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SUB-OPTIMUM GRADE CHANGE PROCEDURES

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Synopsis A numerical optimisation technique has been used to show, computationally, that simple control trajectories can give considerably reduced grade change times. The models studied include one-pump and two-pump systems with and without changing wire rejection factors. Consideration has been given to some simple constraints.

Introduction

THE problem of manually controlling production changes on a Fourdrinier papermachine are numerous. With the advent of computer control, more sophisticated grade changes are possible.

Computers are now used for grade change control[1–4] and Sullivan & Schoeffler have undertaken a theoretical study of the problem.[5] No single policy has been generally adopted on the type of trajectory for this control.

This study demonstrates, computationally, the possible benefits of using simple control trajectories to effect grade changes. A *grade change* in the context of this paper refers to the operation of making a change from one particular paper substance to another, possibly at a different machine speed and different flow box consistency.

Mathematical models

THE particular type of wet end studied is shown in Fig. 1. A model of this type of machine can be used to study basic one-pump and two-pump systems, the former being the special case when flow A is zero. The mathematical model derived relates the system variables to the control variables. The control variables are the slice opening, the machine speed and the thick stock flow; the system variables are the oven-dry basis weight and the web consistency (both ex the suction box section) and the flow box consistency.

The assumptions of the model and the calculations involved at each time

Under the chairmanship of P. E. Wrist

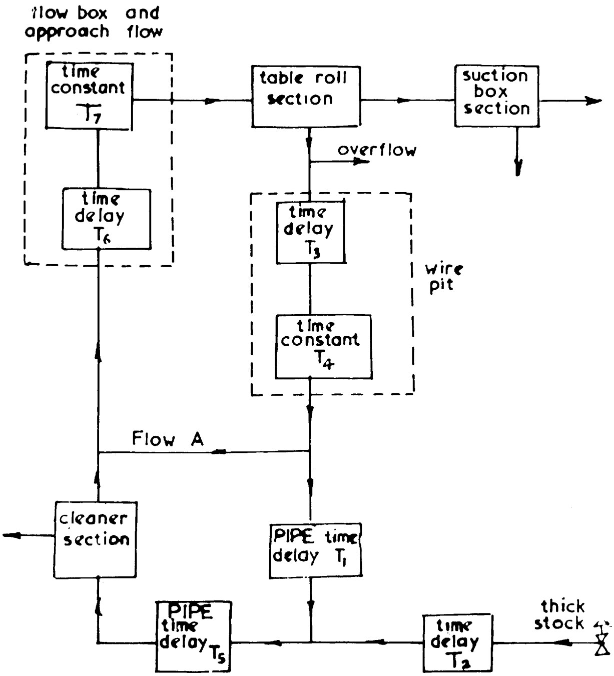

Fig. 1—Wet end system studied

interval for the digital simulation are included in the appendix. A calculation interval of 4 s was used after preliminary investigations indicated that this gave a good representation of the continuous model while keeping the total computation time to an acceptable level. The calculation procedure includes three basic steps at each calculation interval—

1. Choice of (new) values of control variables.
2. Determination of flows around the system by flow balances.
3. Determination of stock consistencies around the system by consideration of the time delays and first order lags.

Constraints of the process

THE constraints consist of both steady state desired values of basis weight, speed and flow box consistency and dynamic constraints dependent upon the particular machine.

Avoidance of web breaks is obviously very important, but it appears to be impossible to put reliable weightings on the relevant factors. In severe cases, it may be necessary to limit both steady state and dynamic states by the condition that the web consistency should remain constant. This restriction would make grade change trajectories very complicated.[5] In this study, the only restriction directly concerned with web breaks has been a minimum web consistency ex the suction box.

In one computer installation,[1] grade changes are controlled within the limit of a specified rate of change of basis weight that appeared to be limiting from previous grade changes made manually. It would appear that this form of grade constraint leads to a safe, if somewhat slower grade change than may otherwise be possible.

Types of trajectory studied

FIG. 2 shows the types of trajectory studied, together with the parameters (X values) describing them. Trajectory d was rejected after preliminary investigations indicated that it gave no improvement over trajectory type a.

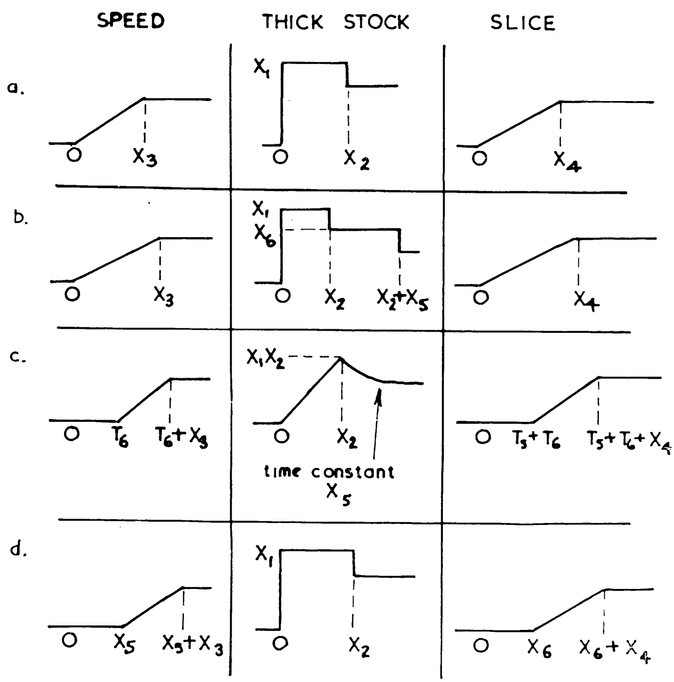

Fig. 2—Trajectory types (control variable plotted against time)

Trajectories *a* and *b* have been used in the simulation of sub-optimum grade changes and trajectory *c* has been used to study trajectories of the type previously referred to.[1]

Sub-optimum control

THE parameters of trajectories *a* and *b* have been varied in a search for a trajectory that minimises a performance index dependent upon the particular constraints assumed. When there is no constraint, the performance index is the time to settle within ± 1 per cent of the desired basis weight. When a constraint is applied to web consistency, the above performance index is modified by the addition of a penalty function proportional to the time integral of 'below limit' web consistency.

A performance index satisfactory for studying specified maximum rate basis weight grade changes, using trajectory type *c*, is the sum of the squares of the differences between actual and desired basis weights at each calculation interval.

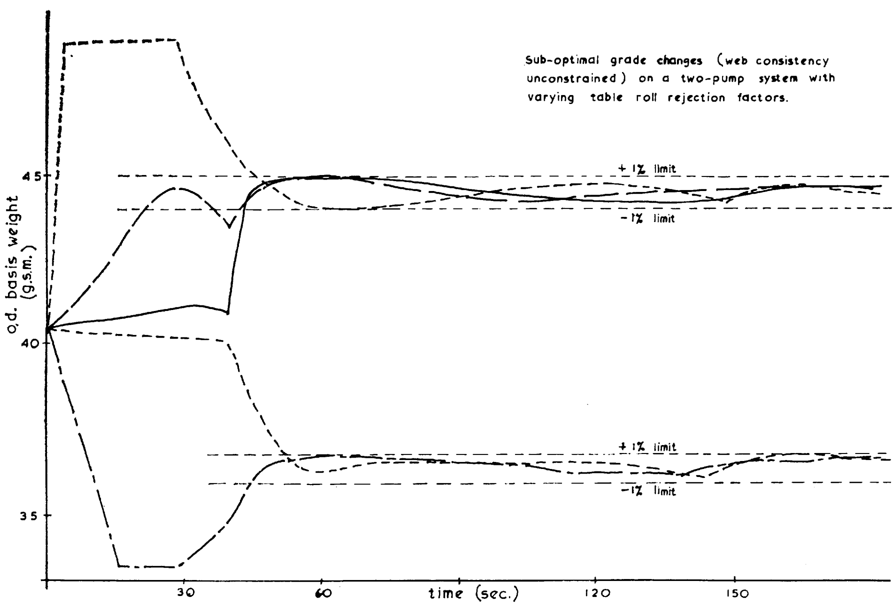

Fig. 3—Sub-optimum grade changes (web consistency unconstrained) on a two-pump system with constant table roll rejection factors

In searching for a minimum performance index, the numerical search technique of Nelder & Mead[6] has been used. This technique is based upon the simplex method, but has the added feature that the search simplex is expanded or contracted, depending on the local 'geometry' of the function space. Its application is highly non-linear problems is recommended by Box[7] for cases in which up to six search variables (parameters) are used. Each optimisation consists of approximately 250 search iterations, each extending over some 80 calculation intervals and requires approximately 30 million basic computer operations.

Results and discussion

SOME typical results are presented in Fig. 3–8 to show basis weight trajectories resulting from sub-optimum controls. The associated Tables 1–6 give details of the machine constants, initial conditions and particular grade changes. Settling times are shown, together with the type of control trajectory and, for comparison, settling times are also presented for control variables following single step trajectories to their final steady state values.

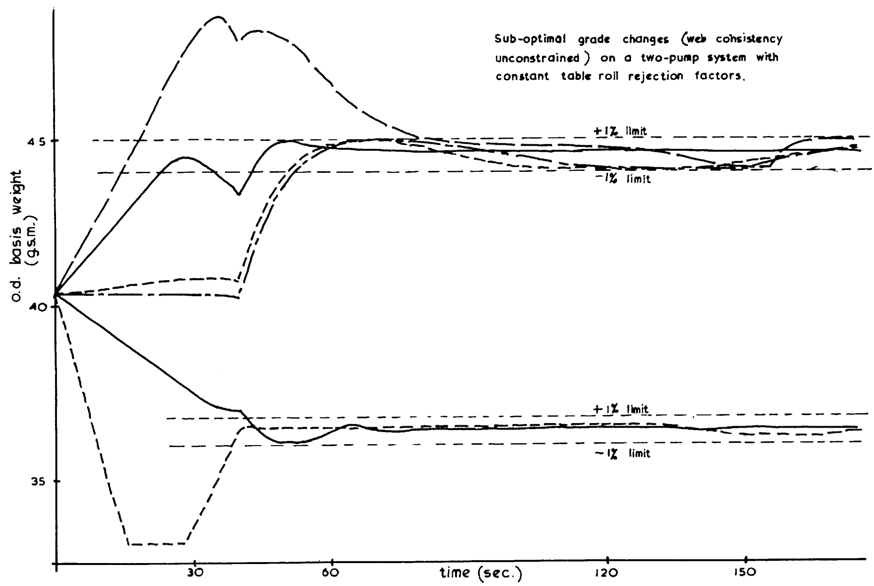

Fig. 4—Sub-optimum grade changes (web consistency unconstrained) on a two-pump system with varying table roll rejection factors

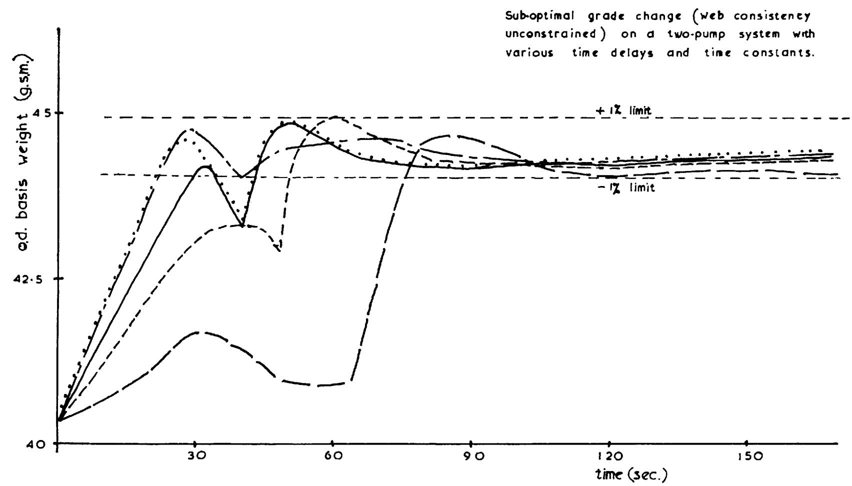

Fig. 5—Sub-optimum grade changes (web consistency unconstrained) with various time delays and time constants

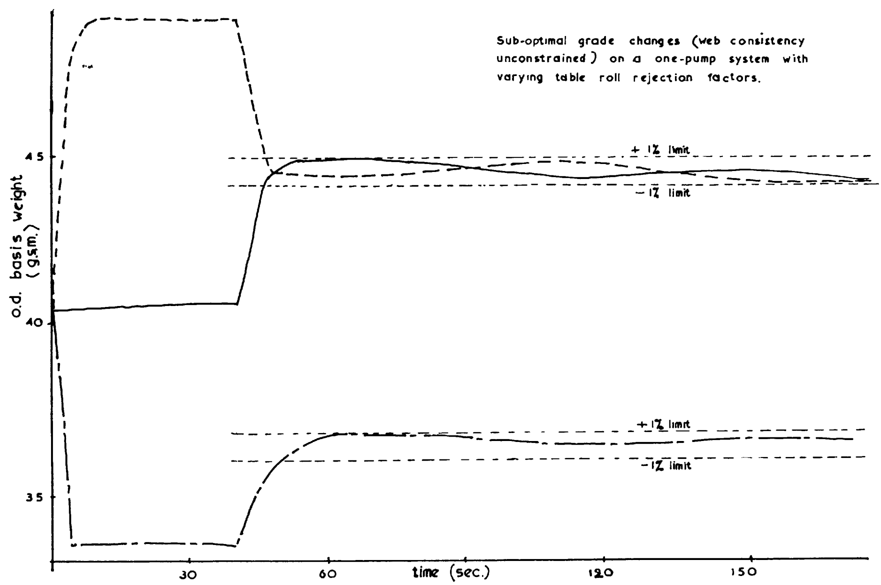

Fig. 6—Sub-optimum grade changes (web consistency unconstrained) on a one-pump system with varying table roll rejection factors

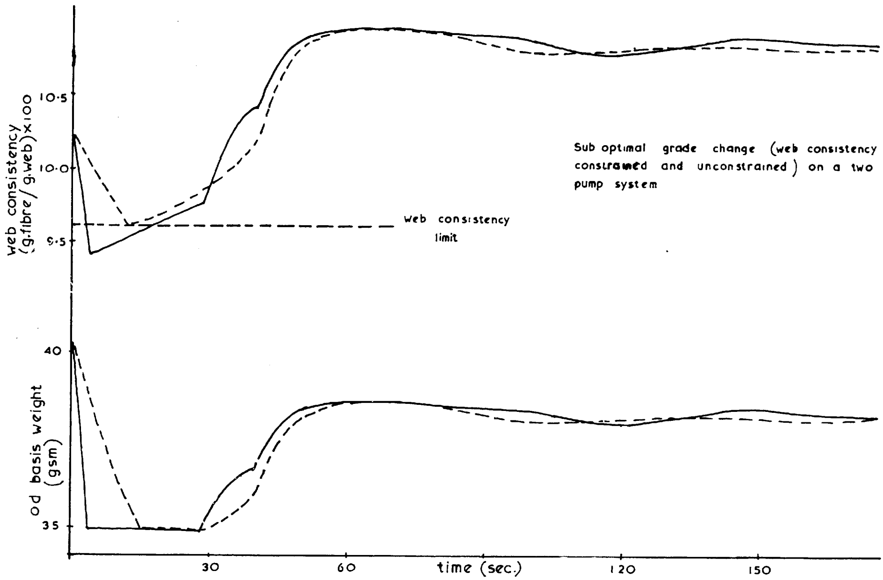

Fig. 7—Sub-optimum grade change (web consistency constrained and unconstrained) on a two-pump system

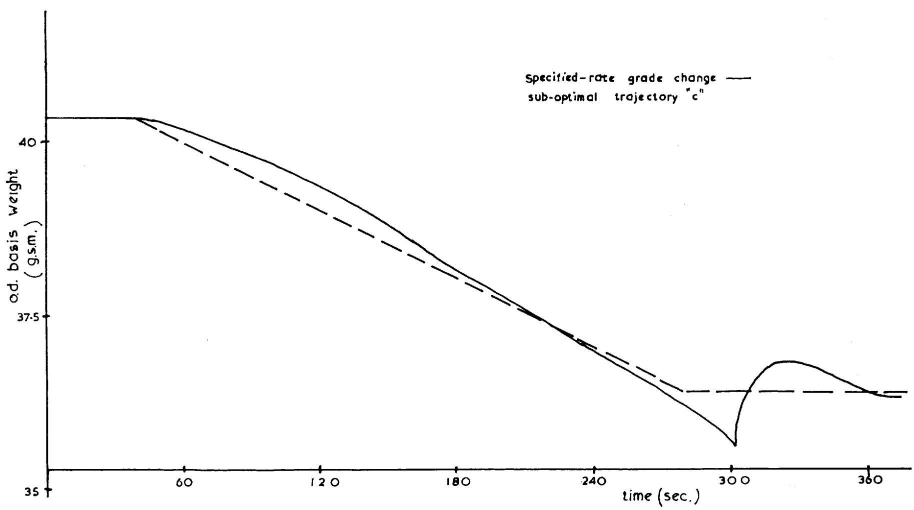

Fig. 8—Specified rate grade change—sub-optimum trajectory *c*

TABLE 1

Sub-optimum grade changes (web consistency unconstrained) on a two-pump system with constant table roll rejection factors (see Fig. 3)

Details
Two-pump system
Table roll rejection factors—constant

Initial conditions—

Machine speed	366 m/min
Basic weight	40·3 g/m^2
Flow box consistency	0·68 per cent

Time delays and time constants—

$T_1 = 12$ s	$T_2 = 16$ s	$T_3 = 44$ s
$T_4 = 16$ s	$T_5 = 12$ s	$T_6 = 28$ s
$T_7 = 8$ s		

Grade changes —unconstrained

Code	———	- - - -	— — —	— — —	———	- - - -
Changes— Basis weight, per cent	+10	+10	+10	+10	−10	−10
Speed, per cent	+10	+10	+10	+10	−10	−10
Flow box consistency, per cent	0	+5	+10	−10	0	+10
Trajectory type	*a*	*a*	*a*	*a*	*a*	*a*
Settling time for sub-optimum trajectory, s	44	52	52	84	40	40
Settling time for step trajectory, s	56	176	256	240	160	232

TABLE 2

Sub-optimum grade changes (web consistency unconstrained) on a two-pump system with varying table roll rejection factors (see Fig. 4)

Details
Two-pump system
Table roll rejection factors—
Solids—constant
Volume—affected by (*1*) machine speed —0·2 per cent/per cent
(*2*) flow box consistency —0·1 per cent/per cent

Initial conditions—

Machine speed	366 m/min
Basic weight	40·3 g/m^2
Flow box consistency	0·68 per cent

Time delays and time constants—

$T_1 = 12$ s	$T_2 = 16$ s	$T_3 = 44$ s
$T_4 = 16$ s	$T_5 = 12$ s	$T_6 = 28$ s
$T_7 = 8$ s		

TABLE 2—*continued*

Grade changes—unconstrained

Code	— — —	———	- - - - -	-- - - - -	— — —
Changes— Basis weight, per cent	+10	+10	+10	−10	−10
Speed, per cent	+10	+10	−10	+10	+10
Flow box consistency, per cent	0	+10	−10	−10	+10
Trajectory type	*a*	*a*	*a*	*a*	*a*
Settling time for sub-optimum trajectory, s	44	44	44	52	44
Settling time for step trajectory, s	152	288	280	272	276

TABLE 3

Sub-optimum grade changes for a particular grade change on a two-pump system with various time constants and time delays (see Fig. 5)

Details
Two-pump system
Table roll rejection factors—
Solids—constant
Volume—affected by (*1*) machine speed −0·2 per cent/per cent
(*2*) flow box consistency −0·1 per cent/per cent

Initial conditions—
Machine speed 366 m/min
Basic weight 40·3 g/m²
Flow box consistency 0·68 per cent

Time delays and time constants, s

Code	T_1	T_2	T_3	T_4	T_5	T_6	T_7	*Settling time for sub-optimum trajectory, s*
———	12	16	16	36	12	28	8	44
- - - -	12	16	16	36	20	28	8	52
— — —	12	16	16	36	40	28	8	76
— - —	12	16	16	36	12	28	20	20
· · · ·	12	16	44	16	12	28	8	44

Grade changes—unconstrained
Basis weight +10 per cent
Machine speed +10 per cent
Flow box consistency 0 per cent

TABLE 4

Sub-optimum grade changes (web consistency unconstrained) on a one-pump system with varying table roll rejection factors (see Fig. 6)

Details
One-pump system

Table roll rejection factors—
Solids—constant
Volume—affected by (*1*) machine speed −0·2 per cent/per cent
(*2*) flow box consistency −0·1 per cent/per cent

Initial conditions—
Machine speed 366 m/min
Basic weight 40·3 g/m²
Flow box consistency 0·68 per cent

Time delays and time constants—
$T_1 = 12$ s $T_2 = 16$ s $T_3 = 16$ s
$T_4 = 44$ s $T_5 = 12$ s $T_6 = 28$ s
$T_7 = 8$ s

Grade changes—unconstrained

Code	———	- - -	— — —
Changes— Basis weight, per cent	+10	+10	−10
Speed, per cent	+10	−10	+10
Flow box consistency, per cent	+10	−10	+10
Trajectory type	*a*	*a*	*a*
Settling time for sub-optimum trajectory, s	48	48	48
Settling time for step trajectory, s	296	352	292

TABLE 5

Sub-optimum grade change (constrained and unconstrained) on a two-pump system (see Fig. 7)

Details
Two-pump system
Table roll rejection factors—constant

Initial conditions—
Machine speed 366 m/min
Basis weight 40·3 g/m²
Flow box consistency 0·68 per cent

Time delays and time constants—
$T_1 = 12$ s $T_2 = 16$ s $T_3 = 44$ s
$T_4 = 16$ s $T_5 = 12$ s $T_6 = 28$ s
$T_7 = 8$ s

Grade changes
Basic weight −5 per cent
Speed +10 per cent
Flow box consistency +10 per cent
Trajectory type *a*

TABLE 5—*continued*

Code	———	- - - - - - -
Limitation	unconstrained	constrained
Web consistency minimum	does not apply	0·94 of initial consistency (that is, 9·62 g fibre/100 g web)
Settling time for sub-optimum trajectory, s	44	48

TABLE 6

Specified rate grade change—sub-optimum trajectory *c* (see Fig. 8)

Details

Two-pump system

Initial conditions—		
Machine speed	366 m/min	
Basic weight	40·3 g/m^2	
Flow box consistency	0·68 per cent	
Table roll rejection factors —		
Solids—constants		
Volume—affected by (*1*) machine speed		−0·2 per cent/per cent
(*2*) Flow box consistency		−0·1 per cent/per cent
Time delays and time constants—		
$T_1 = 12$ s	$T_2 = 16$ s	$T_3 - 44$ s
$T_4 = 16$ s	$T_5 = 12$ s	$T_6 = 28$ s
$T_7 = 8$ s		
Grade changes details		
Basic weight	−10 per cent	
Machine speed	+10 per cent	
Flow box consistency	−10 per cent	

Code	
- - -	Desired (best) trajectory
———	Sub-optimum trajectory

The numerical values of the time delays, time constants and initial conditions were chosen to be representative of actual practice. They are in line with those used by Smethurst.[9]

It is evident from the results obtained that these simple trajectories can give quite substantial reductions in grade change times when compared with those obtained by using step trajectories for the control variables. In most cases, it is possible to reduce the grade change time to a time only slightly greater than the dominant time delay from the primary dilution point to the wire, that is, T_5 plus T_6.

Fig. 3–5 indicate an apparent simple classification of grade changes according to whether the basis weight does or does not overshoot its final desired value. The former case is associated with a change in flow box consistency in the opposite direction to the basis weight change. The latter is associated with either no flow box consistency change or with a change of flow box consistency in the same direction as the basis weight change.

The sub-optimum control variable trajectories can also be classified. From the results obtained for constant and changing rejection factors and for the various time constants and delays, on both one-pump and two-pump systems, it appears that the following general rules are applicable.

1. Changes in which the fractional flow box consistency change is the same in magnitude and direction to the fractional basis weight change

This is an important class, because no significant movement of the slice is involved and the control trajectories should therefore be applicable to machines without slice control.

Direction of speed change	*Trajectory type required*	*Rate of speed change*	*Thick stock trajectory*
Same as basis weight	*a*	Slow $X_3 \simeq 4(T_5 + T_6)$	Slight overshoot ($X_2 \simeq T_6$)
Opposite to basis weight	*b*	Fast as possible ($X_3 \to 0$)	Temporary change in the direction of the basis weight change ($X_2 + X_5 \simeq 4T_6$)

2. Changes in which the flow box consistency is to remain the same

Direction of speed change	*Trajectory type required*	*Rate of speed change*	*Rate of slice change*	*Thick stock trajectory*
Same as basis weight	*a*	Quick ($X_3 \simeq T_5 + T_6$)	Quick ($X_4 \simeq T_5 + T_6$)	Step ($X_2 \to 0$)
Opposite to basis weight	*a*	Fast as possible ($X_3 \to 0$)	Fast as possible ($X_4 \to 0$)	Variable

3. Changes in which the flow box consistency change is in the opposite direction to the basis weight change

Direction of speed change	*Trajectory type required*	*Rate of speed change*	*Rate of slice change*	*Thick stock trajectory*
Same as basis weight	*a*	Fas as possible ($X_3 \to 0$)	Fast as possible ($X_4 \to 0$)	Undershoot $X_2 \simeq 4T_6$)
Opposite to basis weight	*a*	Slow ($X_3 \simeq 4(T_5 + T_6)$)	Fast as possible ($X_4 \to 0$)	Variable

There appear to be no general rules for carrying out grade changes when the fractional change of flow box consistency is the same in direction, but not in magnitude to the fractional change in basis weight. Trajectory type *a* is adequate for this type of grade change.

The results for case *2* (also see Tables 1 and 2) show that grade changes when the desired flow box consistency change is zero are the simplest to carry out—there is very little scope for improvement over step control trajectories.

Web consistency restriction

IN CONSIDERING the possible restricting effect of a minimum allowable web consistency ex the suction box, it is important to use an accurate representation of the action of the suction box. In the simulation, it has been assumed that the volume rejection factor of the suction box section is a linear function of the volumetric flow rate to it; more specificially, it has been assumed that a 1 per cent increase in flow rate gives a 1·4 per cent increase in the volume rejection factor. This implies that drainage is improved through the better sealing of the wire over the boxes obtained by having more stock over them. The value of 1·4 per cent was chosen as a reasonable value on the basis of steady state data obtained by Brauns & Oskarsson,[8] who carried out experiments on a pilot-plant machine at speeds approaching 400 m/min.

Under these particular conditions, the results obtained so far do not indicate any severe restrictions, owing to the application of a web consistency constraint. In some cases, the sub-optimum grade change time is increased if the web consistency is not allowed to drop below 0·92 of the lowest steady state value. (Fig. 3 E shows an example in which the allowable limit is 0·94 of the initial web consistency and no appreciable increase of the grade change time results.)

Specified maximum-rate basis weight grade changes

FIG. 7 shows the results obtained by 'optimum' selection of the parameters of trajectory type *c*. A reasonable approximation to the best possible basis weight trajectory (within the limits of the constraint) is obtained.[1]

Conclusions

THE application of a numerical optimisation technique to the search for sub-optimum grade change procedures on a simulated papermachine has been shown to be successful.

The results indicate that simple control trajectories are sufficient to obtain considerable reduction of the settling time involved in a grade change. This conclusion is shown to hold for both one-pump and two-pump systems with two different wire drainage effects.

The imposition of a minimum web consistency constraint does not markedly affect the above conclusions under the particular conditions assumed to describe the drainage effect of the table rolls and the suction box section.

Some general rules governing the sub-optimum procedures are evident from consideration of the results.

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Appendix—Assumptions in the mathematical model

1. Level control in the flow box and thin stock flow rate control are such that the efflux ratio can be maintained constant. (This eliminates the possibility of an independent thin stock flow control variable.)

2. Volume and solids rejection factors at the table rolls are either constant or linear functions of flow box consistency and machine speed.

3. Volume rejection factor of the suction box section is a linear function of the volumetric flow rate to the suction box section.[8]

4. Pipes can be characterised by constant time delays in transmitting stock consistencies.

5. Time constants of perfectly mixed tanks remain constant.

6. Mixing characteristics of both the flow box and the wire pit can be described by a combination of a time delay and a perfectly mixed tank.

7. Consistency of the suction box rejects remains constant.[8]

8. Flow rate to the cleaning section is constant in the two-pump system.

9. Volume and solids rejection factors of the cleaning section are constant.

10. There is zero time delay at the wire.

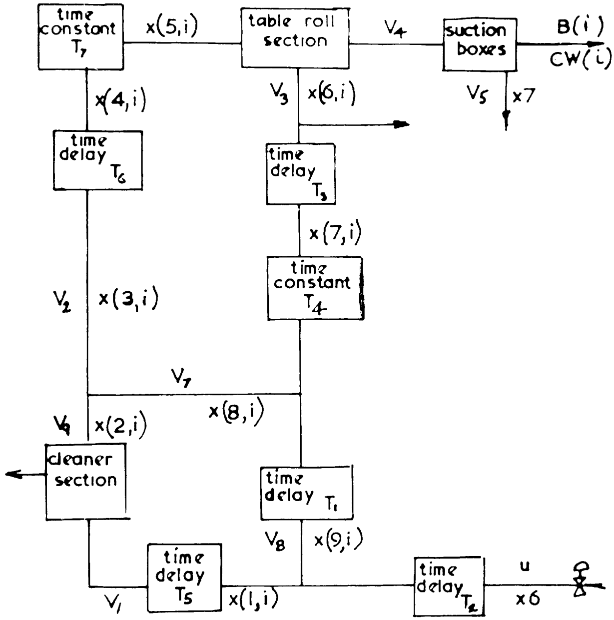

Fig. 9—Terminology for simulation calculation of interval *i*

Simulation—calculations after time interval number i

Terminology (see also Fig. 9)

Volume rejection factors	
Cleaner section	$k1$
Table roll section	$k3$
initially	$c3$
speed effect	$c5$
flow box consistency effect	$c6$
Suction box section	SBR
effect of flow	$C10$
Solids rejection factors	
Cleaner section	$k2$
Table roll section	$k4$
initially	$c4$
speed effect	$c7$
flow box consistency effect	$c8$
Basis weight after time interval *i*	$B(i)$
Web consistency ex the suction box section after time interval *i*	$CW(i)$

Slice opening	h
Machine speed	v
Thick stock flow rate	u
Efflux ratio	e
Flow box jet constant	FBK
Deckle	w

Primed conditions denote initial conditions
Volumetric flow rates denoted by V values
Stock consistencies denoted by x values

Calculations

1. Select control variables as functions of trajectory parameters (see Fig. 2)

$$u = f1(X \text{ values})$$
$$h = f2(X \text{ values})$$
$$v = f3(X \text{ values})$$

2. Calculate flows

$$V_2 = FBK*e*w*h*v$$

Calculate $x(4,i)$, $x(5,i)$ so that $k3$ can be found

$$x(4,i) = x(3,i-T_6)$$
$$x(5,i) = (x(4,i)+T_7*x(5,i-1))/(1+T_7)$$
$$k_3 = c3+c5*(v-v')/v'+c6*(x(5,i)-x5')/x5'$$
$$V_4 = (1-k3)*V_2$$
$$V_7 = V_2-V_9$$
$$V_8 = V_1-u$$
$$V_9 = (1-k1)*V_1$$
$$V_5 = V_4*SBR*(1+C10*(V_4-V_4')/V_4')$$

3. Calculate stock consistencies, basis weight and web consistency

$$x(9,i) = x(8,i-T_1)$$
$$x(7,i) = x(6,i-T_3)$$
$$x(8,i) = (x(7,i)+T_4*x(8,i-1))/(1+T_4)$$
$$x(2,i) = (1-k2)*x(1,i-T_5)/(1-k1)$$
$$x(1,i) = (V_8*x(9,i)+u*x6)/V_1$$
$$x(3,i) = (V_7*x(8,i)+V_9*x(2,i))/V_2$$
$$k4 = C4+C7*(v-v')/v'+C8*(x(5,i)-x5')/x5'$$
$$x(6,i) = k4*x(5,i)/k3$$
$$B(i) = (V_2*x(5,i)-V_3*x(6,i)-V_5*x7)/(v*w)$$
$$CW(i) = B(i)*v*w/(V_4-V_5)$$

Transcription of Discussion

Discussion

Dr I. D. McFarlane Are not our basis weight and other control strategies likely to become much simpler when we have better instruments for on-line measurement? For instance, there is no fundamental reason not to measure oven-dry basis weight profiles at the wet end instantaneously with electronic instead of mechanical scanning.

Mr R. E. Johnston Since my paper was concerned with feedforward control, feedback from any instrument will make no difference. I hope I made it clear that we were looking for simple trajectories.

Mr E. Justus I would like to ask about design for control or lack of need for control, perhaps. First of all, I agree with Dr McFarlane. One question to be considered in the design of head box control is whether we are trying to control a process or trying to eliminate noise—hydraulic noise—in the system. We should therefore design a flow system and the rest of the system to eliminate what are really noise problems so that we can then consider the basic variables of the system. It is most important to rule out noise, just as in audio amplifiers.

The Chairman Lest there be any confusion, the noise referred to was random flow variations that are uncontrolled rather than any audible sound.

Mr G. Gavelin Referring to an earlier question by the Chairman, I think there are two parameters we should definitely take into account in head box control—the volume of the air cushion and the area of the liquid surface. The effect of these two variables on head box control has been studied quite extensively at the Swedish Institute and the results have recently been published (in Swedish). I hope they will be made available to you later on.

The Chairman This is an important point. Control systems become effective only when noise has been reduced to a reasonably low level, otherwise any improvement will be lost in the uncontrollable variations that persist.

Mr J. S. Harris Dr Sanborn and Dr Brewster mentioned the problems associated with process identification—finding the value of constants for empirical equations. For dynamic studies, it is unnecessary to carry out changes in big machine equations to find these constants. Tracer studies at the wet end and sampling down the machine are effective methods of process identification.

Mr J. A. Bennett With regard to Mr Johnston's paper, the original white-water time constant at Grove Mill was of the order of 20 min. This was reduced to 3 min before computer control was applied.

Secondly, I am indebted to Mr Hoath this morning for highlighting one of the most important aspects of computer control. Our work on computer control has taught us to question accepted papermaking practices and this has led to a very substantial reduction in the complexity—hence, high capital cost—of our papermaking process.