly different from unity can be accommodated by a compensation in the setting for efflux ratio—

$$\rho' = \rho/c_v$$

where ρ' is akin to the paper quality constant set by the operator at Wolvercote Mill.

Discussion

For machine speeds in excess of 400 ft/min, the coefficient at the slice is effectively unity and no problems have been encountered through movement of the slice lip.

In my experience, control of pressure head at the slice or of efflux ratio is very important and sheet formation is likely to be affected if intentional fluctuations in breast box level are made to compensate for basis weight.