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BASIS WEIGHT PROFILE CONTROL OF A PAPER MACHINE

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Abstract: During the 1980s, the use of high-speed printing and copying machines which will not tolerate much variation in paper weight has increased. As a result, there is a growing demand for improved basis weight control systems for paper machines. Basis weight, the weight of a square meter sheet of paper, is the most important measure of paper consistency.

Until quite recently, basis weight could only be controlled manually; this required experienced operators. The reasons for the difficulty in automating control of basis weight is due to the complexity and variability of process characteristics, the "noisiness" of the process (process disturbances), and actuator inadequacies.

This paper describes a method of automatic control that we have developed; it incorporates the experience of expert operators, and the results of simulation, in confidence factors.

1. Introduction

Paper is manufactured by extruding a 0.2% to 0.3% solution of paper pulp at a constant pressure from a headbox through a slice lip onto a moving wire screen. Moisture drains through the wire screen, and is further removed by passing the paper sheet through roller presses and over drier cylinders. The paper then passes over calender rollers and is smoothed, slit to width and formed into continuous rolls. Figure 1 shows a diagram of the paper machines, sensors, and control system. The CD basis weight profile is controlled by operating "slice screws" which are at intervals of 100 to 150 mm across the width of the paper at the exit where the pulp is extruded from the headbox. Up to now, these slice screws have been operated by an experienced operator, and it has not been possible to automate the process for the following reasons:

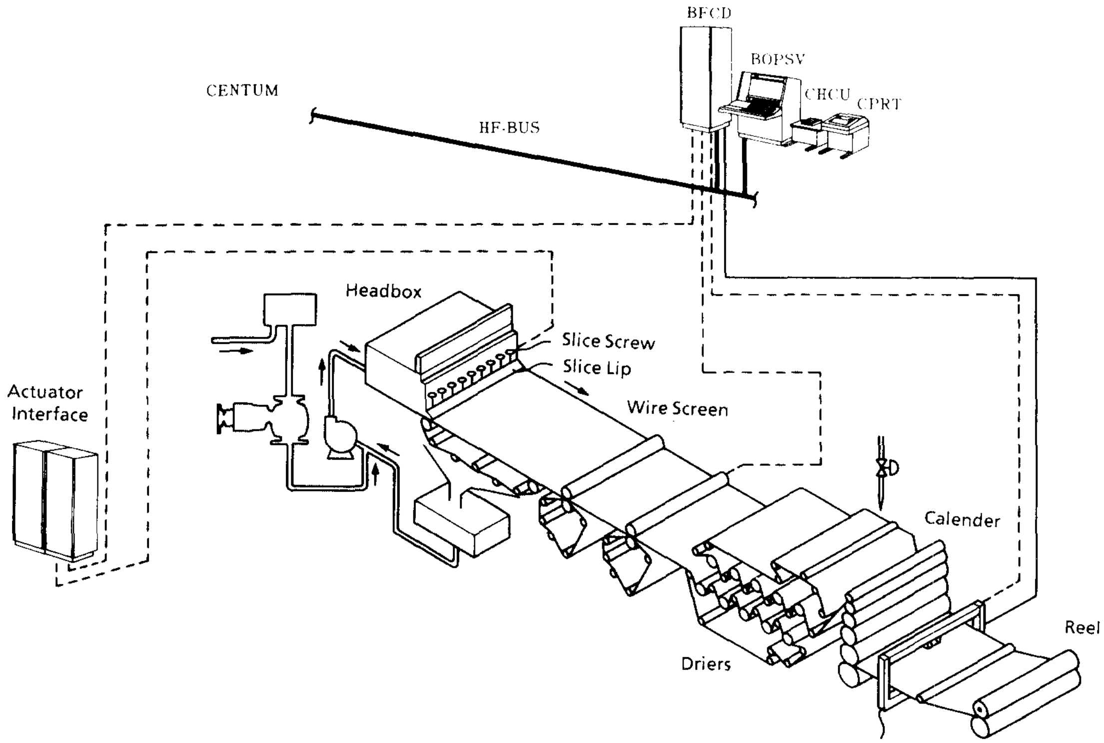


Fig. 1. Paper Machine and Control System

(1) **Effect of Slice Screw Movement on BW Profile is Complex.** When a single slice screw setting is changed, the effect on basis weight slice profile is as shown in Fig. 2. Opening a slice screw increases the pulp flow (basis weight) not only under the slice screw but also at positions corresponding to adjacent slice screws; however, (assuming a constant total flow) the flow at positions that are further from the slice screw is decreased accordingly.

(2) **Pulp Flow Causes a Transverse Shift in BW Profile.** When the pulp is extruded from the slice lip, it can flow in the crosswise direction as it moves along the wire mesh. The paper also shrinks as it is dried, resulting in a movement from the edges towards the center. The positional correspondence between the movement of a slice screw and the change in the paper profile is thus quite complex (Fig. 3).

(3) **Variability of BW Profile and Transverse Shift.** The above two effects vary with paper speed and batch composition. Effect (1) is less pronounced for ordinary low basis weight paper, produced with the paper machine running at high speed, than for heavier paper produced with the paper machine running more slowly (see Fig. 4).

(4) **Preventing Ripples in the Paper.** If ripples are allowed to develop in the paper sheet, it is very difficult to remove them by operating the slice screws. To preventing such bunching and ripples, the difference between adjacent slice lip apertures must generally be limited to a maximum of 0.2 or 0.3 mm.

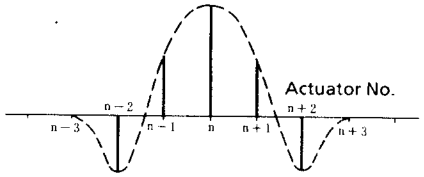


Fig. 2. Response of Basis Weight Profile to a Slice Screw Adjustment.

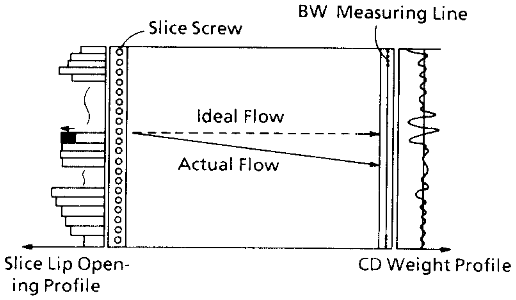


Fig 3. Positional Response.

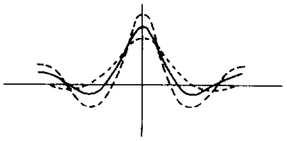


Fig. 4. Variation in Basis Weight Profile.

2. Process Model.

If there were a simple one-to-one relationship between actuator movement and the change in profile at the corresponding point, the control solution would reduce to n independent feedback controllers, where n is the number of actuators. However, as described above, there is a significant degree of interaction between the actuators due to the fluid mechanics both at the slice and on the wire screen (cf. Fig. 2).

The model may be described by the matrix equation:

$$X = G(s) \cdot K \cdot Um \qquad (1)$$

where

X is the 1-D array of basis weight profiles

$$X = (X_1, X_2, \ldots X_i \ldots X_n)^T \qquad (2)$$

X_i is the basis weight at the point corresponding to the i-th actuator;

G(s) is the transfer matrix; each element of it can be modelled by dead time plus first order lag;

K is the matrix representing interaction between the actuators, If the responses of all actuators are similar and symmetric about the actuator positions, matrix K will be band diagonal and symmetric, of the form:

$$K = \begin{bmatrix} k_0 & k_1 & k_2 & 0 & & & 0 \\ k_1 & k_0 & k_1 & k_2 & 0 & & 0 \\ k_2 & k_1 & k_0 & k_1 & k_2 & 0 & 0 \\ 0 & & & & & & \\ & & & & & & \\ 0 & & & 0 & k_2 & k_1 & k_0 \end{bmatrix} \qquad (3)$$

k_0, k_1, and k_2 represent the profile response to a unit change in one slice screw centered on that slice screw, the adjacent screws, and the screws two positions away, respectively.

Um is the manipulated output, the array of slice lip apertures.

3. Control System.

3-1. **Non-Interacting Control.** First we consider a method of decoupling to produce non-interacting control. If we implement the controller as:

$$Um = F\,P\,(Xset - X) \qquad (4)$$

where F is an $n \times n$ matrix, Xset is the 1-D array of profile settings, and P is the controller matrix. The diagonal elements of P represent PI controllers. Substituting Eq. (4) into Eq. (1) gives:

$$X = G(s)\,K\,F\,P\,(Xset - X) \qquad (5)$$

so $$(1 + G(s)\,K\,F\,P)\,X = G(s)\,K\,F\,P\,Xset \qquad (6)$$

If $$F = K^{-1} \qquad (7)$$

then Eq. (6) can be written as:

$$(1 + G(s)\,P)\,X = G(s)\,P\,Xset \qquad (8)$$

Since G(s) and P are diagonal matrices, there is no interaction between actuators in this case. In practice, however, the profile response matrix K varies as a function of many variables, including paper machine speed, condition of the wire screen, distortion of the slice lip, and pulp composition. The profile response K varies with time, but because the value of n is also quite large -- typically 50 to 100 -- it is impractical to recalculate K at frequent intervals. A simulation was performed to determine the effect of such changes on process stability, and the results are shown in Fig. 5(a). A more robust form of control, that is not affected by changes in K, is obviously required.

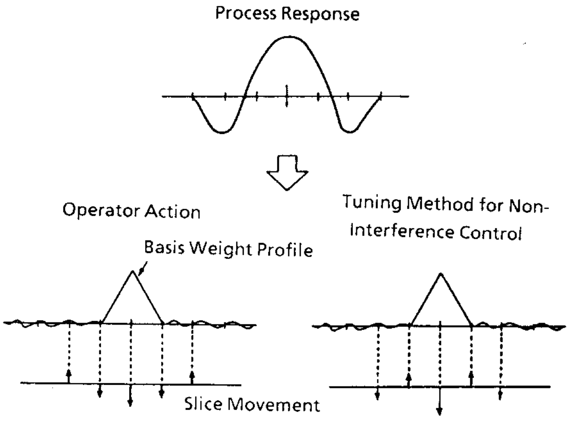
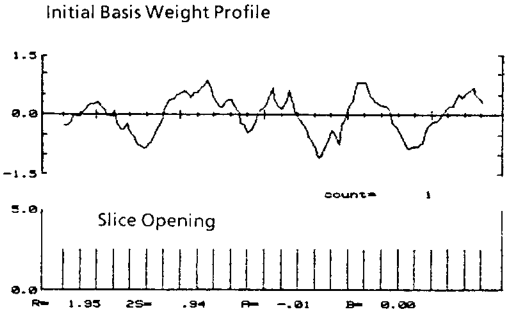


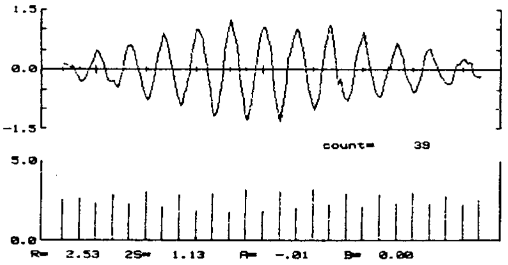
Fig. 6. Comparison of Operator Response and Non-Interference Control.

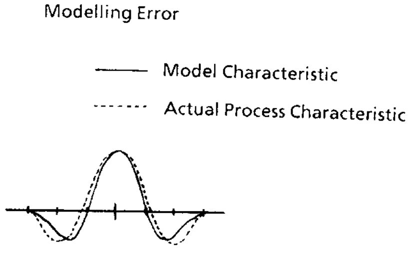
3-2. **Manual Operating Rules.** It's instructive to look at how an operator adjusts the basis weight profile.

(1) To eliminate a profile deviation, the operator adjusts not only the slice screw at the center of the deviation but also the slice screws on either side, as shown in Fig. 6. The operator's response -- to change the slice screw settings in a pattern that represents the inverse of the response -- differs from non-interference control, as shown. However, when we simulated the effect of varying the F matrix in the same way (see Fig. 5(b)) we found that this was a relatively robust form of control.



(a) Simulation of Non-Interacting Control with Modelling Error





(b) Simulation of Control with Confidence Factor Matrix

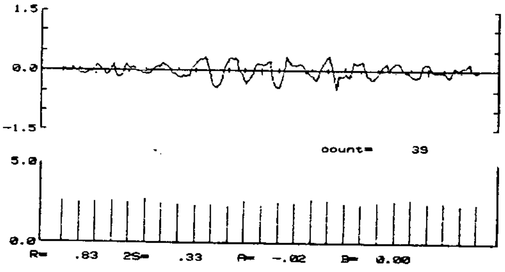


Fig. 5. Effect of Modelling Error on Controllability.

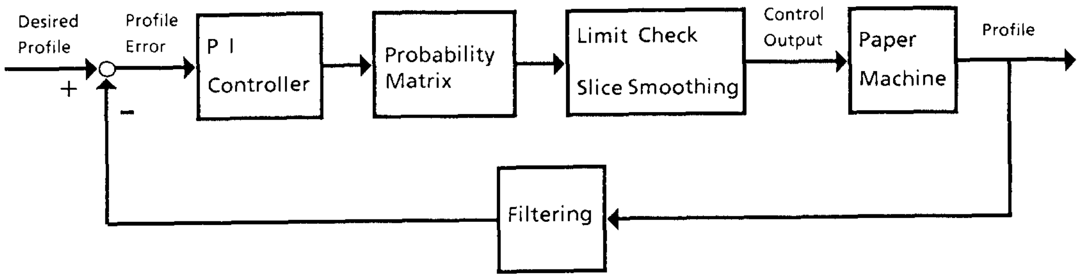


Fig. 7. Block Diagram of Basis Weight Profile Control

(2) It is also important to change the slice opening smoothly, limiting the difference between the opening of adjacent slice lips, or control can be lost due to bunching and ripples. This can be described by the expression:

$$\frac{U_{i-1} + U_{i+1}}{2} - U_i < C \qquad (9)$$

Here U_i is the i-th slice lip opening.
C is a limit value to ensure a smooth slice profile,

If each U_i does not meet this condition, it is adjusted as follows:

$$U_i = \alpha_{-1}\, U_{i-1} + \alpha_0\, U_i + \alpha_{+1}\, U_{i+1} \qquad (10)$$

Here α_{-1} thru' α_{+1} are smoothing constants.

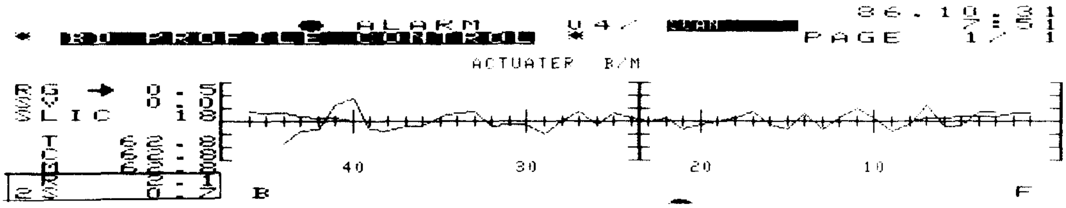
Figure 7 shows a control block diagram. We found that this control algorithm gave very good results in practice.

4. Operating Test Results.

Before describing an implementation of basis weight control we will explain how we evaluate a basis weight controller. We use R, the difference between maximum and minimum values of the profile data, and 2 σ, a measure of the variability of the data, as a measure of the "goodness" of process control. The smaller these values, the better the control.

4.1 Control Results for Paper Machine "A". The results for paper of basis weight 67 g/m2 and sheet velocity of 630 m/min are shown in Fig. 8. Before the automatic control system was implemented, the value of R was 2.1, and the value of 2 σ was 0.7 . Two hours after starting automatic control, R had been reduced to 1.0 and 2 σ had been reduced to 0.4 .

Manual Control



Automatic Control

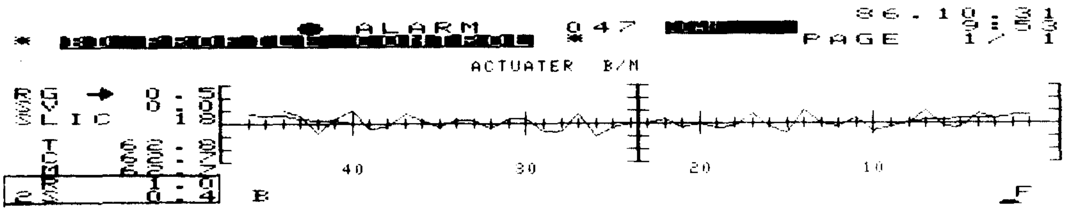
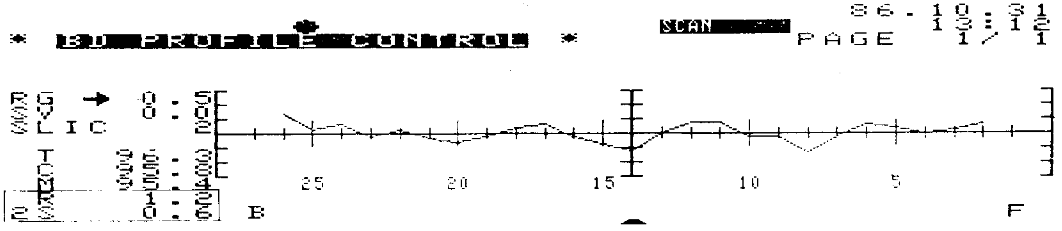


Fig. 8. Control Data for Paper Machine "A.

Manual Control



Automatic Control

Fig. 9. Control Data for Paper Machine B.

4.2 **Control Results for Paper Machine "B".** The results for paper of basis weight 102 g/m2 and sheet velocity of 460 m/min are shown in Fig. 9. Before the automatic control system was implemented, the value of R was 1.2, and the value of 2 σ was 0.6 . Two hours after starting automatic control, R had been reduced to 0.6 and 2 σ had been reduced to 0.3 .

4.3 **Summary of Results.** In the two examples above, the values of both R and 2 σ were approximately halved when automatic control was implemented; similar results have been achieved with other paper machines.

5. Conclusions.

It is nearly three years since this basis weight profile control system went into production. The algorithm has been fine-tuned, and is working very well. We feel that there will be a growing demand for such systems as the demand for high quality paper increases.

With some types of paper there are still occasional complex, difficult-to-solve problems in automatic control of the profile near the paper edges -- the problem is related to a complex mix of factors such as the flow of pulp from the head box and on the wire screen, and cannot be solved by changing the slice aperture alone.

Future work will involve solving these edge problems, and applying similar multivariable non-interference control techniques to other process control problems.

References

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(2) Shigehiko Yamamoto, "Thickness Profile Control of a Paper Machine", ISA Instrumentation Conf., Shanghai, 1983, pp. 901-908.
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