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HEAD BOX CONTROL

H. H. CHAO, Development Engineer and I. B. SANBORN, Process Control Manager, Consolidated Papers Incorporated, Wisconsin Rapids, U.S.A.

Synopsis Head box control requirements have been reviewed and the equipment required to achieve control has been discussed briefly. In addition, methods that have been used to model the head box successfully are described and discussed from both an analytic and practical point of view. Finally, six head box control schemes varying in complexity from a simple analog level control to a complex decoupled 3×3 controller (controlling head box total head, liquid level and flow from the box) are described and fully discussed. The paper is closed by a brief discussion of work that ought to be done in the relatively near future.

Introduction

THE head box is of central importance to the papermaker, for with it he generates the thin jet of stock subsequently deposited on the Fourdrinier wire and formed into paper. In the past, this operation has required considerable papermaking art, but engineers have recently made significant progress in systemising the means by which head boxes are operated and controlled. The result has been not only to make head boxes easier to operate, but to increase the efficiency and accuracy with which they can be run.

Head box requirements

THOUGHTFUL consideration indicates that the optimum control system for an air-loaded head box should be able to meet six criteria—

1. A constant liquid level must be maintained in the box for practical reasons.
2. The total head within the box must be controlled to close tolerances to ensure that a constant difference (drag) between wire speed and jet velocity is maintained, despite changes in wire speed.
3. The flow through the box must be controlled to allow adjustments for changes in drainage, retention, formation and the like.
4. A constant jet escape angle (as defined in Fig. 9) should be maintained to achieve delivery of stock to the Fourdrinier machine in a controlled manner.

Under the chairmanship of P. E. Wrist

5. The mass flow rate of fibre across the head box slice must be held constant to ensure a flat basis weight profile in the finished paper.
6. Turbulence within the head box must be controlled closely to ensure that stock of a reproducible flock size is delivered to the slice and formed into a sheet showing good formation as well as stable strength and optical properties.

At present, it is practicable to meet only the first three of the above criteria on a closed loop basis. The three most convenient and economic manipulated variables to accomplish such control are air valves stem position, water valve stem position and slice opening. Unfortunately, the adjustment of any one of these variables causes a change in all three controlled variables (liquid level, total head and liquid flow); hence, the trick is to know how and when to adjust the valves and slice. This problem will be discussed in quite some detail later.

Control of escape angle, basis weight profile and jet flock size, though theoretically possible, is difficult on a practical basis for several reasons. First, in the case of escape angle and jet flock size, there is no good means of measuring the variable to be controlled. Second, there is not enough known about the effect of convenient manipulated variables on these controlled variables. Third, very little control can be exercised over the degree of activity on a Fourdrinier wire; hence, it is very possible that the beneficial effects of proper head box operation can be completely masked by unfortunate conditions on the wire. Lastly, there is only very limited evidence about how profound an effect the last three variables have on final sheet properties (perhaps because of variations in wire activity); and it is difficult to justify work in this area on a strictly economic basis.

Such difficulties should not be unduly discouraging, however, for until recently the benefits of total head and flow control were not generally recognised. Now, anyone having such controls will attest to their practical and economic worth. As a result, some hypothesising and discussion on how closed loop control of escape angle, basis weight profile and slice flock size can be achieved will be included at the end of the paper.

The head box as a system

THE physical limitation of a system are invariably the factors that determine its controllability. Hence, system controllability is affected not only by shortcoming in the mechanical design of the head box, but also by deficiencies in the equipment used to sense and adjust controlled and manipulated variables. Such drawbacks are best appreciated by studying Fig. 1, a schematic sketch of a typical, air-loaded head box system designed to operate in the 1 000–1 500 ft/min speed range. No controllers are included in the sketch to simplify matters and concentrate attention on process flows, manipulated and controlled variables.

Two flows are of interest in the system—

1. The flow of stock through the system and out the slice.
2. The flow of air to and from the head box air pad.

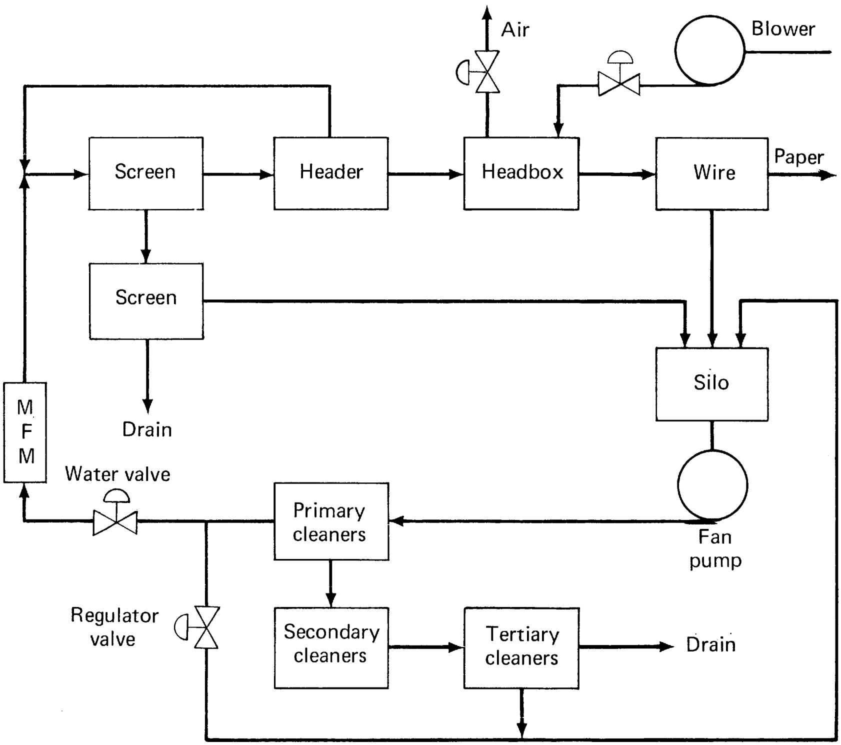


Fig. 1—Wet end system

Stock flow originates at the fan pump (a constant speed centrifugal pump), the prime mover for the entire whitewater system. From there, is passes to a bank of primary centrifugal cleaners, where approximately 80 per cent of the flow (3 500–4 500 gal/min at 0·5–0·8 per cent consistencies) is accepted and sent on through the system. Rejects are recirculated to the silo (by way of the secondary and tertiary cleaners depicted in Fig. 1) and from there to the fan pump again. On the exit side of the cleaners, the accepts stream encounters a pressure regulating valve, which serves to maintain constant pressure on the upstream side of the systems water valve or stream flow valve by recirculating part of the accepts back to the silo. The function of the water valve is to control the entire flow rate of stock in the whitewater system. In addition, it is one of the manipulated variables used by the head box control system.

Surprising as it seems, in at least one instance, this manipulated variable is a conventional 90° butterfly valve (without the benefit of a 'fishtail') equipped with a pneumatic stem positioner controlled by an electrically driven precision pressure regulator. Initially, it was felt that a small by-pass valve with good control characteristics would be required to achieve the accuracy of adjustment demanded by the head box control system, but subsequent practical experience proved this not to be the case and it has been found that a simple digital controller capable of gain adjustment when load changes require it is sufficient for the purpose. Feedback of valve stem position or pressure is possible, but not used, because of a lack of accuracy. Instead, a difference type algorithm is used in the digital controller, doing away with the need for a feedback signal from the manipulated variable.

Immediately after the water valve is located a 14 in magnetic flow meter used to measure the total flow to the head box. As previously mentioned, liquid flow to the head box is a controlled variable and, in this instance, it can be sensed with an accuracy and reproducibility of 1 per cent and 0·5 per cent of full scale, respectively. Since the principle of operation of the magnetic flow meter is well understood, it will not be discussed here. Suffice it to say that this meter generates an electric signal that makes it quite compatible with modern control systems hardware.

Just before it enters the centrifugal screen, the main stock stream is joined by a recirculated stream coming from the exit side of the head box distribution header. This recirculated stream amounts to about 10 per cent of the whole flow and enters the centrifugal screen along with the main stream, whereupon fibre bundles and the like are removed and sent to a vibratory screen for further purification before being either accepted and returned to the silo or rejected to the sewer. Accepted stock at the screen flows on directly to the head box distribution header. At the distribution header, the stock stream is converted into a slowly moving mass of stock of roughly rectangular shape before its narrowing into the narrow rectangular jet subsequently deposited on the wire. Excess stock at the end of the header is recirculated to the centrifugal screen as previously mentioned.

The two other controlled variables in the head box system are sensed at the head box proper. These variables are head box liquid level and head box total head. Both are essentially pressure measurements made with the aid of differential pressure (DP) cells equipped with a diaphragm, the position of which is sensed by a lever system that in turn converts mechanical movement into a pneumatic signal by a flapper-nozzle arrangement. In the case of liquid level, the variable is sensed by attaching one side of the cell to a tap in the bottom of the head box and the other side to a tap connected to the air pad of the box. Total head, on the other hand, is sensed by connecting one side of the cell to the atmosphere and the other to another tap located at the bottom of the head box. The total accuracy of DP cells is usually about 0·5 per cent of range, but usually the pneumatic signal put out must be converted to its electric analog via a PI converter, which has an accuracy and repeatability in the order of 0·2 per cent and 0·10 per cent of range, respectively. Time lags generated in sensing these signals are not substantial, though it must be admitted that nothing is stated in the instrument specification about this matter.

Slice opening is a head box manipulated variable and is adjusted by means of a conventional electric motor (with all winding sealed from the atmosphere to prevent problems caused by the hostile environment) controlled by an ordinary open/close contact, which may or may not be remotely driven. Slice position is not sensed, since experience has shown that it is difficult to obtain an accurate signal. Hence, slice adjustments are calculated with the aid of a difference type digital controller, which eliminates the need for manipulated variable feedback.

Modern head box control systems also require a knowledge of wire speed to allow drag calculations to be made and total head set points to be adjusted accordingly. Normally, the papermaker wishes to control drag at a given wire speed. Hence, he is not interested in total head as a control variable directly, but rather in maintaining a drag set point. This means that, although total head is a true control variable, it very frequently is the slave of a cascaded loop in which drag is specified wire speed measured and total head set point calculated. Wire speeds may be sensed by a variety of methods. The method used in our particular instance was to attach a magnetic pulse generator to the couch roll of the Fourdrinier machine and use an electronic digital computer to count the pulses generated and to calculate wire speed accordingly. The accuracy and reproducibility seems very good, amounting to perhaps 0·1 per cent of the range.

The second flow of interest in the study of the head box as a system is the flow of air to and from the air pad. Compressed air for this purpose is provided by a small water-sealed, centrifugal blower. Air passes from the blower through a control valve and into the head box, from which it subsequently escapes via an outlet equipped with a second control valve. These valves taken as a pair are the final manipulated variables used by the head box control system. They are usually mounted in a push/pull arrangement, which allows the very rapid adjustment of air pad pressure with an air supply and air lines of minimum size. The valves themselves are usually pneumatically operated by stem positioners that have remotely adjustable electric pneumatic converters controlling their stem positions. In this case, a serious time lag (in the order of

5 s or more) results whenever these valves must be moved, but such lags are unavoidable at the present time and may be compensated for quite adequately if controllers are properly tuned.

In summary, it should be noted that there are two flows, three manipulated variables, four controlled variables and wire speed that are of interest in a head box system. The flows of course are liquid flow through the box and air flow through the air pad. The manipulated variables are water valve stem position, slice opening and air valves stem position. Controlled variables are liquid flow through the box, total head, liquid level and drag. Wire speed information is required to allow total head set points to be calculated from a knowledge of the drag desired.

Model development

AS PREVIOUSLY mentioned, three manipulated variables (air valves stem position, water valve stem position and slice opening) are used to maintain control of the head box systems. Unfortunately, each of the system's controlled variables is affected by all three of its manipulated variables. For example, if the air valves are adjusted, they not only affect total head by changing air pad pressure, but also upset liquid level and stock flow rate as well. Interactions can make the design and tuning of a control system quite tedious. Hence, it is essential to establish the dynamic response of all the controlled variables to adjustments in each of the manipulated variables as a first step in developing a suitable control scheme for a head box system.

TABLE 1

No.	*Basic equation*	*Laplace transform upon linearisation*	*Description*
1	$\frac{dM}{dt} = M_a$	$M = \frac{M_a}{s}$	The rate of air mass change in air pad is equal to the net air flow
2	$P_a = \frac{M}{V}RT$ $V = V_a - Ah$	$P_a = C_1M + C_2h$	The pressure in air pad is related to air mass and volume by a gas equation, where V_o is total head box volume and Ah is the volume occupied by water
3	$H = h \times \frac{P_a - 14{\cdot}7}{e}$	$H = h + C_3P_a$	Total head is equal to the water head plus pressure head
4	$Q_o = CdWY\sqrt{2gcH}$	$Q_o = C_4H + C_5Y$	The jet velocity is $\sqrt{2gcH}$, the flow rate through slice is the product of jet velocity, cross-section of slice and flow coefficient
5	$\frac{dh}{dt} = \frac{1}{A}(Q_i - Q_o)$	$h = \frac{1}{A_s}(Q_i - Q_o)$	The rate of liquid level change is equal to the difference between incoming and outgoing flows divided by cross-section of head box

A list of nomenclature is given in Appendix 2

In 1960, Mardon *et al.*[1] developed the basic equations describing the head box system (see the first column in Table 1) and linearised them so that they could be Laplace transformed and used to characterise the system in block diagram form (Fig. 2). A typical example of how this was accomplished is described below for equation (*2*) of Table 1.

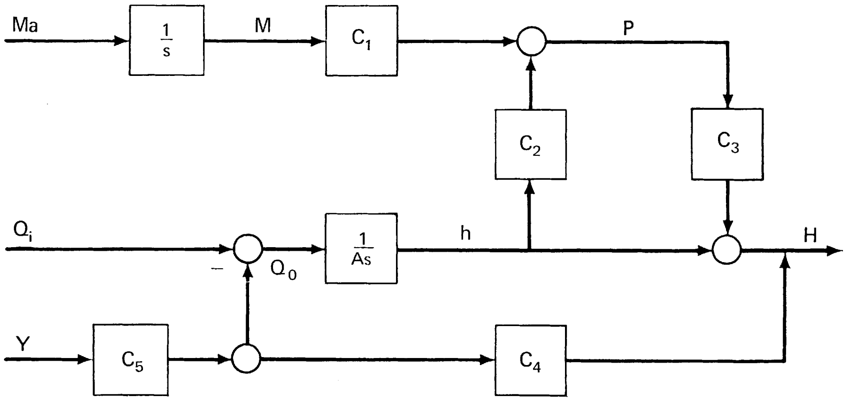


Fig. 2—Block diagram of head box

Consider the pressure P in the air pad of a typical head box. If it is assumed that variations in this pressure are characterisable by the perfect gas law, then—

$$P = M.RT'/V \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

Now if—

$$V = V_o - Ah$$

then equation (*1*) becomes—

$$P = \frac{M}{V_o - Ah} RT' \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If M and h are independent variables, then—

$$dP = \frac{\partial P}{\partial M} dM + \frac{\partial h}{\partial P} dh \quad . \quad . \quad . \quad . \quad (3)$$

$$\text{where} \quad \frac{\partial P}{\partial M} = \frac{RT'}{V_o - Ah}; \quad \frac{\partial P}{\partial h} = \frac{-AMRT'}{(V_o - Ah)^2}$$

If the perturbations of M and h are small, then both partial derivatives will be a constant. Hence—

$$\Delta P = C_1 \Delta M + C_2 \Delta h \qquad (4)$$

where $\dfrac{\partial P}{\partial M} = \dfrac{RT'}{V_o - Ah} = C_1 \qquad \dfrac{\partial P}{\partial h} = \dfrac{-AMRT'}{(V_o - Ah)^2} = C_2$

and the Δ operator signifies the magnitude of the deviations from an original or reference value. Taking the Laplace transform of equation (*4*), we obtain—

$$P(s) = C_1 M(s) + C_2 h(s) \qquad (5)$$

which is equivalent to the expression listed in column 2 of Table 1.

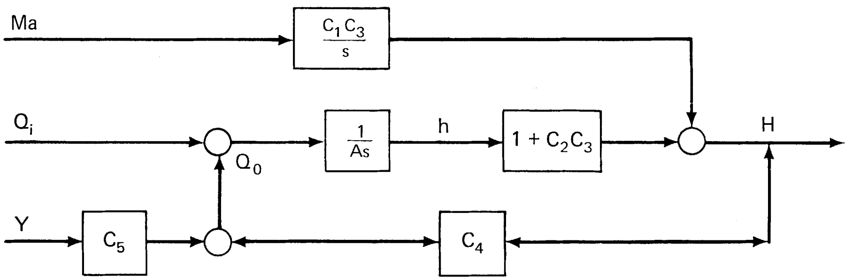


Fig. 3—Condensed block diagram of head box

The block diagram of the head box system shown in Fig. 2 may be reduced to a simpler form as shown in Fig. 3. Before the development of a system model is discussed further, however, it should be pointed out that the manipulated variables assumed in the equations of Table 1 are not the same as discussed previously. Slice position is assumed to be a manipulated variable in each case, but stock flow to the box and the mass of gas in the air pad in the theoretical model are taken as manipulated variables instead of air and water valves stem position, which are the true variables. Assuming these intermediate variables to be manipulated variables leads to a considerable simplification of the modelling problem, however, without any serious consequences to model validity (as will be shown in a subsequent section) and is justified on practical grounds.

From Fig. 3, it is possible to obtain the general transfer functions of system-controlled variables (H, h and Q_0) with respect to system-manipulated variables (Q_i, M_a and Y). For instance, the transfer function between total head H and flow to the box Q_i is of the form—

$$\frac{H}{Q_i} = \frac{\frac{1}{A_s}(1+C_2C_3)}{1+\frac{1}{A_s}(1+C_2C_3)C_4} = \frac{1+C_2C_3}{A_s+(1+C_2C_3)C_4} \quad . \quad . \quad (6)$$

Nine transfer functions are required completely to characterise system dynamics. The other eight functions along with the one developed here are presented in Table 2, from which it may be seen that seven of the nine transfer functions are simple first order lags. This is of considerable import, as will be evident later when practical identification methods are discussed.

The two transfer functions that differed from the rest were G_{22} and G_{33}. G_{22} relates h to M_a and is of the form $K/S(Ts+1)$. Hence, it contains a first order lag, but includes an integrator as well. The function G_{33}, which relates Q_o and Y, is unique, because, although it also contains a first order lag, derivative action is present as well. These last two types of transfer function present somewhat different identification requirements.

Before proceeding further with a discussion of practical identification procedures, one additional complication should be discussed. As has already been mentioned, the transfer functions contained in Table 2 represent the dynamics between intermediate variables and system-controlled variables. Hence, the dynamics relating the intent (on the part of a controller) to move the water valve, the air valves or the slice and the intermediate variables of Table 2 must be discussed.

TABLE 2

Value	*Total head* (H)	*Liquid level* (h)	*Outlet liquid flow* (Q_o)
Inlet liquid flow (Q_i)	$G_{11} = \frac{1+C_2C_3}{A_s+C(1+C_2C_3)}$	$G_{12} = \frac{1}{A_s+C_4(1C_2C_3)}$	$G_{13} = \frac{(1+C_2C_3)C_4}{A_s+(1+C_2C_3)C_4}$
Net air flow (M_a)	$G_{21} = \frac{AC_1C_3}{A_s+(1+C_2C_3)C_4}$	$G_{22} = \frac{1}{s}\frac{C_1C_3C_4}{A_s+(1+C_2C_3)C_4}$	$G_{23} = \frac{AC_1C_3C_4}{A_s+(1+C_2C_3)C_4}$
Slice position (Y)	$G_{31} = \frac{-(1+C_2C_3)C_5}{A_s+(1+C_2C_3)C_4}$	$G_{32} = \frac{-C_5}{A_s+(1+C_2C_3)C_4}$	$G_{33} = \frac{AC_5s}{A_s+(1+C_2C_3)C_4}$

Consider the case of a controller being used to cause a change in flow into the head box via an adjustment in water valve stem position. At least three distinct transfer functions are involved in achieving this objective (Fig. 4).

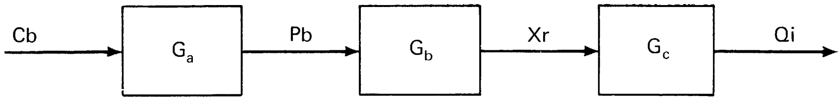


Fig. 4—Water valve transfer function

First, the controller signal $C(s)$ must be converted to bonnet pressure P_b, which in turn is converted to a new valve stem position X_r by means of the stem positioner. The change in stem position causes a change in the flow into the head box Q_i. Each of these transfer functions G_a, G_b and G_c are at best a first order lag, with a decided possibility that G_b could be a second order system. In addition, dead time may exist in all three transfer functions as a result of slippage and the like. The net effect of this is to give a general transfer function of at least third and probably fourth order with dead time. Nevertheless, the situation is not as formidable as might be expected, for such actuating systems are invariably set up to be decidedly overdamped. The net result is that the complete dynamics of the actuation system can be characterised quite adequately via a first order lag with dead time. The applicability of this simplifying assumption has profound beneficial effects for a practical identification procedures.

In summary, it may be said that adequate analytical models are currently available to relate the various manipulated variables to their controlled variable counterparts. In addition, the dynamics of the various actuation systems adjusting manipulated variables have been studied and found to be characterisable by a first order lag plus dead time. With the form of the general transfer functions thus established, the task remaining is to describe the methods used to estimate the specific numerical values of the parameters appearing in said models.

System identification

A DETAILED description of the identification procedure used to characterise model parameters is uncalled for in this text, since it has already been described in detail elsewhere.[2] Suffice it to say here that the technique used consists of—

1. Choosing a model of a form capable of characterising system dynamics adequately.
2. Inducing a rather prolonged, closed pulse in each manipulated variable of interest (water valve position, air valves position and slice opening in this case) while taking particular pains to note the response of each controlled variable to said upset.
3. Employing a rather specific mathematical search technique to estimate the model parameters giving the best fit to the data at hand.

Fig. 5–7 contain plots of the response of total head and liquid level to pulse upsets in air valves stem position, water valve position and slice opening, respectively. The magnitude and duration of these pulses are such that undue upsets in the process are avoided. Hence, it is possible to identify transfer functions for the head box system at will with considerable convenience. The first requirement is that the control loops on each controlled variable be

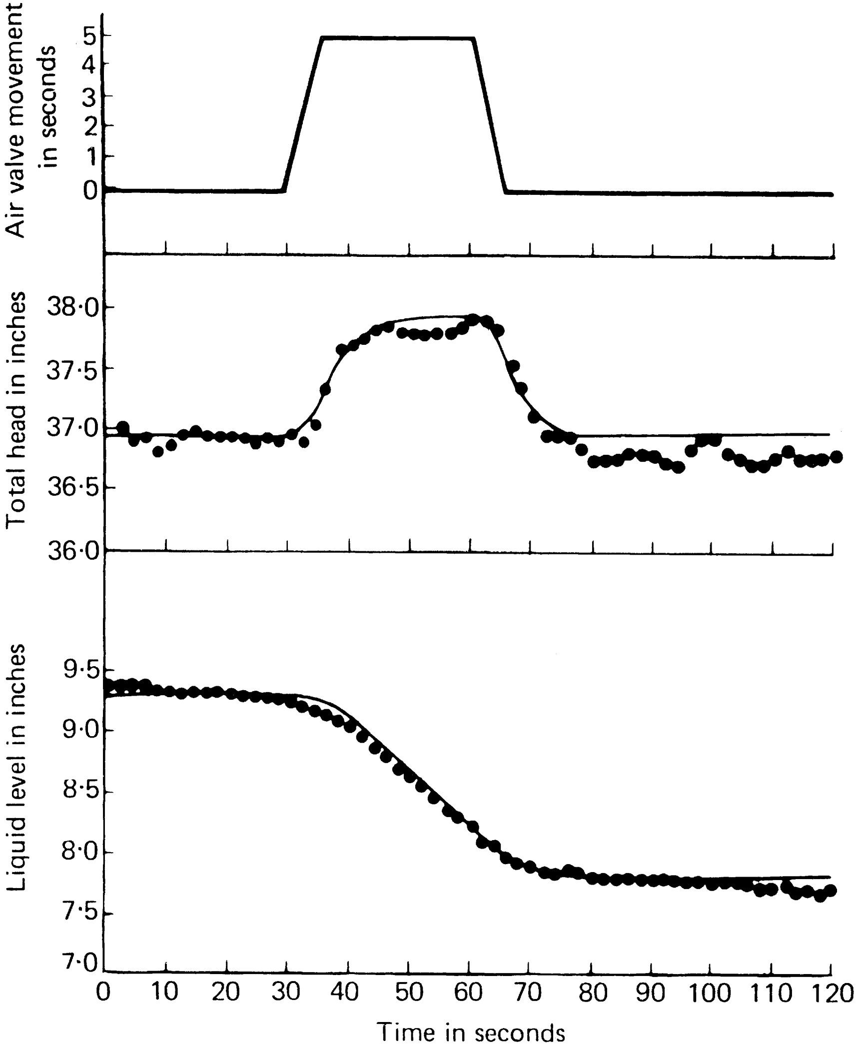


Fig. 5—Air valve identification data

opened shortly before the identification is to begin. Subsequently, the manipulated variable of interest is pulsed as required, with pains being taken that all appropriate data is obtained (usually automatically). The net effect is to put quite a convenient method of determining complete head box dynamics at the disposal of the engineer.

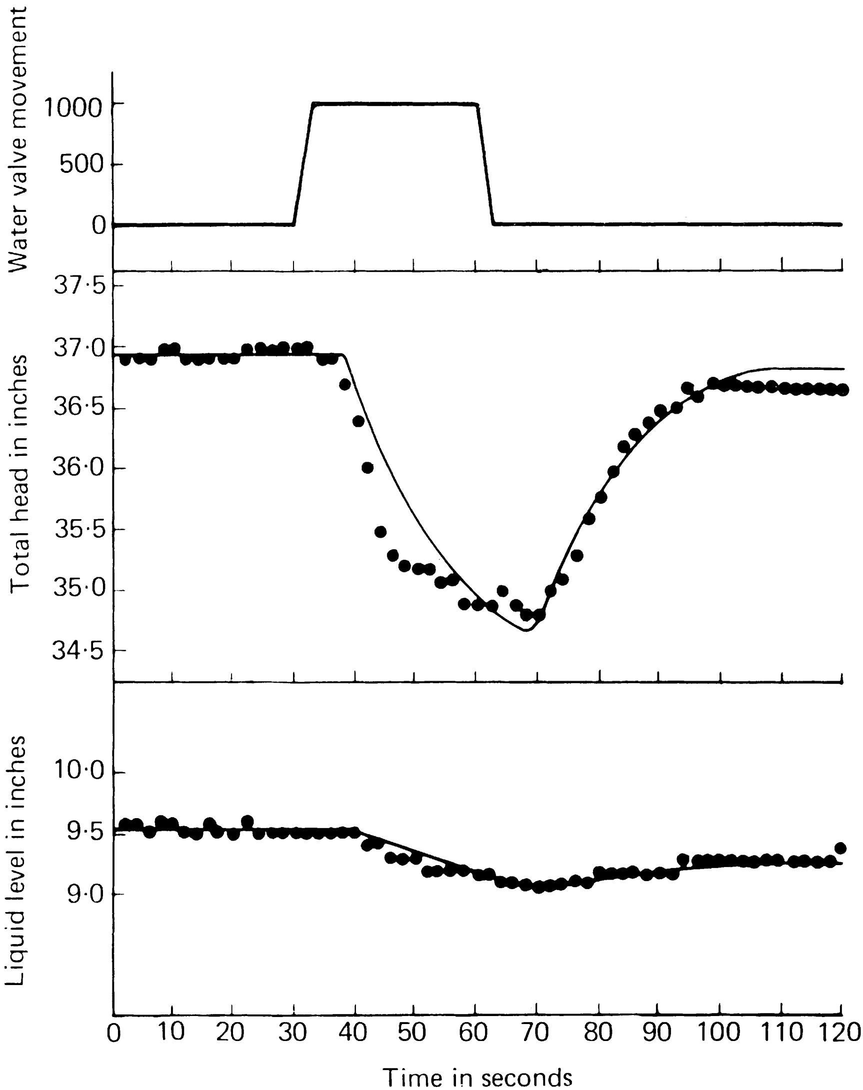


Fig. 6—Water valve identification data

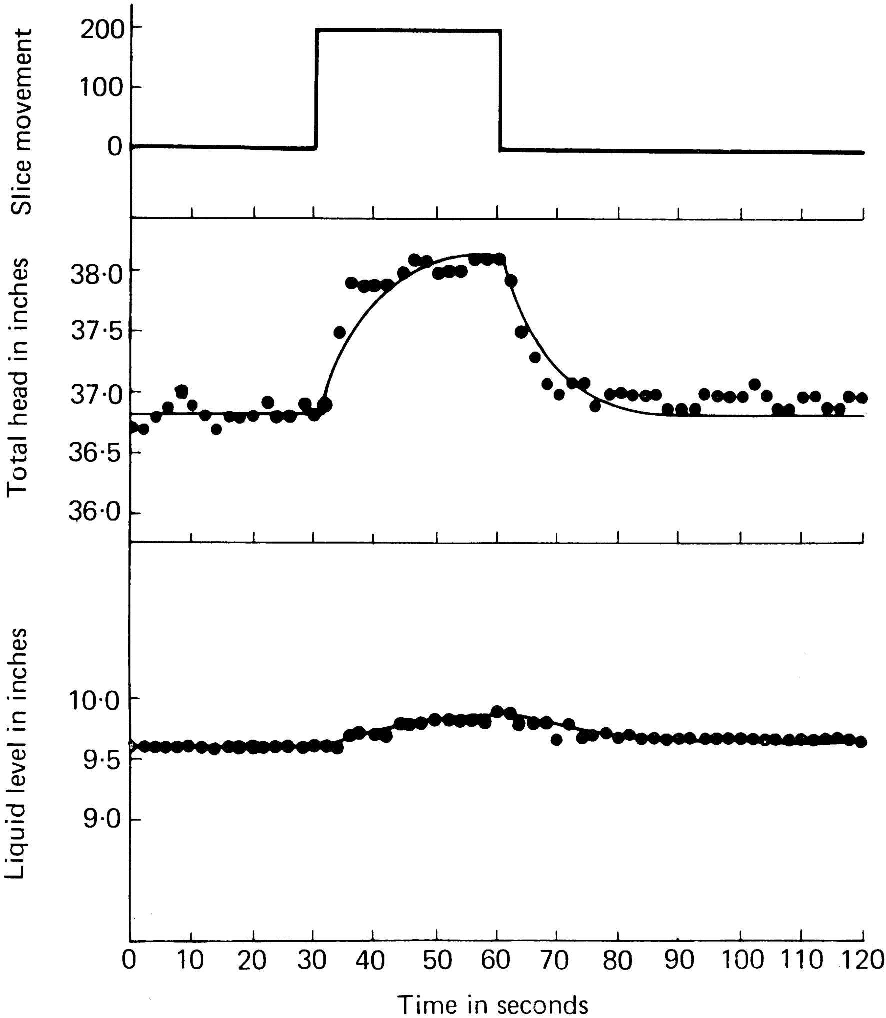


Fig. 7—Slice opening identification data

The closed circles in Fig. 5–7 represent actual data points with the continuous lines (in the case of liquid level and total head) being the response expected of the system if it were in fact completely characterised by the process model subsequently identified by our search procedure as being best. Needless to say, the fit in all six cases is quite good. The transfer functions identified are presented in Table 3. In each case, a dead time as well as a time constant and gain was identified. These dead times can probably best be ascribed to time delays in the actuation systems for the various manipulated variables; yet time constants and gains are undoubtedly the result of a combination of actuation and process dynamics. The integrator appearing in P_{22}, on the other hand, is completely the result of process dynamics as already discussed.

TABLE 3

Value	*Total head* (H)	*Liquid level* (h)
Water valve position (W)	$P_{11}(s) = \frac{0{\cdot}262e^{-8s}}{14{\cdot}62s+1}$	$P_{12}(s) = \frac{0{\cdot}142e^{-8s}}{75{\cdot}3s+1}$
Air valve position (X)	$P_{21}(s) = \frac{0{\cdot}02e^{-1{\cdot}5s}}{4{\cdot}46s+1}$	$P_{22}(s) = \frac{0{\cdot}001}{s}\frac{e^{-1{\cdot}5s}}{4{\cdot}46s+1}$
Slice position (Y)	$P_{31}(s) = \frac{0{\cdot}667e^{-s}}{6{\cdot}95s+1}$	$P_{32}(s) = \frac{-0{\cdot}21e^{-s}}{27{\cdot}5s+1}$

System non-linearities

As previously mentioned, the basic equations defining the head box system are non-linear and need to be linearised via a perturbation technique. Experience has shown that this approach has worked well for head boxes operated close to one standard set of operating conditions, but that difficulties are encountered when appreciable changes are made in system operating points. Studies of the situation have shown that the difficulties experienced are a result of changes generally in process dynamics reflected by differences in identified process gains and time constants. Dead times for the most part have remained relatively constant, indicating that they are strongly related to actuator rather than to process dynamics.

TABLE 4

Type of transfer function	*At 50 lb/ream grade*	*At 80 lb/ream grade*	*At 100 lb/ream grade*
$\frac{H}{W}(s)$	$\frac{0{\cdot}354e^{-5{\cdot}5s}}{20{\cdot}6s+1}$	$\frac{0{\cdot}262e^{-8s}}{14{\cdot}6s+1}$	$\frac{0{\cdot}132e^{-8{\cdot}5s}}{16{\cdot}2s+1}$
$\frac{H}{Y}(s)$	$\frac{0{\cdot}749e^{-s}}{6{\cdot}9s+1}$	$\frac{0{\cdot}669e^{-s}}{6{\cdot}95s+1}$	$\frac{0{\cdot}628e^{-s}}{4{\cdot}5s+1}$

The data presented in Table 3 was obtained while producing an 80 lb/ream (3 300 ft^2) coated sheet at a speed of approximately 800 ft/min. To appreciate the effect that changes in operating conditions can have on system dynamics, refer to Table 4, which contains the transfer functions relating total head to water valve position and slice opening for three sets of operating conditions—the manufacture of a 50 lb/ream sheet at 1 100 ft/min, an 80 lb/ream sheet at 800 ft/min and a 100 lb/ream sheet at 600 ft/min. From Table 4, it is apparent that there are significant differences in process dynamics, indicating that system dynamics form a continuum varying continuously across the entire spectrum of operating conditions. During normal operations (at a fixed set of points), this fact causes no great difficulties, provided the appropriate system dynamics are used in calculating controller parameters. Occasionally, most papermachines must be moved from one set of operating conditions to another. This grade change presents particular difficulties from a control standpoint as a result of the head box non-linearities now being discussed. Steps taken to alleviate the problems encountered will be discussed at some length later under the heading *Controller design—part 5.*

Controller design—part 1

THE transfer functions given in Table 2 can be used to determine the effect of changes in any manipulated variable (Q_i, M_a or Y) on any one or all three of the controlled variables (H, h or Q_o). To be specific, consider the magnitude of the steady state error in total head resulting from a step change (of unit size) in liquid flow to the box. If the final value theory is applied, then we have—

$$\lim_{t\to\infty} H_{(t)} = \lim_{s\to o} (s)\left(\frac{1}{s}\right) G_{11}(s) = \lim_{s\to o} \frac{1+C_2C_3}{As+C_4(1+C_2C_3)}$$

$$\lim H_{(t)} = 1/C_4 \qquad (7)$$

This means that, if a unit step in flow to the box takes place, a constant offset equal to $1/C_4$ will be experienced in total head. Following the same procedure, it can be shown that all the controlled variables save one will suffer a constant offset as a result of a step change in any one of the system's manipulated variables. The one exception to this rule is head box liquid level during a step change in air flow. Applying the final value theory in this instance shows that—

$$\lim_{t\to\infty} h_{(t)} = \lim_{s\to o} (s)\left(\frac{1}{s}\right) G_{22}(s) = \lim_{s\to o} \frac{1}{s} \frac{C_1C_3C_4}{As+(1+C_2C_3)C_4}$$

$$\lim_{t\to o} h_{(t)} = \infty \qquad (8)$$

Hence, if there is an upset in air flow, the head box will eventually eithe completely fill or empty itself of stock, because of the integrator that appear in G_{22}.

As a result of the characteristic just discussed, it is an absolute necessity to provide each and every air-loaded head box with some type of liquid level controller. Originally, this controller was the Hornbostel hole; but now analog pneumatic controllers with liquid level as a controlled variable and air valves stem position as the manipulated variable are usually provided for the purpose. An air-loaded box with any less of a control system would be inherently unstable. Hence, at the very least, liquid level control must be provided as back-up for every head box system, regardless of its sophistication and complexity.

Further use of the final value theory will show that it is possible to stabilise the head box system with a simple proportional liquid level controller. If offsets are to be avoided, however, both proportional and integral action must be provided. As a result, modern head boxes are invariably supplied with at least a PI liquid level controller as standard equipment.

Generally speaking, tuning of simple liquid level controllers is no problem, for only one loop is involved and the interaction between manipulated and controlled variables is intuitively easy to grasp. As a result, any competent instrument man can tune the controller in the field using trial and error methods, thereby eliminating the need for formal identification and tuning procedures. It should be pointed out, however, that in all cases the controller used must be tuned with its parameters set so that the closed loop system will be stable under all possible operating conditions. The system is therefore usually somewhat sluggish over most of its operating range in order to avoid instability when process gains are at a maximum (usually when lightweight sheets are being made at high speeds).

Controller design—part 2

THOUGH only liquid level control is an absolute necessity for an air-loaded head box, systems are now supplied with both liquid level and total head control provided. The reasons for supplying the more sophisticated system are numerous, but boil down to the fact that it makes a head box (and hence its associated papermachine) easier to operate. For example, a total head/liquid level controller simplifies grade change procedures considerably. In addition, if a total head/liquid level controller is combined with means for automatically sensing wire speed, all the ingredients are available for providing automatic drag control on a Fourdrinier machine.

Fig. 8 contains a block diagram of a typical total head/drag control loop, from which it may be seen that—

1. The operator is allowed to specify either total head or drag for the sake of convenience.

2. Total head set point can be calculated directly from a knowledge of wire speed and drag set point.

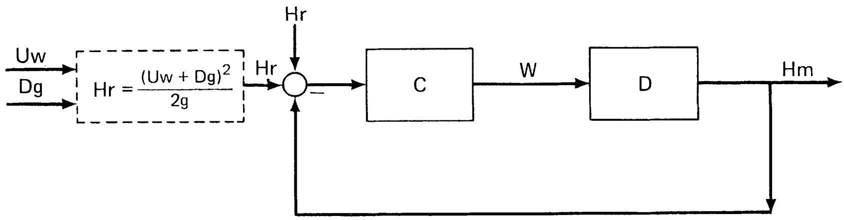


Fig. 8—Block diagram of drag controller

The main advantage of such a drag control feature is that it allows an important sheet forming condition to be held constant with time. This leads to more stable operations on the wet end and allows the manufacture of paper of better uniformity and quality.

Mardon *et al.*[1] have studied two specific controller configurations with which total head and liquid level can be controlled. Both proportional and integral action were required in all loops, which made one configuration very difficult to tune and the other moderately so. Nevertheless, the systems were studied extensively via analog simulation and it was concluded that the configuration shown in Fig. 9 was the best for stability and tuning generally. Unfortunately, no performance data for an operating head box was reported by Mardon *et al.*; but experience on the part of the authors indicates that such a system is very workable in a practical sense. Not only is it stable and dependable, but has the added benefit that, should the total head controller fail, liquid level will still be maintained via the conventional approach outlined in part 1. This latter feature has been of considerable practical benefit when it has been necessary to go on and off total head control.

Control according to Fig. 9 is usually implemented via analog hardware and, though tuning is possible by trial-and-error methods, it is difficult. Recently, Lee *et al.*[3] described a tuning method using a root contour approach that can successfully choose advantageous starting points for controller parameters. This greatly reduces the amount of 'witchcraft' involved in tuning such a multi-loop, interacting system as the head box. In addition, the analysis involved leads to a better appreciation for factors important to system stability.

In summary, it is possible to control both total head and liquid level with conventional analog hardware attached to a head box in a straightforward manner. In addition, experience shows that the control system diagrammed in

Fig. 9 works best on a practical basis. Tuning methods are also available to give good starting points for controller parameters. This simplifies system tuning considerably.

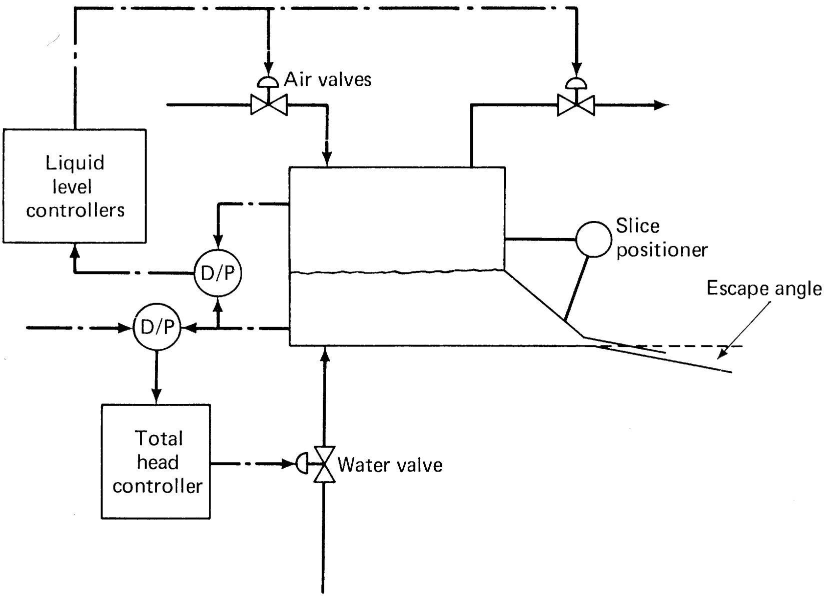


Fig. 9—Schematic diagram for best analog controller configuration

Controller design—part 3

HEAD box dynamic parameters are affected by changes in operating point (Table 4). This means that a control system tuned is an optimum under one set of circumstances may be useless for a second set. To illustrate the point, consider the response curves shown in Fig. 10. These data were obtained via simulation (on a digital computer), but should be quite representative of the response shown by a full-scale operating head box, because the model and identified parameters previously reported in Tables 3 and 4 were used. (A block diagram of the simulation program and an explanation of it are included in Appendix A.) In addition, the use of analog controller hardware with invariant parameters was assumed. The upset studied was a 1 in change in total head set point and the controllers were set to give relatively good response for a 100 lb/ream sheet.

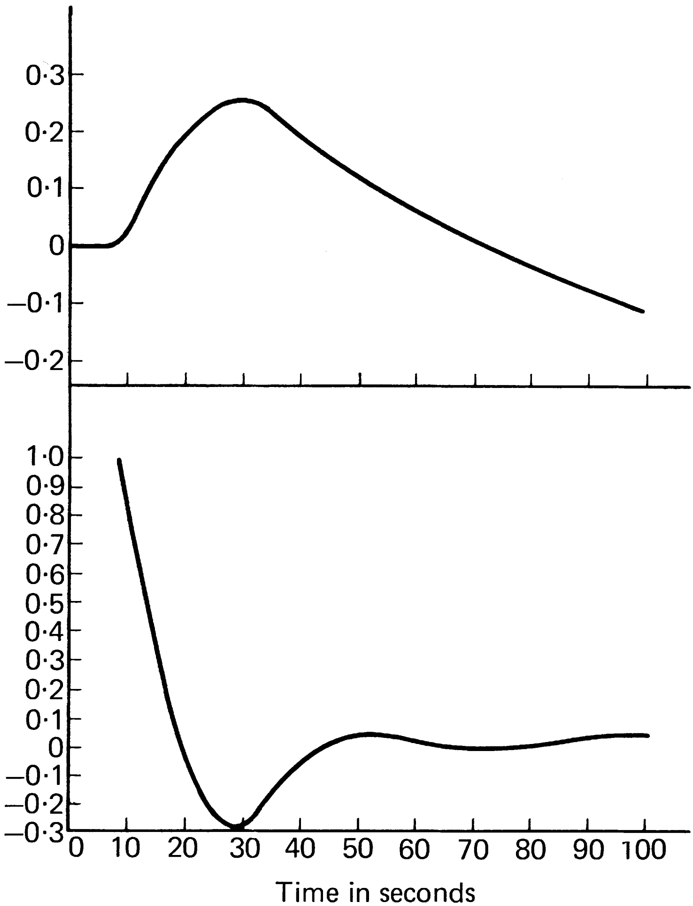


Fig. 10a—Simulated response of an analog control system of 100 lb/ream grade

If settling time to a 10 per cent error and amount of overshoot are taken as performance criterion, it may be seen that—

1. Total head control though somewhat oscillatory (overshoot 27 per cent, settling time 37 s) is adequate in the case of 100 lb/ream paper manufacture (Fig. 10*a*).
2. The total head controller is definitely too active (overshoot 61 per cent, settling time 47 s) in the case of a 50 lb/ream sheet (Fig. 10*b*).

3. Though upsets in liquid level were minor in each case, liquid level showed a greater deviation and slower period of oscillation in the case of 100 lb/ream paper manufacture than for a 50 lb/ream sheet.

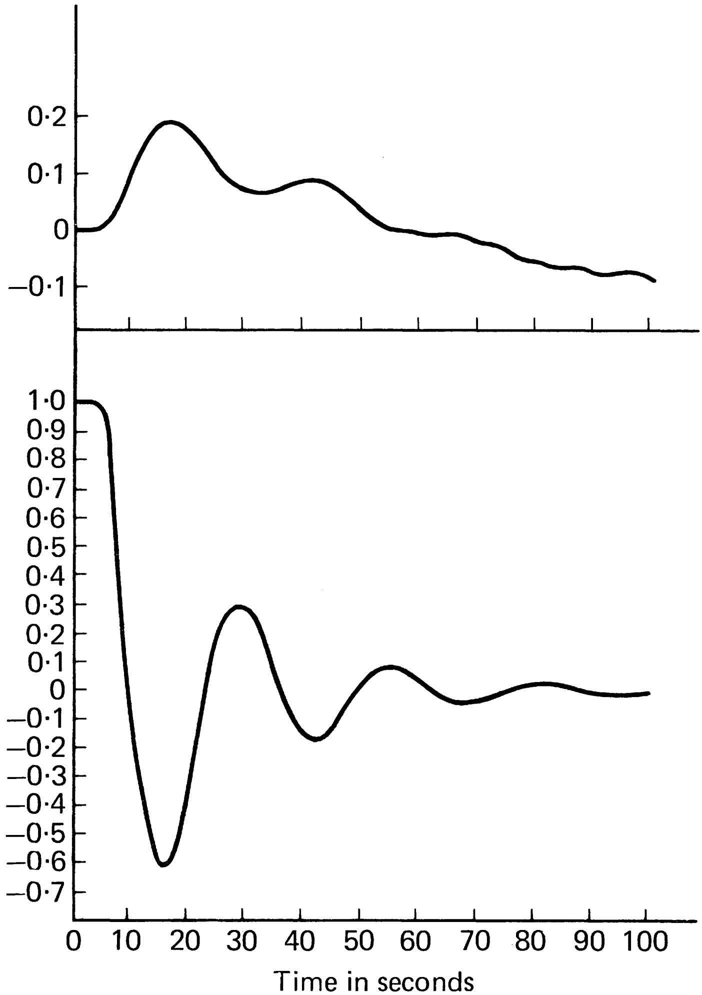


Fig. 10b—Simulated response of an analog control system at 50 lb/ream grade

This sacrifice of liquid level control undoubtedly helped the system in the case of the 100 lb/ream sheet, but it still must be recognised that the primary cause of the trouble in the case of the 50 lb/ream sheet was the change in head box dynamics.

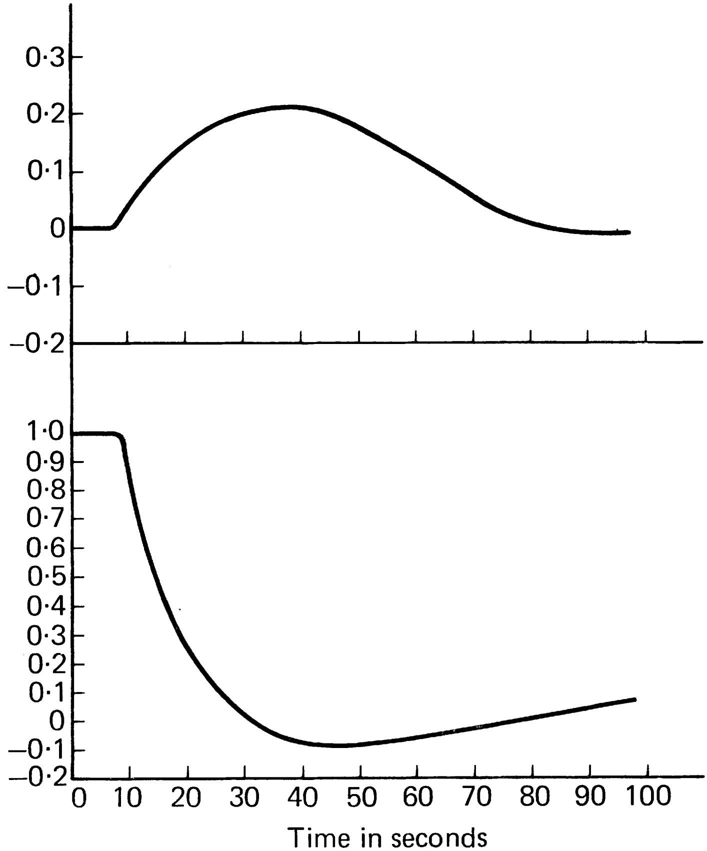


Fig. 11a—Simulated response of a digital control system at 100 lb/ream grade

Fig. 11 contains the same type of simulation results for a head box equipped with a digital, adjustable parameter, total head controller and analog liquid level control. Two major advantages of the digital controller are illustrated by these data. First, comparison of the response curves in Fig. 10(*a*) and 11(*a*) (manufacture of a 100 lb/ream sheet) shows that the digital controller (9 per cent overshoot and a 25 s settling time) out performed the analog controller, despite the fact that they were both tuned to give the same initial response to the total head upset. This was the result of the digital system's better ability to deal with the 8 s dead time in the head box.

The second advantage of the digital controller is best illustrated by comparing Fig. 10(*b*) and 11(*b*) (manufacture of a 50 lb/ream sheet). Here the digital system's advantage lies in its adjustable parameters and the result is far better performance (no overshoot and a 30 s settling time) than the analog system. In addition, it should be noted that less of a load was placed on the analog liquid level controller when a digital total head control was used and this resulted in less liquid level disturbance and a slower period of oscillation.

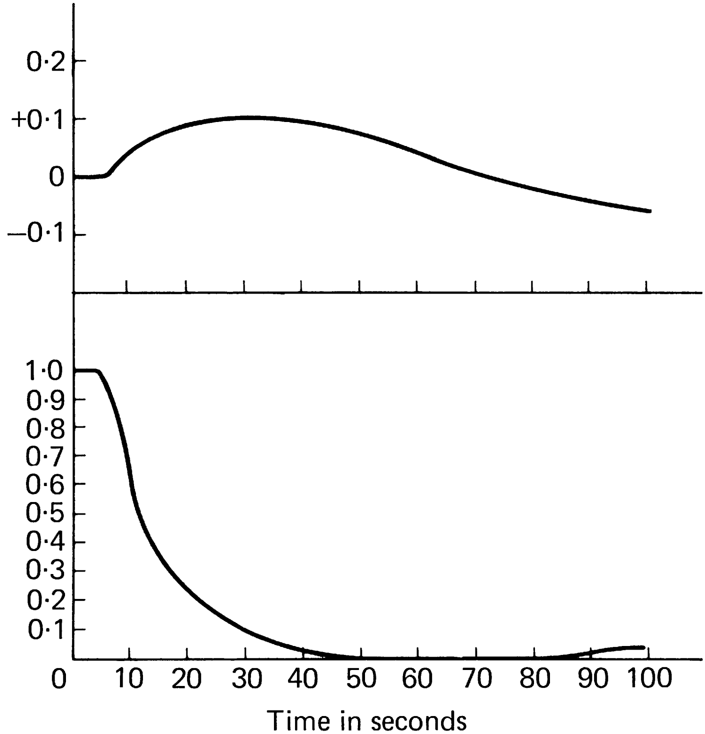


Fig. 11b—Simulated response of a digital control system at 50 lb/ream grade

The digital controller used in the above simulation was designed by a cancellation compensation procedure reported by Dahlin *et al.*[4] The approach used was to first specify the closed loop response desired, then derive the form of the controller required algebraically from a previous knowledge of the process' open loop response. For example, consider the system block diagram in Fig. 12. The general transfer function is of the form—

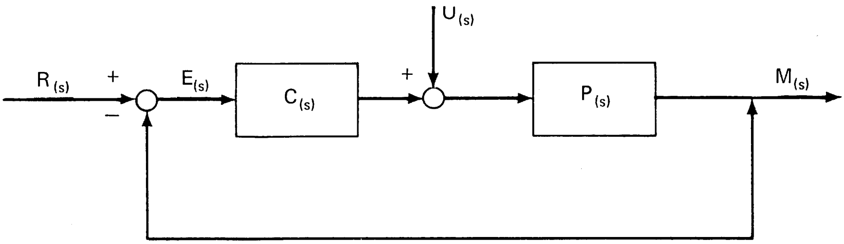


Fig. 12—Block diagram for generalised control loop

$$\frac{M(s)}{R(s)}=\frac{P(s)C(s)}{1+P(s)C(s)} \quad . \quad . \quad . \quad . \quad . \qquad (9)$$

where $P(s)$ and $C(s)$ are the open loop transfer function of the process and the controller, respectively. If we specify that—

$$\frac{M(s)}{R(s)}=F(s) \quad . \quad . \quad . \quad . \quad . \quad . \qquad (10)$$

then $C(s)$ is defined and may be solved for algebraically.

$$C(s)=\frac{F(s)}{1-F(s)}P(s)^{-1}. \quad . \quad . \quad . \quad . \quad . \qquad (11)$$

Now if, as in the case of the head box, $P(s)$ is a first order system with time constant T, gain K and dead time D, then it is most practical to specify that—

$$F(s)=\frac{\lambda}{s+\lambda}e^{-sD} \quad . \quad . \quad . \quad . \quad . \qquad (12)$$

where λ is the reciprocal of the system's closed loop time constant and is referred to as its cut-off frequency. Making the substitution indicated in equation (*11*), we obtain—

$$C(s)=\frac{1}{K}\cdot\frac{Ts+1}{\lambda s+1-\lambda e^{-sD}} \quad . \quad . \quad . \quad . \quad . \qquad (13)$$

Such a transfer function is difficult if not impossible to implement via conventional analog hardware. Nevertheless, it can be easily implemented digitally as evidenced by the fact that, if the z-transform of equation (*13*) is taken, of we obtain—

$$C(z)=\frac{1-\theta}{K(1-\eta)}\,\frac{1-\eta z^{-1}}{1-\theta z^{-1}-(1-\theta)z^{-d-1}} \quad . \quad . \quad . \quad . \qquad (14)$$

where T is the sampling interval and—

$$\theta = e^{-\lambda T},\ \eta = e^{-T/T},\ d = D/T,$$

but, since $C(z)$ denotes the transfer function between the manipulated and controlled variables of the system, we may say that—

$$C(z) = \frac{W(z)}{\Delta H(z)} \quad . \quad . \quad . \quad . \quad . \quad (15)$$

which, if substituted in equation (*14*), gives—

$$W(z) = \frac{(1-\theta}{K(1-\eta)}(\Delta H - \eta\ \Delta Hz^{-1}) + \theta W(z)z^{-1} + (1-\theta)W(z)z^{-d-1} \quad . \quad (16)$$

which when reduced to its recursive form becomes—

$$W_i = \frac{(1-\theta)}{K(1-\eta)}(\Delta H_i - \eta\Delta H_{i-1}) + \theta W_{i-1} + (1-\theta)W_{i-d-1} \quad . \quad . \quad (17)$$

the digital algorithm required to achieve the closed loop response $\lambda e^{-sD}/s+\lambda$.

Such an algorithm has been used to control the total head in the head box of an operating machine for some two years now. Typical responses for this box to upsets in total head and slice opening are illustrated in Fig. 13, from which it may be seen that response is somewhat sluggish, but dependable. This response is by design, since an entire closed loop time constant of 25 s for the digitally controlled total head loop has been chosen. This allows a sampling interval (T) of 8 s to be used, which greatly simplifies programming problems and allows one computer to be spread further while still providing adequate control.

In summary of this section, a digital total head controller holds certain advantages over an analog system—namely, better dead time compensation and easy parameter adjustment. In addition, cancellation compensation design techniques taking advantage of the versatility of digital algorithms are available and one design procedure was reviewed. Finally, the actual performance of an operating head box was illustrated and shown to be satisfactory from a practical standpoint.

Controller design—part 4

THUS far, the controls of only total head and liquid level have been discussed, but occasionally the papermaker wishes to adjust the flow of stock from his box as well. Under normal steady-state conditions, the effect of this is to change the consistency of the stock in the head box. Such a change is one of the most direct methods by which a machine tender can adjust the paper's formation. Hence, though there is a definite need for flow control, flow set

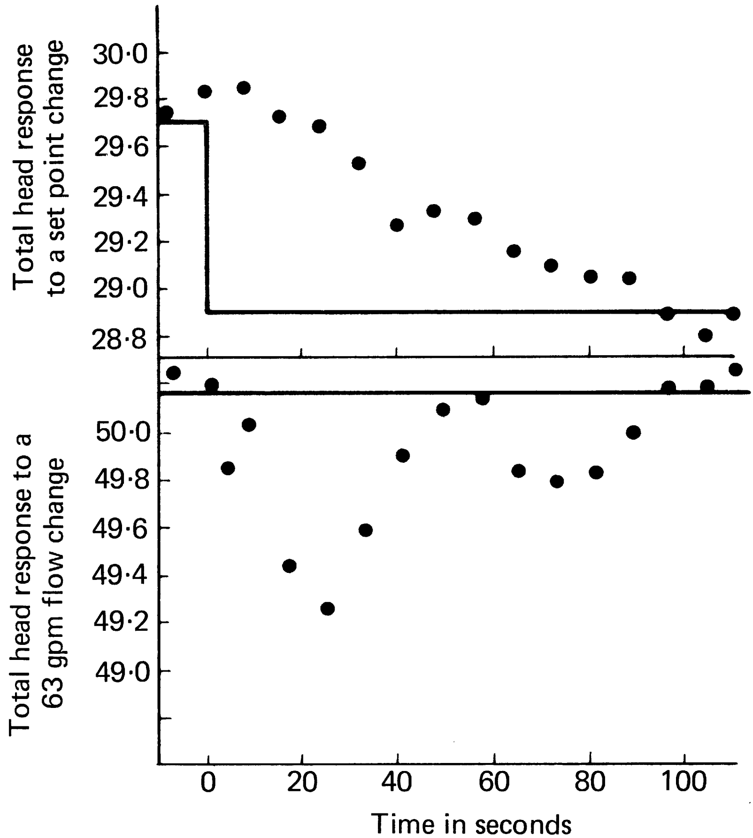


Fig. 13—Actual digital controller

point is adjusted infrequently, because the papermaker does not usually wish to toy with a property as elusive as formation.

As already mentioned, the manipulated variables used in gaining control of total head and liquid level were water valve and air valves stem position. The only other variable that can be conveniently manipulated in the head box system is slice position. Consequently, it is used somewhat indirectly to achieve control of this third controlled variable—flow from the box. In other words, in the control system found to be most convenient by these authors, water valve stem position, air valves stem position and slice opening were the variables used to control total head, liquid level and flow from the box, respectively. Other combinations of manipulated and controlled variables can be devised, of course, but this arrangement has seemed to give the best general head box performance.

The ideal feedback signal for a head box flow controller is flow from the box, which should be returned to the controller via a set point comparator. Unfortunately, it is not possible to measure flow from the box directly, but, under steady state conditions, it is a fact that flow to the box must equal flow from the box. Hence, it is possible to use a measure of flow to the box (which can be measured) as an estimate of flow from the box, but this complicates the control system considerably (as will be illustrated in the next section) by virtue of the fact that the total head controller's dynamics are inserted into the feedback path of the flow control loop. Under normal (non-grade change) circumstances, however, this complication is not particularly restrictive, because an active flow controller is not particularly desirable (the papermaker does not appreciate having adjustments made to 'his' slice however small and for whatever reason). This means that the controller is intentionally designed to be sluggish (low gain) and a dead band of appreciable size (2 per cent of the mean flow) is incorporated to avoid unnecessary slice movements.

Experience has shown proportional action to be quite adequate for this application and a digital algorithm was used to close the loop because of the ease with which a dead band could be incorporated and the fact that the necessary hardware was at hand. Under normal circumstances, however, it is doubtful if the extra cost of digital adjustment could be justified. Finally, it should be stated that such a controller has been in operation for some two years now with no mishaps of wire flooding and the like. Set points are entered in terms of gal/min of stock desired and so far the machine tenders involved seem well pleased by the results.

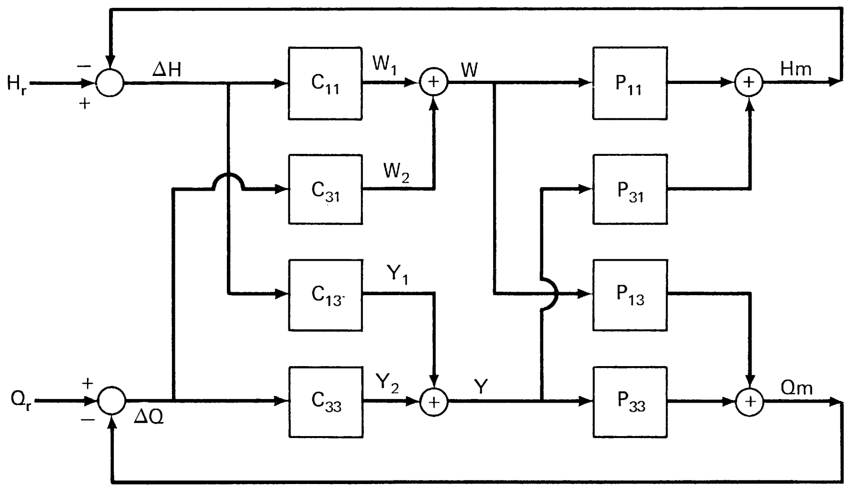
Controller design—part 5

ALTHOUGH an intelligent combination of the control approaches described in parts 3 and 4 of this paper seem best at present for normal operating conditions, the requirements during a grade change are markedly different. For example, it might take as long as 20 min for the head box controller to settle down after a grade change of substantial magnitude (300 ft/min speed change or the like) due to interactions between the total head and flow from the box control loops. Such performance would be intolerable in that it would delay grade changes inordinately, as well as increasing the danger of a wet end break.

The best way to achieve fast, accurate response in both the total head and flow loops during grade change is to use a decoupled controller that takes the above-mentioned interactions into account. Decoupling in this context requires that—

1. When only a total head set point change is imposed, both the water valve and slice are used to achieve said change while holding the flow constant.
2. When only a flow change is required, again use both the water valve and slice to achieve it while holding total head constant.
3. If set point changes in both total head and flow are called for, use both manipulated variables to achieve the change while simultaneously taking into account interactions and correcting for them.

Such a procedure will insure not only fast, but accurate changes to reach the new operating point.



Fjg. 14—Block diagram for the 2×2 decoupled controller

A block diagram of the approach proposed is contained in Fig. 14 with the *C* values and *P* values denoting the appropriate transfer functions of the controllers and the process, respectively. From Fig. 14, it can be seen that—

$$W = C_{11}\Delta H + C_{13}\Delta Q \quad . \quad . \quad . \quad . \quad (18a)$$

$$Y = C_{31}\Delta H + C_{33}\Delta Q \quad . \quad . \quad . \quad . \quad (18b)$$

$$H_m = P_{11}W + P_{31}Y \quad . \quad . \quad . \quad . \quad . \quad (19a)$$

$$Q_m = P_{13}W + P_{33}Y \quad . \quad . \quad . \quad . \quad . \quad (19b)$$

Now, if equations (*18a*) and (*18b*) are substituted into equations (*19a*) and (*19b*)—

$$\begin{aligned} H_m &= P_{11}(C_{11}\Delta H + C_{13}\Delta Q) + P_{13}(C_{31}\Delta H + C_{33}\Delta Q) \\ &= (P_{11}C_{11} + P_{13}C_{31})\Delta H + (P_{11}C_{13} + P_{13}C_{33})\Delta Q \quad . \quad . \quad . \quad (20a) \\ Q_m &= P_{31}(C_{11}\Delta H + C_{13}\Delta Q) + P_{33}(C_{31}\Delta H + C_{33}\Delta Q) \\ &= (P_{31}C_{11} + P_{33}C_{31})\Delta H + (P_{31}C_{13} + P_{33}C_{33})\Delta Q \quad . \quad . \quad . \quad (20b) \end{aligned}$$

where $\Delta H = H_r - H_m$ and $\Delta Q = Q_r - Q_m$.

From the first definition of decoupling, it can be stated that—

$$Q_m = 0 \text{ when } \Delta H = 0$$

which is the necessary and sufficient condition for—

$$P_{31}C_{11}+P_{33}C_{31} = 0 \qquad \qquad (21a)$$

Likewise, from the second definition, it may be shown that—

$$P_{11}C_{13}+P_{13}C_{33} = 0 \qquad \qquad (21b)$$

Now, if equations (*21*) are substituted into equations (*20*), we have—

$$H_m = (P_{11}C_{11}+P_{13}C_{31})(H_r-H_m) \qquad \qquad (22a)$$

$$Q_m = (P_{31}C_{13}+P_{33}C_{33})(Q_r-Q_m) \qquad \qquad (22b)$$

If the closed loop transfer functions are now specified to be—

$$\frac{H_m}{H_r} = \frac{\lambda_1}{s+\lambda_1}e^{-sD1} \qquad \qquad (23a)$$

$$Q_m = \frac{\lambda_3 e^{-sD3}}{s+\lambda_3-\lambda_3 e^{-sD3}}(Q_r-Q_m). \qquad \qquad (24b)$$

Hence, by comparing equations (*22*) and (*24*), it is obvious that—

$$P_{11}C_{11}+P_{33}C_{31} = \frac{\lambda_1 e^{-sD1}}{s+\lambda_1-\lambda_1 e^{-sD_3}} \qquad \qquad (25a)$$

$$P_{31}C_{13}+P_{33}C_{33} = \frac{\lambda_3 e^{-sD3}}{s+\lambda_3-\lambda_3 e^{-sD3}} \qquad \qquad (25b)$$

Combining equations (*21*) and (*25*) and expressing the result via matrix notation, one obtains—

$$\begin{bmatrix} C_{11} & C_{13} \\ C_{31} & C_{33} \end{bmatrix} \begin{bmatrix} P_{11} & P_{13} \\ P_{31} & P_{33} \end{bmatrix} = \begin{bmatrix} \dfrac{\lambda_1 e^{-sD1}}{s+\lambda_1-\lambda_1 e^{-sD1}} & 0 \\ 0 & \dfrac{\lambda_3 e^{-sD3}}{s+\lambda_3-\lambda_3 e^{-sD3}} \end{bmatrix}. \qquad (26)$$

If the four controller functions are then solved for, one obtains—

$$\begin{bmatrix} C_{11} & C_{13} \\ C_{31} & C_{33} \end{bmatrix} = \begin{bmatrix} \dfrac{\lambda_1 e^{-sD1}}{s+\lambda_1-\lambda_1 e^{-sD1}} & 0 \\ 0 & \dfrac{\lambda_3 e^{-sD3}}{s+\lambda_3-\lambda_3 e^{-sD3}} \end{bmatrix} \begin{bmatrix} P_{11} & P_{13} \\ P_{31} & P_{33} \end{bmatrix}^{-1}. \qquad (27)$$

The process transfer functions required in equation (*27*) are contained in Table 5 (for both the *s* and *z* domains), from which it should be noted that P_{33} (the transfer function between slice changes and flow to the box) is equal to zero, showing that flow to the box is not substantially affected by changes in slice opening. Hence, the P matrix in equation (27) may be inverted in the following manner—

$$\begin{bmatrix} P_{11} & P_{13} \\ P_{31} & P_{33} \end{bmatrix}^{-1} = \begin{bmatrix} P_{11} & P_{13} \\ P_{31} & 0 \end{bmatrix}^{-1} = \begin{bmatrix} 0 & 1/P_{31} \\ 1/P_{13} & -P_{11}/P_{13}P_{31} \end{bmatrix}$$

By definition—

$$P_{11} = H/W \text{ and } P_{31} = Q/W$$

therefore—

$$\frac{P_{11}}{P_{31}} = \frac{H}{Q}$$

Since H/Q can be identified directly, this is the method used to estimate it rather than by taking the ratio of P_{11} to P_{31}, which are also identified.

TABLE 5

Transfer function	*s domain*	*z domain*
$\frac{H}{W} = P_{11}$	$\frac{a_1 g_1}{s+a_1} e^{-sD_1}$	$g_1(1-\eta_1)\frac{z-d_1-1}{1-\eta_1 z-1}$
$\frac{Q}{W} = P_{13}$	$\frac{a_2 g_2}{s+a_2} e^{-sD_1}$	$g_2(1-\eta_2)\frac{z-d_1-1}{1-\eta_2 z-1}$
$\frac{H}{Y} = P_{31}$	$-\frac{a_3 g_3}{s+a_3}$	$-g_3(1-\eta_3)\frac{z-1}{1-\eta_3 z-1}$
$\frac{Q}{Y} = P_{33}$	0	0
$\frac{H}{Q} = \frac{P_{11}}{P_{13}}$	$\frac{a_4 g_4}{s+a_4}$	$g_4(1-\eta_4)\frac{z-1}{1-\eta_4 z-1}$

Remark: $\eta_i = \exp(-a_i T)$, $d_i = Di/T$

Using the notation of Table 5, the P matrix becomes—

$$\begin{bmatrix} 0 & \frac{s+a_2}{a_2 g_2} e^{sD1} \\ \frac{-s+a_3}{a_3 g_3} & \frac{a_4 g_4}{s+a_4} \cdot \frac{s+a_3}{a_3 g_3} \end{bmatrix}$$

Actually, a_3 and a_4 are essentially equal, because they are the reciprocal time constants of total head to flow from and to the box, respectively. Hence, the P matrix may be reduced further to the form—

$$\begin{bmatrix} 0 & \frac{s+a_3}{a_2 g_2} e^{sD1} \\ \frac{-s+a_3}{a_3 g_3} & \frac{g_4}{g_3} \end{bmatrix}$$

which, when substituted in equation (*27*), gives—

$$\begin{bmatrix} C_{11} & C_{13} \\ C_{31} & C_{33} \end{bmatrix} = \begin{bmatrix} \frac{\lambda_1 e^{-sD1}}{s+\lambda_1-\lambda_1 e^{-sD1}} & 0 \\ 0 & \frac{\lambda_3 e^{-sD3}}{s+\lambda_3-\lambda_3 e^{-sD3}} \end{bmatrix} \begin{bmatrix} 0 & \frac{s+a_3 e^{-sD1}}{a_2 g_2} \\ \frac{-s+a_3}{a_3 g_3} & \frac{g_4}{g_3} \end{bmatrix} \qquad (28)$$

Expressions equivalent in the z domain as well as the appropriate recursive formulas are shown in Table 6.

TABLE 6

Value	*z domain*	*Recursion formula*
$\frac{W}{H}C_{11}$	0	$W_1 = 0$
$\frac{W}{Q}C_{31}$	$\frac{(1-\theta)(1-\eta_2 Z^{-1})}{g_2(1-\eta_2)[1-\theta Z^{-1}-(1-\theta)Z^{-\Gamma-1}]}$	$W_2^i = \frac{(1-\theta)}{g(1-\eta_2)}(Q^i-\eta_2 Q^{i-1})+ W_2{}^{i-1}+(1-\theta)W_2{}^{i-\Gamma-1}$
$\frac{Y}{H}C_{13}$	$\frac{-(1-\theta)(1-\eta_3 Z^{-1})Z^{-\Gamma}}{g_3(1-\eta_3)[1-\theta Z^{-1}-(1-\theta)Z^{-\Gamma-1}]}$	$Y_2^i = \frac{-(1-\theta)}{g_3(1-\eta_3)}(H^{i-\Gamma}-\eta_3 H^{i-\Gamma-1})+ \theta Y^{i-1}+(1-\theta)Y^{i-\Gamma-1}$
$\frac{Y}{Q}C_{33}$	$\frac{g_4(1-\theta)Z^{-\Gamma-1}}{g_3[1-\theta Z^{-1}-(1-\theta)Z^{-\Gamma-1}]}$	$Y_2^i = \frac{g_4(1-\theta)}{g_3}Q^{i-\Gamma-1}+ \theta Y_2{}^{i-1}(1-\theta)Y^{i-\Gamma-1}$

Needless to say, the algorithms required by this approach are considerably more complex than any of those discussed previously. In addition, considerably more identification work is required because interactions between loops must be quantified. Nevertheless, the added effort is well repaid as evidenced by the excellent response shown by total head and flow to the box during a typical grade change (Fig. 15).

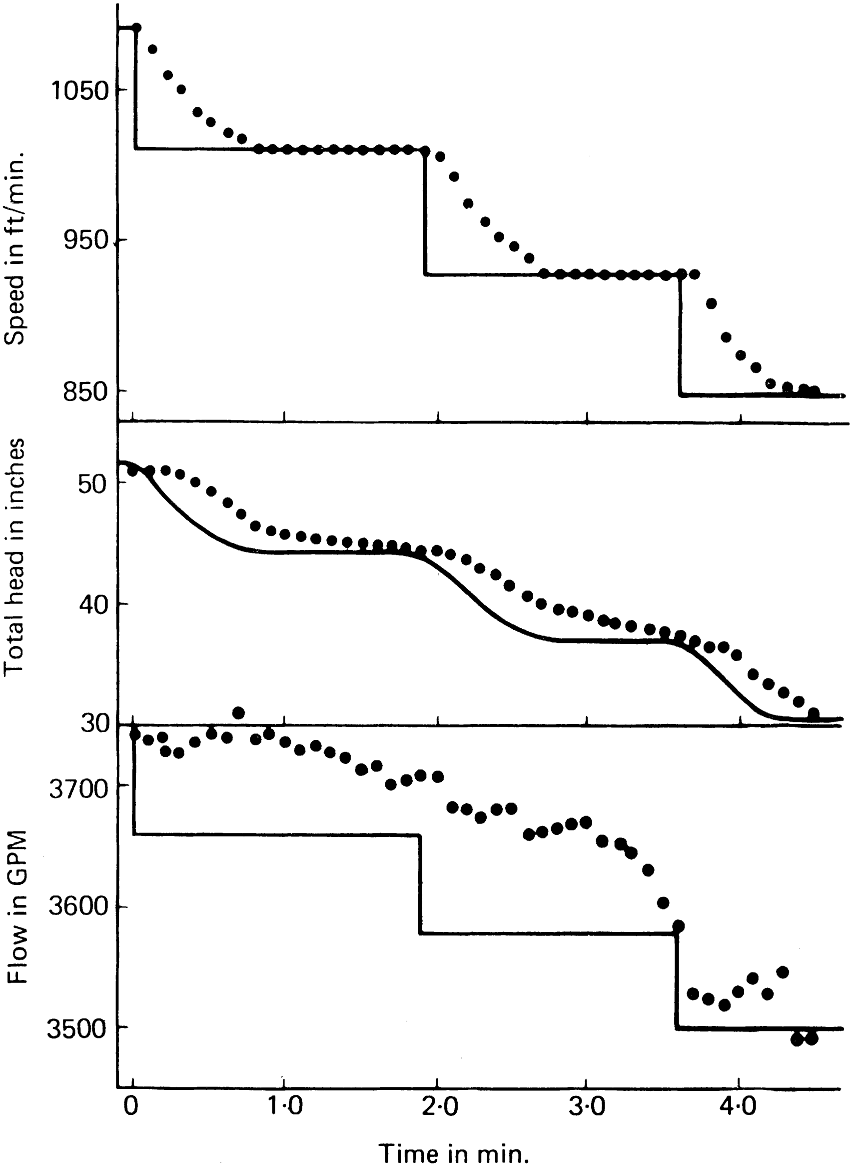


Fig. 15—Head box response during a grade change

The grade change program serviced by the head box control system in this instance is built around a series of large steps (80 ft/min) in machine speed, which are used to drive the papermachine from one operating point to another. The net effect of this is to impose a series of step-like changes in total head set point (as calculated by the head box drag controller) and step adjustments in flow rate set point. The job of the head box controller is to respond to these set point changes in minimum time and with minimum overshoot. Fig. 15 shows that the 2×2 decoupled controller described there seems well able to meet these requirements.

The changes in total head and flow operating points were 19·9 in and 250 gal/min, respectively. The maximum error encountered in each of the two loops were 3·7 in and 127 gal/min, which is very good considering that the 80 ft/min speed changes engendered 6·5 in and 84 gal/min total head and flow set point changes each time they occurred. Experience so far has shown that the head box system is the one limiting the speed of grade change. Hence, the next speed step is not allowed to occur until the total head error is reduced to 0·5 in. Nevertheless, the 240 ft/min change was accomplished in a mere 4·5 min, which explains the importance of having an active, accurate head box control system.

In summary, it is possible to design a 2×2 decoupled controller for total head and flow from the box via Dahlin's method of cancellation compensation. Liquid level control was ignored in the derivation, since its set point is seldom, if ever, changed and it is felt that a conventional analog controller arranged as described in part 1 would provide adequate performance.

Additional identification work was required to quantify all the interactions in the 2×2 controller, but this effort was well repaid via a decided improvement in head box control without the necessity of resorting to exotic manipulated variables or controlled variable sensing devises. Needless to say, the 2×2 algorithms were implemented digitally because of their complexity. Level control, on the other hand, continued to be via a conventional analog PI controller. Finally, it should be noted that adjustments to the 2×2 controller's parameters have been found to be necessary to retain good operating performance over the entire head box's operating range. When such changes are necessary during a grade change they are made automatically via the digital computer used to implement the algorithms.

Controller design—part 6

PART 5 having just outlined the advantages of a 2×2 total head/flow from the box, decoupled control, one might ask, 'If a 2×2 decoupled controller is superior to the simpler systems described in parts 3 and 4, would not a 3×3 decoupled controller be still better?' The answer is, 'Yes, it is in certain circumstances, but a 3×3 controller also places a substantial load on the digital data acquisition and control systems.' Nevertheless, let us proceed with a description of how such a system can be designed and worry about its limitations later.

The first thing to realise when designing a 3×3 controller for the head box is that complete decoupling is not required or even desirable. To be specific, complete decoupling is desired between total head and liquid level, whereas only partial decoupling is needed between total head and flow and no decoupling is required between liquid level and flow. The practical reasons for this are best understood by referring to Fig. 16, from which it may be seen that—

1. Total head and liquid level are completely decoupled as evidenced by the fact that controllers C_{11}, C_{12}, C_{21} and C_{22} exist. This design is justified by the fact

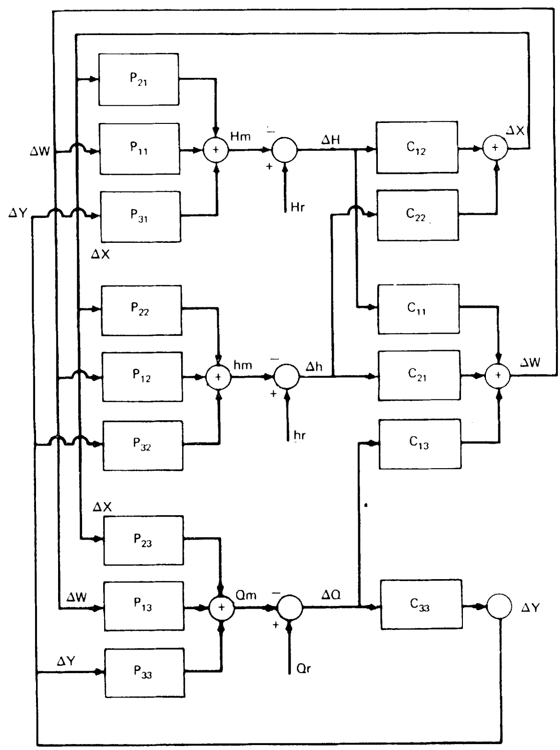


Fig. 16—Block diagram for the 3×3 decoupled controller

that it does give optimum total head and liquid level control and the papermaker does not object to rapid and/or extensive manipulation of the head box air and water valves.

2. Total head and flow from the box are only partially decoupled, because the papermaker objects to excessive adjustment of his slice. Hence, controller C_{13} is included to minimise the effect of slice adjustments on total head and liquid level, but no controller C_{31} is provided to allow slice adjustments when a total head error exists.
3. Liquid level and flow from the box are not decoupled at all, because the papermaker again objects to excessive slice manipulation, thereby eliminating controller C_{32}; controller C_{23} was left out, because air valve manipulation was considered to be inconsequential when dealing with flow errors.

Mathematically, the relationships depicted in Fig. 16 can be expressed as follows—

$$\begin{aligned} H_m &= P_{11}\Delta W + P_{12}\Delta X + P_{13}\Delta Y \\ h_m &= P_{21}\Delta W + P_{22}\Delta X + P_{23}\Delta Y \\ Q_m &= P_{31}\Delta W + P_{32}\Delta X + P_{33}\Delta Y \end{aligned} \qquad . \quad . \quad . \quad (29)$$

Actually, however, P_{32} and P_{33} turn out to be very near to zero, because changes in air valve position and slice opening have very little effect on the flow of stock to the box the variable being measured. Hence, equation (*29*) reduces to—

$$Q_m = P_{31}\Delta W$$

Also from Fig. 16, it may be seen that—

$$\begin{aligned} \Delta W &= C_{11}\Delta H + C_{12}\Delta h + C_{13}\Delta Q \\ \Delta X &= C_{21}\Delta H + C_{22}\Delta h \\ \Delta Y &= C_{33}\Delta Q \end{aligned} \qquad . \quad . \quad . \quad (30)$$

Reducing equations (*29*) and (*30*) to matrix form, we have—

$$\begin{bmatrix} H_m \\ h_m \\ Q_m \end{bmatrix} = \begin{bmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & 0 & 0 \end{bmatrix} \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & 0 \\ 0 & 0 & C_{33} \end{bmatrix} \begin{bmatrix} \Delta H \\ \Delta h \\ \Delta Q \end{bmatrix}$$

which may be reduced to—

$$\begin{bmatrix} H_m \\ h_m \\ Q_m \end{bmatrix} = \begin{bmatrix} P_{11}C_{11}+P_{12}C_{21} & P_{11}C_{12}+P_{12}C_{22} & P_{11}C_{13}+P_{13}C_{33} \\ P_{21}C_{11}+P_{22}C_{21} & P_{21}C_{12}+P_{22}C_{22} & P_{21}C_{13}+P_{23}C_{33} \\ P_{31}C_{21} & P_{31}C_{22} & P_{31}C_{13} \end{bmatrix} \begin{bmatrix} \Delta H \\ \Delta h \\ \Delta Q \end{bmatrix} \qquad (31)$$

From the decoupling restrictions discussed above, it can be shown that—

$$P_{11}C_{12}+P_{12}C_{22} = 0 \quad (32a)$$
$$P_{21}C_{11}+P_{22}C_{21} = 0 \quad (32b)$$
$$P_{11}C_{13}+P_{13}C_{33} = 0 \quad (32c)$$
$$P_{21}C_{23}+P_{23}C_{33} = 0 \quad (32d)$$

where equations (*32a*) and (*32b*) imply complete decoupling between total head and liquid level. Equation (*32c*), on the other hand, expresses the partial decoupling between flow and total head. This also forces a partial decoupling between flow and liquid level—see equation (*32d*)—because, in order to achieve the decoupling specified in equation (*32c*), the water valve is adjusted before the slice so that flow in and out of the box are held in equilibrium. This not only eliminates bumps in total head, but in liquid level as well. As a result of the above, equation (*31*) reduces to—

$$\begin{bmatrix} H_m \\ h_m \\ Q_m \end{bmatrix} = \begin{bmatrix} P_{11}C_{11}+P_{12}C_{21} & 0 & 0 \\ 0 & P_{21}C_{12}+P_{22}C_{22} & 0 \\ P_{31}C_{21} & P_{31}C_{22} & P_{31}C_{13} \end{bmatrix} \begin{bmatrix} \Delta H \\ \Delta h \\ \Delta Q \end{bmatrix} \quad (33)$$

which may be stated as a series of algebraic equations in the following manner—

$$H_m = (P_{11}C_{11}+P_{12}C_{21})\Delta H \quad (34a)$$
$$h_m = (P_{21}C_{12}+P_{22}C_{22})\Delta h \quad (34b)$$
$$Q_m = P_{31}(C_{21}\Delta H+C_{22}\Delta h+C_{13}\Delta Q) \quad (34c)$$

Equations (*34a*) and (*34b*) show that total head and liquid level will only be affected by changes in their set points, whereas flow to the box is affected by changes in any of the three variables—see equation (*34c*). Therefore, it is necessary to have a dead band around flow set point or the decoupling so laboriously avoided in the case of slice adjustments will be negated.

To complete the design of the six controllers required (Fig. 16), it is necessary to specify the response desired for each of the loops. Mathematically, this is accomplished via equations (*35*)—

$$\frac{H_m}{H_r} = \frac{\lambda_1}{s+\lambda_1} e^{-sD1} \quad (35a)$$

$$\frac{h_m}{h_r} = \frac{\lambda_2}{s+\lambda_2} e^{-sD2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (35b)$$

$$\frac{Q_m}{Q_r} = \frac{\lambda_3}{s+\lambda_3} e^{-sD3} \quad . \quad . \quad . \quad . \quad . \quad (35c)$$

which state that each loop is expected to show a closed loop response equivalent to a first-order system with dead time. If equations (*35*) are now combined with equations (*32*) and (*34*), the result is a matrix analogous to equation (*26*) in part 5. This expression can in turn be manipulated as shown previously to obtain an equation analogous to equation (*28*) (in part 5) that specifies the controllers required to achieve the performance specified by equation (*35*) and Fig. 16.

Needless to say, the control system required to achieve 3×3 decoupling of the type specified is complex, but it has been implemented and shown to work on a practical basis. Such a system does not show substantially superior performance to the system described in parts 3 and 4 however. Hence, its utility is rather severely limited, because it requires a considerably more complex algorithm and identification structure than previous approaches. In addition, this approach requires a considerably faster sampling rate (once per second or less) than other systems, because the transfer functions between air valves position and both total head and liquid level show a 3·5 s time constant (Table 3) plus an integrator in the case of liquid level. This integrator is the worst offender, since it tends to make liquid level oscillate unless given continual attention. Hence, it has been the authors' experience that the use of an analog controller on the liquid level system is best. Decoupling between the air valves and total head is sacrificed, but this has been found to be a small price to pay for the greater stability and lower sampling rates achieved.

To summarise, it is possible to design and implement a 3×3 digital control system for the head box. Such a system is not substantially superior in performance to the systems described in parts 3, 4 and 5, however and the increase in sampling and algorithm complexity required to implement it are not justifiable.

Conclusions

FROM the above, it should be obvious that it is possible to characterise the head box as a control system, to identify its dynamic parameters as a function of operating point and to design a variety of control systems with which to control it with varying degrees of facility. In addition, it should be obvious that though many Fourdrinier machines are still equipped only with head box liquid level control systems, there is no reason that the papermaker must tolerate such inconvenience. A 2×2 digital head box controller with analog control of liquid level is recommended as the best system currently available. Finally, it should be noted that no modern head box should be installed without means for sensing not only liquid level and total head, but flow to the box as well. Such sensors are required to implement modern control systems, which it should also be remembered require an ability to adjust head box water valve, air valves and slice opening automatically. In concluding, the reader is again reminded that all of the work reported has been carried out at speeds of 1 100 ft/min or less. It is expected, however, that the insights gained should be transferable to Fourdrinier machines operating at considerably greater speeds.

Future work

So far, attention has been directed almost entirely toward gaining good total head, liquid level and flow control for the head box and relatively efficient means for accomplishing this have been achieved. Other factors associated with the head box do have a significant effect on Fourdrinier machine operation, however and should be brought under control. For example, industrial experience shows that the basis weight profile of a sheet of paper can be obtained by merely averaging several successive beta-gauge traces. In addition, the authors have determined that this profile can be manipulated via slice screw adjustments without encountering the anomalous side effects reported in papermaking lore and fable. As a result, it would seem quite possible to achieve true basis weight profile control in the relatively near future by merely designing a matrix controller, using the basis weight profile as a controlled variable and slice screws position as the manipulated variables. The algorithm structure required will not be simple, particularly if decoupling between adjacent screws is required, but it is feasible with existing equipment and should be implemented as soon as adequate means for controlling moisture profile are also available. We at Consolidated Papers have already shown that control to within a range of 0·3 lb/ream is attainable with a simple supervisory type controller.

Another factor having an important bearing on sheetforming is the jet escape angle from the head box. No good method is currently available for sensing this angle directly, but it can be estimated using the data developed by Nelson[5] if slice opening and lower lip extension are known. Using these data as feedback, it is then possible to adjust lower lip position when making slice adjustments on the head box to ensure delivery of the jet to the wire at a fixed point. This in turn should aid in stabilising drainage on the machine substantially.

Finally, a third factor having a decided effect upon sheet formation and drainage is the degree of flocculation existing in the jet as it is delivered to the wire. Many factors influence this property and it is not at present possible to measure it on-line in a practical manner. Nevertheless, it is known that holey roll position and rotational speed as well as stock velocity in the box affect flocculation. Hence, there should be variables that can be manipulated to control the parameter, provided it is subsequently found to be of sufficient importance to merit closed loop control.

Appendix 1—Head box simulation program

SIMULATION methods have been used extensively throughout the work reported here. Fortunately, the authors had a modest sized IBM 360 computer available to them and were able to modify IBM's continuous systems modelling program[6] to operate on this computer. The material presented in the following consists of a block diagram for the head box equipped with analog controllers (Fig. A–1) and the CSMP diagram (Fig. A–2) corresponding to it. Tables A–1 to A–3 contain the configuration and specifications for the analog controlled head box depicted in Fig. A–2, whereas Tables A–4 to A–6 do the same for a digitally controlled box.

TABLE A–1 CONFIGURATION SPECIFICATION OF HEAD BOX MODEL WITH ANALOG CONTROLLERS

Output name	*Block number*	*Type*	*Input 1*	*Input 2*	*Input 3*	*Description*
Air valve movement	1	1	21			Dead time block
Water valve movement	2	3	31			Dead time block
Total head error	3	t	11	−12		Summer
Liquid level error	4	W	6	8		Weighted summer
	5	I		1	5	First order lag
	6	I	5			Integrator
	7	I		9	7	First order lag
	8	I		9	8	First order lag
	9	t	2	10		Summer
Disturbance	10	K				Constant block
Total head set point	11	K				Constant block
Total head response	12	W	13	5	7	Weighted summer
Initial total head	13	K				Constant block
Analog liquid level controller	21	W	4	22		Weighted summer
	22	I	4			Integrator
Analog total head controller	31	W	3	32		Weighted summer
	32	I	3			Integrator

TABLE A–2 NUMERICAL VALUES OF HEAD BOX MODEL AT 50 lb/ream GRADE

Parameter name	*Block number*	*Parameter of input 1*	*Parameter of input 2*	*Parameter of input 3*
Dead time, D_2	1		1·0	
Dead time, D_1	2		5·5	
Process gain, $-g_2$, g_4	4	−0·001	0·142	
a_1, $-a_1$	5		0·224	−0·224
a_3, $-a_3$	7		0·0484	−0·0484
a_4, $-a_4$	8		0·0133	−0·0133
Total head set point	11	31·0		
Process gains, g_1 and g_3	12	1·0	0·02	0·354
Gain and reset, p_1 and i_1	21	20·0	1·0	
Gain and reset, p_2 and i_2	31	11·1	0·555	
Initial total head	13	30·0		

TABLE A–3 NUMERICAL VALUES OF HEAD BOX MODEL AT 100 lb/ream GRADE

Parameter name	*Block number*	*Parameter of input 1*	*Parameter of input 2*	*Parameter of input 3*
Dead time, D_2	1		1·0	
Deaa time, D_1	2		8·5	
Process gain, $-g_1$ and g_4	4	−0·001	0·142	
a_1 and $-a_1$	5		0·224	−0·224
a_3 and $-a_3$	7		0·0619	−0·0619
a_4 and $-a_4$	8		0·0091	−0·0091
Total head set point	11	18·0		
Total gains	12	1·0	0·02	0·132
Initial total head	13	17·0		
Gain and reset, p_1 and i_1	21	20·0	1·0	
Gain and reset, p_2 and i_2	31	11·1	0·555	

TABLE A–4 CONFIGURATION SPECIFICATION OF HEAD BOX MODEL WITH DIGITAL TOTAL HEAD CONTROLLER AND ANALOG LIQUID LEVEL CONTROLLER

Output name	*Block number*	*Type*	*Input 1*	*Input 2*	*Input 3*	*Description*
Air valve movement	1	1	21			Dead time block
Water valve movement	2	3	31			Dead time block
Total head error	3	t	11	−12		Summer
Liquid level error	4	W			5	Weighted summer
	5	I		1	5	First order lag
	6	I	5		7	Integrator
	7	I		9	7	First order lag
	8	I		9	8	First order lag
	9	t	2	10		Summer
Disturbance	10	K				Constant
Total head set point	11	K				Constant
Total head response	12	W	13	5	7	Weighted summer
Initial total head	13	K				Constant
Analog liquid level controller	21	W	4	22		Weighted summer
	22	I	4			Integrator
Digital total head controller, W_i	31	W	32	37	39	Weighted summer
	32	W	35	33		Weighted summer
H_{i-1}	33	Z	34	40		Zero order holder
	34	U	35			Unit delay
H_i	35	Z	3	40		Zero holder order
	36	U	31			Unit delay
W_{i-1}	37	Z	36			Zero order holder
	38	U	37			Unit delay
W_{i-2}	39	Z	38	40		Zero order holder
	40	t	76			Time trigger
	76					Time

TABLE A–5 NUMERICAL VALUES OF HEAD BOX MODEL WITH DIGITAL CONTROLLER AT 50 lb/ream GRADE

Parameter name	*Block number*	*Parameter of input 1*	*Parameter of input 2*	*Parameter of input 3*
Dead time, D_2	1		1·0	
Dead time, D_1	2		5·5	
Process gain, $-g_2$, g_4	4	−0·001	0·142	
a_1, $-a_1$	5		0·224	−0·224
a_3, $-a_3$	7		0·0484	−0·0484
a_4, $-a_4$	8		0·0133	−0·0133
Total head set point	11	1·0		
Process gains, g_1 and g_3	12	1·0	0·02	0·354
Gain and reset, p_1 and i_1	21	20·0	1·0	
	31	5·223	0·428	0·572
	32	1·0	−0·691	
Sampling interval	40	8·0		

TABLE A–6 NUMERICAL VALUES OF HEAD BOX MODEL WITH DIGITAL CONTROLLER AT 100 lb/ream GRADE

Parameter name	*Block number*	*Parameter of input 1*	*Parameter of input 2*	*Parameter of input 3*
Dead time, D_2	1		1·0	
Dead time, D_1	2		8·5	
Process gain, $-g_2$, g_4	4	−0·001	0·142	
a_1, $-a_1$	5		0·224	−0·224
a_3, $-a_3$	7		0·0619	−0·0619
a_4, $-a_4$	8		0·0091	−0·0091
Total head set point	11	18·0		
Process gains, g_1 and g_3	12	1·0		
Initial total head	13	17·0		
Gain and reset, p_1 and i_1	21	20·0	1·0	
	31	11·1	0·428	
	32	1·0	−0·61	
Sampling interval	40	8·0		

Needless to say, such a simulation tool has been invaluable to the authors and has been found to be far more convenient to use than a conventional analog computer, because scaling problems are virtually eliminated. The program used does require more or less easy access to a modest sized computer, but, if this condition can be met, it is the authors' opinion that one would be foolish to use an analog machine in preference to it.

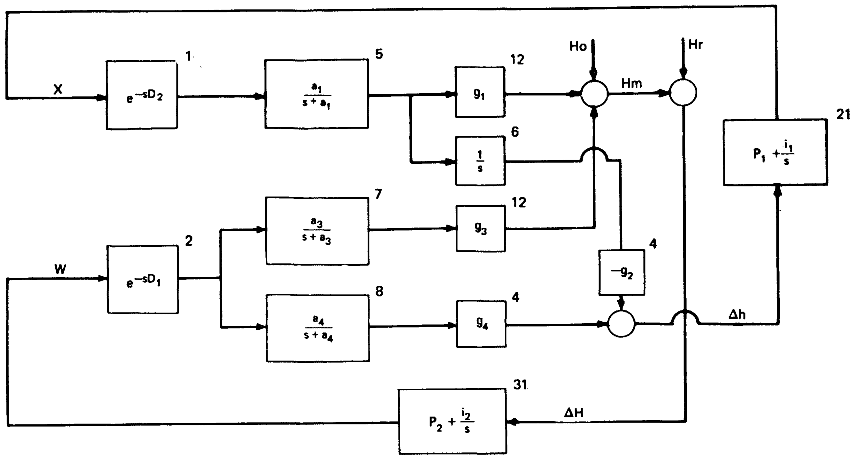


Fig. A1—Block diagram of head box model with analog controllers

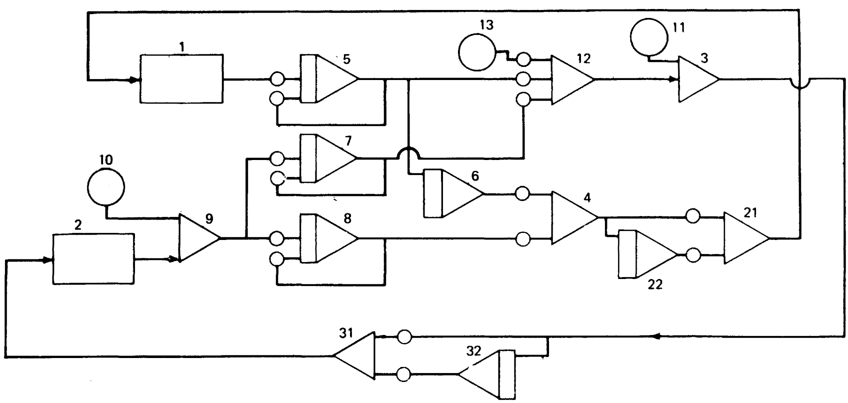


Fig. A2—CSMP block diagram

Appendix 2—Table of nomenclature

A	Cross-section of head box
a	Reciprocal of time constant in process transfer function
$C(s)$	Generalised transfer function for a controller
C_1–C_4	Physical constants of head box
C_{11}	Controller transfer function between water valve and total head

C_{12}	Controller transfer function between air valve stem positions and total head
C_{13}	Controller transfer function between slice position and total head
C_{21}	Controller transfer function between water valve and liquid level
C_{22}	Controller transfer function between air valve stem positions and liquid level
C_{23}	Controller transfer function between slice position and liquid level
C_{31}	Controller transfer function between water valve and flow
C_{32}	Controller transfer function between air valve stem positions and flow
C_{33}	Controller transfer function between slice and flow
D	Dead time
d	Integral of dead time to sampling interval ratio
d_g	Drag (in feet)
e	Natural lag base
$E(s)$	Generalised error
$F(s)$	Generalised close loop transfer function
G	Theoretical transfer function
g	Gravitational constant
g_1–g_4	Gain in process transfer function
H	Total head (in inches)
h	Liquid level (in inches)
K	Gain
M	The mass of air pad
M_a	The net air flow into head box
$M(s)$	Generalised output
P	Air pad pressure
$P(s)$	Generalised transfer function for a process
P_{11}	Process transfer function between total head and water valve
P_{12}	Process transfer function between liquid level and water valve
P_{13}	Process transfer function between flow and water valve
P_{21}	Process transfer function between total head and air valve stem positions
P_{22}	Process transfer function between liquid level and air valve stem position
P_{23}	Process transfer function between flow and air valve stem position
P_{31}	Process transfer function between total head and slice
P_{32}	Process transfer function between liquid level and slice
P_{33}	Process transfer function between flow and slice
Q_i	Inlet liquid flow
Q_o or Q	Outlet liquid flow
R	Gas constant
$R(s)$	Generalised set point
s	Laplace operator
T'	Absolute temperature
T	Sampling interval
t	Time

$U(s)$	Generalised disturbance
U_w	Wire speed
V	Volume of air pad
V_o	Total volume of head box
W	Water valve movement (in seconds)
X	Air valve stem movement (in seconds)
Y	Slice movement (in seconds)
z	z-transform operator
Υ	Time constant
λ_1	System cut off frequency for total head box
λ_2	System cut off frequency for liquid level loop
λ_3	System cut off frequency for flow loop
Γ	Dead time, same as d
η	Dummy variable
θ	Dummy variable

Subscripts—

i	Flow to head box
m	Measured response
o	Flow from head box
r	Set point

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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.