BASIS WEIGHT PROFILE FUZZY CONTROL FOR PAPER MACHINES

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ABSTRACT

We have developed a new fuzzy control method for paper machine basis weight profile.

The conventional linear control method has not yielded good results on some machines. This new control method, however, realizes long-term stability and convergence of the profile as good or better than that achieved under manual control by an operator.

1. INTRODUCTION

Basis weight (weight per square meter, in g/m^2) is one of the fundamental properties of paper, and its uniformity across the paper width is one of the most important properties of paper for printing. Failure to achieve that uniformity frequently results in waste-stuff (unsalable paper).

The function that keeps that profile uniform across the paper width is basis weight profile control. The BMSYSTEM and BM7000XL paper machine control systems have demonstrated proven effectiveness on numerous paper machines through the use a robust control algorithm which combines a multivariable decoupling mechanism called "output distribution" with a special slice smoothing mechanism. However, on one paper machine at a certain plant (hereafter called the "A" machine), due to process considerations that will be described later, we were unable to achieve continuous automatic control over long periods with this conventional algorithm. The control system dealt with here was developed by taking a different viewpoint from that of the conventional control system, by embodying the operators' manual operating methods in rules and using fuzzy logic. Automatic control with this system commenced in March 1990, and has been well received by the customer.

2. PROCESS OVERVIEW

(1) About the Paper-making Process

The paper-making process is the last phase of the paper pulp process, and control in this phase greatly affects the product quality.

The material coming from the stock preparation process (liquid with a 0.2% to 0.3% pulp concentration) is extruded onto the wires from the head box by applying a constant head pressure.

The stock loaded onto the wires is dehydrated and dried by presses and dryers, squeezed out by calenders, and wound up as paper on a reel.

In a BM system (BM7000XL) a basis weight signal is read in from a moveable sensor mounted ahead of the reel and subjected in a computer to averaging and other signal processing followed by control computations, after which the control outputs are sent to the slice actuator drive motors via an interface panel.

Let us look now in a little more detail at the procedure by which the basis weight profile is constructed.

The raw material for the paper is evened within the head box and then ejected onto the wires, at a high speed of 500 to 1000 m/min, from a 3m to 8m wide outlet called a slice lip. The shape of the basis weight profile across the width of the paper can be considered to be decided by complex process factors such as the effectiveness of the evening phase at the inlet, the warping of the slice lip, and the initial dehydrating on the wires.

3. PROFILE FREQUENCY ANALYSIS -- SAWTOOTH PROFILE

The slice lip is a one-piece metal plate with several tens of "slice bolts" attached to it with a 100 or 150 mm pitch; these are used to control the basis weight profile through control of the shape of the opening by vertical movements in steps of 1 (or 10) microns.

Figures 2 and 3 show profiles and profile frequency analyses for the "B" machine in automatic operation using the conventional robust control algorithm. Figure 2 shows the profile and its spectrum immediately before initiating control. The numbers along the power spectrum horizontal axis show the wavelengths as multiples of the slice pitch (slice bolt spacing). From this we can see that the major components are at wavelengths equal to or greater than six times the slice pitch. Next we have Figure 3, for the point where three hours have elapsed since initiating control. We can see that the power at wavelengths more than six times the slice wavelength has been greatly attenuated, and that the profile "R" (a frequently used profile management criterion, equal to the maximum value minus the minimum value for the measurement points).

On the other hand, what about on the A machine? Figure 4 shows the profile and spectrum after it has been left to operate for several hours without manipulating the slice. It can be seen that, unlike with the B machine, the major components are at wavelengths from 1.5 to 2.0 times the slice wavelength. If we look at the actual profile, hills and valleys are frequently found in the intervals between the slice bolts (a sawtooth waveform in the interval between the slice bolts). In cases such as this, profile adjustment requires quite some time for even an expert operator. Moreover, even if control was attempted with the conventional algorithm, there was no improvement in the sawtooth waveform; contrarily, as time passed the profile was seen tending to become gradually worse.

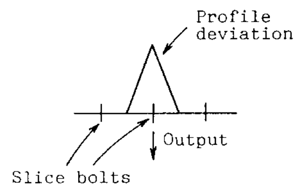
4. THE OPERATOR'S OPERATING RULES

Based on the above circumstances, development was desired of a new control method which would incorporate into the control algorithm the operating techniques of an expert operator, so that there would be no disruption even if automatic control were continued for long periods, and which would provide improvement in the sawtooth waveform to the same level achieved by a human operator. Thus we spent more than two months out in the plant with the A machine, and were able to condense the operating methods of an expert operator to the following rules.

① Main Rules

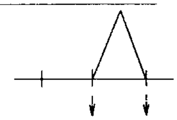
We found that even an apparently complex sawtooth waveform if analyzed to its detailed elements would be a combination of the following three elemental patterns. (For simplicity, we will consider a sawtooth waveform for which one wavelength equals twice the slice pitch.) Therefore, if we find an operating method for each of the elemental patterns, then we will be able to express the operations for any general sawtooth waveform as a combination of those methods. The following three rules were obtained for the individual elemental patterns by analyzing the operating methods of expert operators.

Elemental Pattern 1



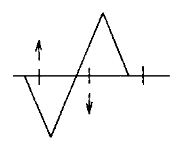
. When there is a hill or valley directly on a slice bolt, adjust only that one.
... Rule 1

Elemental Pattern 2



. When there is a hill (valley) between two slice bolts, raise (lower) both at the same time.
... Rule 2

Elemental Pattern 3

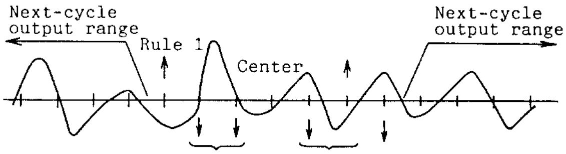


. When a hill/valley is offset one-quarter of a slice bolt spacing, move both together in opposite directions.
... Rule 3

② Global Rules

In the conventional robust control algorithm, if the profile deviation exceeds the deadband, any number of manipulated outputs are generated regardless of the slice position. However, expert operators of the A machine will not perform such actions. Rather, they try moving two or three slice bolts, wait to see the response in the basis weight profile, and then proceed to the next manipulation step, eliminating the sawtooth by superimposing a series of manipulations. Then, for the profile as a whole, the operators move the slice bolts in sequence proceeding outward from the center as if stretching out the wrinkles in the paper. This is done because there is no repeatability between the slice opening and profile, so that the raw material flow will be different depending on the sequence in which the slice is manipulated, causing the profile to differ.

Thus as a global rule the whole is divided into two zones left and right, and within each zone no more than two slice bolts at a time are manipulated in any single control period, with those to the inside having priority. Then in the next control period the slice bolts outside those manipulated in the previous period will become the object of manipulation. The outputs as a whole are composed of outputs due to the main rules stated in ①, combined according to this global rule.



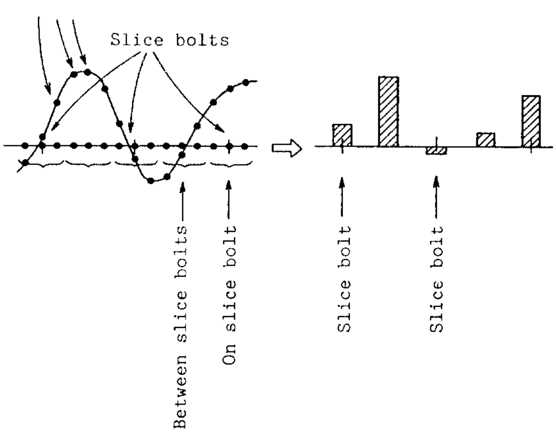
5. CONTROL ALGORITHMS

Converting the foregoing rules to an algorithm, we obtain the following.

① Half-Slice Profile

The basis weight measurement points total 360 in the width direction, and the curve formed by taking those as a continuous line is the basis weight profile. However, since it is not possible to feed back all 360 points, a certain amount of averaging is required.

As indicated above, to grasp the individual elemental patterns it has been found most effective to perform averaging directly over each slice bolt and between the slice bolts, and thus construct a profile composed of twice as many points as slice bolts. This is called the half-slice profile.



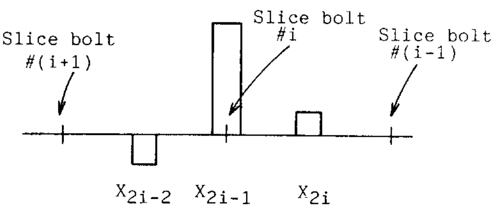
② Adaptability Computation

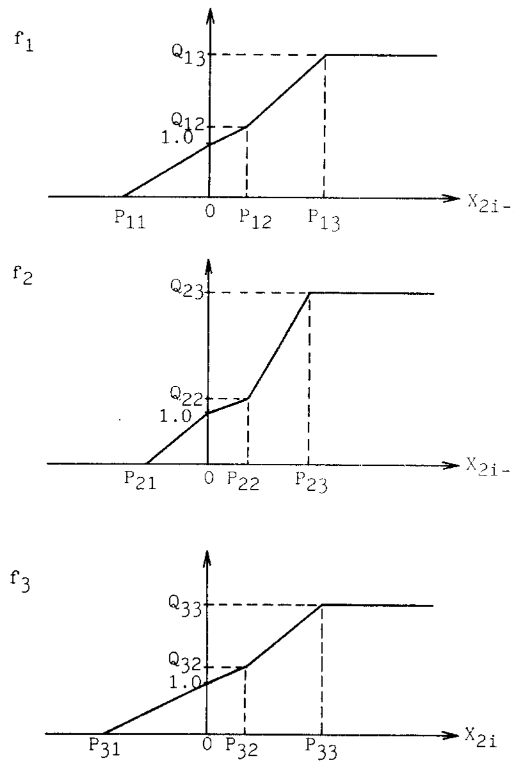
The extent to which the half-slice profile adapts to each of the three elemental patterns is computed using fuzzy logic membership functions.

For example, by rule 1, since there is a hill directly on the slice bolt, we think of this as case in which to adjust the slice down.

Rule 1 has three membership functions f1, f2 and f3, and the membership functions $f1(X_{2i-2})$, $f2(X_{2i-1})$ and $f3(X_{2i})$ are computed for the half-slice deviations X_{2i-2}, X_{2i-1} and X_{2i} around the i'th slice bolt. The degree of adaptability A1 for this case is then given by the following formula.

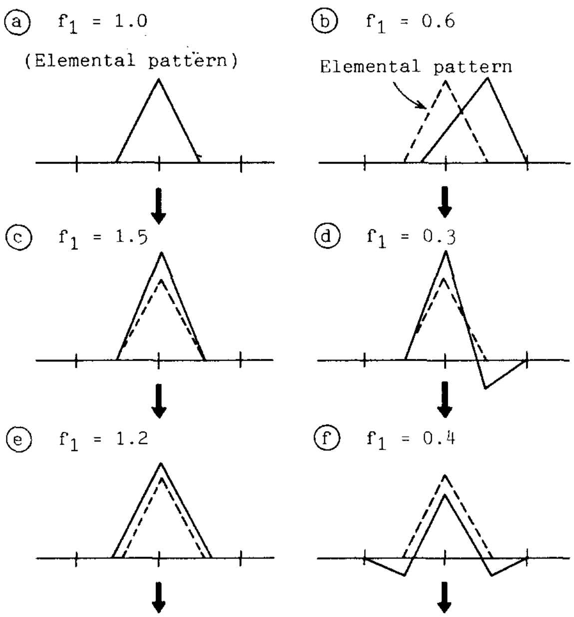
$$A1 = f1(X_{2i-2}) \times f2(X_{2i-1}) \times f3(X_{2i})$$





* Tune P_{ij}, Q_{ij}.

Looking at what the value should be for degree of adaptability A1, we have the following based on the operators' subjective judgements for various control deviation patterns.



- Although (a), (b) and (d) are the same by area computation, their degrees of adaptability are (a) > (b) > (d).
- Although (e) and (f) are off from elemental pattern (a) by the same distance, the degree of adaptability is (e) > (a) > (f).
- Although (c) is off from elemental pattern (a), its degree of adaptability is greater than that of (a).

Conversely, tuning is carried out so that the membership function degree-of-adaptability computation results yield values as shown in the figure above. As this shows, neither simple area computation nor Euclidean distance pattern matching is adequate for degree of adaptability computation, and we can see that fuzzy logic is extremely effective.

③ Output Computation

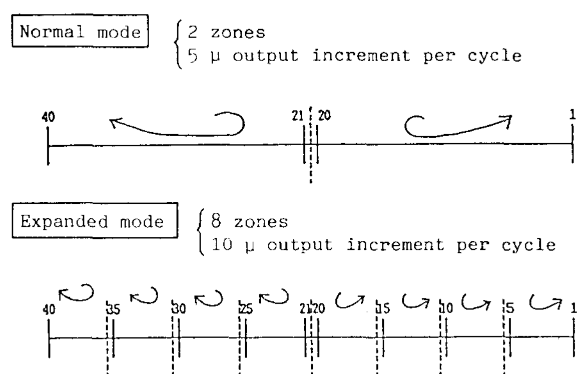
A typical half-slice profile will be in the form of a compound of elemental patterns 1 to 3. Therefore, it will be necessary to decide which of the individual rules should be applied. To do this we compute the max. value Amax after computing the adaptability degree Ai of each rule.

$$Amax = max\{Ai\}$$

If Amax is greater than a predetermined criterion value B, output is performed for the rule given by adaptability degree Amax.

④ For global rules, a switching system for two modes normal/expanded is used. In expanded mode, the overall width is divided into eight zones, and the global rule is applied in each of the zones. Since outputs can be generated for a maximum of two locations per cycle in a single zone, this means that outputs can be generated to maximum of 16 locations across the total width in a single cycle. Additionally, the output increment per cycle is made larger than in normal mode. This is done because at times such as machine start when the process is greatly disturbed, the number of output points must be increased quite a lot in order to make the profile settle quickly. Once the profile "R" (maximum value minus minimum value) decreases below a certain value, the system determines that it has entered normal status, and automatically transfers to normal mode.

Switching Between Expanded and Normal Modes



6. CONTROL RESULTS

① Normal mode sawtooth waveform improvement

Viewed in terms of half-slice profile R (maximum value minus minimum value) and 2σ (two times standard deviation), the control results are as shown in Figure 5. There was an 18% improvement in R, and a 20% improvement in 2σ.

Figure 6 shows by profile time series changes how the sawtooth waveform improves over time. We can see how the operators' operating rules are skillfully applied.

② Expanded mode settling

Looking at the changes in R and 2σ at machine start time when using expanded control, after 1 hr 20 min there has been a 62% improvement in R, and the saleable product level has been reached. With conventional manual adjustments this normally required about four to eight hours. Figure 8 shows a 60-point profile at machine start and 1 hr 30 min later.

7. FUTURE DIRECTION

Extremely delicate tuning was required for the membership functions used to compute the main rule adaptability values. It will now be necessary to test this control method on other machines and establish a system for membership function tuning.

References

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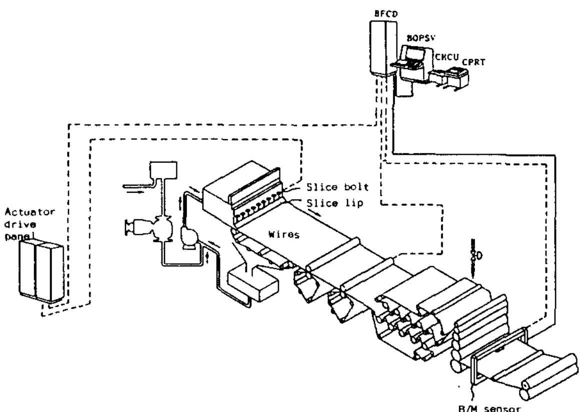

Figure 1 Paper Machine and B/M System

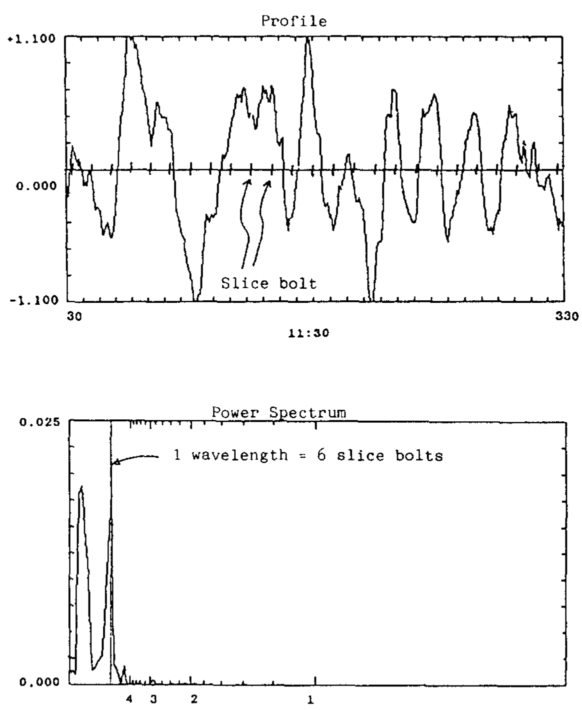

Figure 2 "B" Machine Profile and Frequency Analysis
(Just Before Initiating Control)

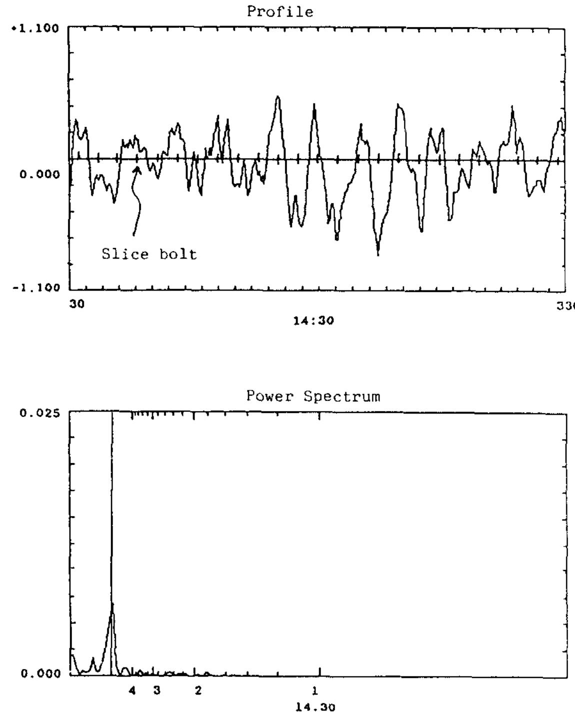

Figure 3 "B" Machine Profile and Frequency Analysis
(Three Hours After Initiating Control)

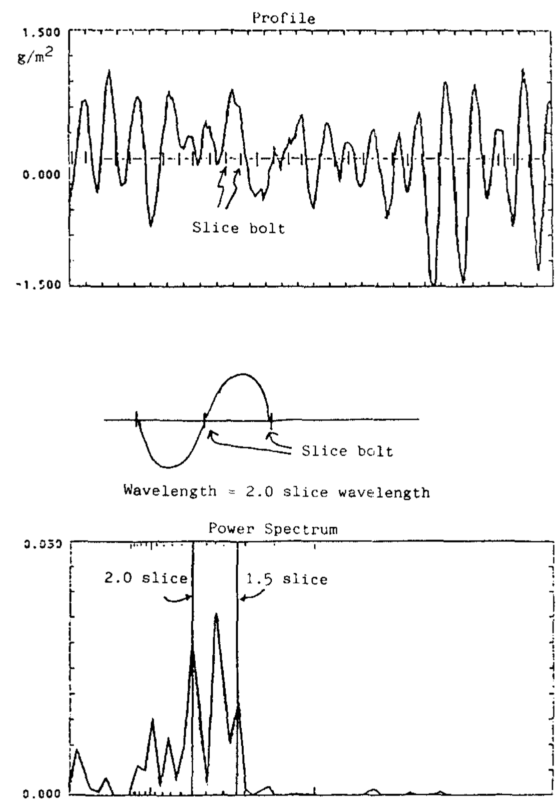

Figure 4 "A" Machine Profile and Frequency Analysis
(With No Slice Manipulation)

Basis weight = 62.8 g/m^2
Machine speed = 94.4 m/min

	At control start	After 14 hours	Improvement rate
R	1.77	1.45	18%
2δ	0.76	0.61	20%

Figure 5 R and 2δ for Half-Slice Profile in Normal Mode

Basis weight = 63.5 g/m^2
Machine speed = 852 m/min

	Just after machine start	After 1 hour 20 min	After 2 hour 10 min
R	3.83	1.46	1.23
Improvement rate		62%	68%
2δ	1.40	0.66	0.63
Improvement rate		53%	55%

Figure 7 R and 2δ for Half-Slice Profile at Machine Start

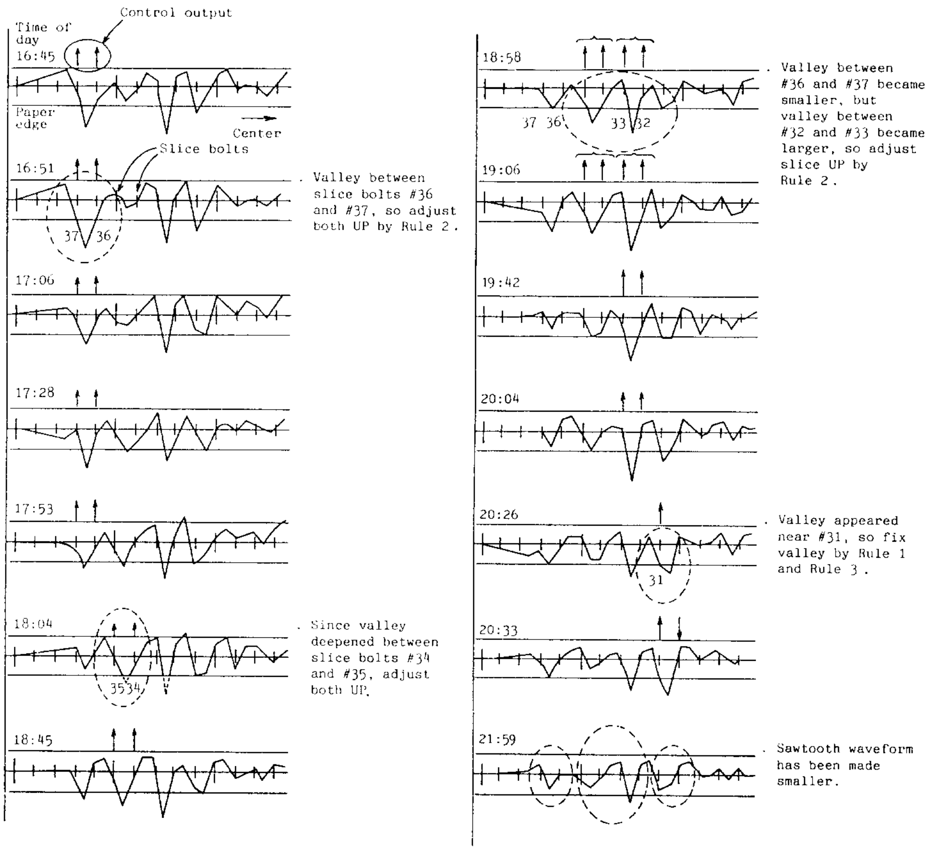

Figure 6 Improvement in Sawtooth Waveform

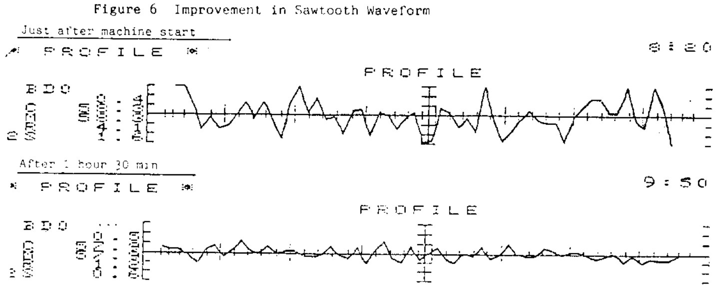

Figure 8 Profile Settling in Expanded Mode