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DESIGNING FOR CONTROL

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Synopsis The best way to achieve a well-controlled process is to consider the control during design of the equipment. The steps in designing for control are stated, then expanded in a discussion of the design of flow boxes. An analysis shows how the control of a flow box is affected by the geometry of the box and the characteristics of the air pad supply system.

Introduction

IN THE eighteenth century, millers found that they had to change the gap between the millstones of a flourmill when the wind speed changed. They did this by including a Huygens' conical pendulum, which rose when the mill speed increased and lifted one of the millstones. Clearly, the modification of equipment to achieve more uniform operation in the face of disturbances is not new, but the realisation that automatic control can give improved performance of many systems has led to greater emphasis being placed on control in recent years. Often the cause of poor control is a plant deficiency rather than an instrumentation fault and the need to design systems that are inherently self-regulating or at least amenable to automatic control has become apparent.[1] This is in contrast to the practice of trying to add suitable instrumentation and automatic controllers after the plant design has been completed.

The aim of this paper is to show how a consideration of control can be included as an extension of the normal design procedure and sets out a classification of the commonly used methods for achieving satisfactory control. These general principles are expanded in a discussion of the control of stock level and slice flow from a papermachine flow box.

General design procedure

THE method followed in a systematic design follows a logical sequence—

1. Specification of the requirements to be met by the equipment.
2. Characterisation of the environment in which the equipment must operate.
3. Development of criteria by which the anticipated performance of alternative designs may be judged.

Under the chairmanship of P. E. Wrist

4. Synthesis of alternative proposals for satisfying the requirements.
5. Analysis of alternatives and choice of the best by reference to the criteria previously developed.

When applied to the design of a flow box, the details under each of these headings would include those given in Appendix 1.

If the requirements for satisfactory control are considered from the start, the design follows the same steps, but is enlarged to include control aspects as follows—

1. The quantities to be maintained within prescribed limits are specified and the priority of conflicting requirements is established.
2. Control is necessary because of the presence of disturbances that reach a level when they cause unacceptable variation. Control is also needed when the system is required to settle quickly after a change. The sources of disturbance should be identified as far as possible and the form and magnitude of the disturbances specified.
3. The criteria by which control is judged are the residual variation in the system variables and the speed of reaching equilibrium after a change. The cost of attaining satisfactory performance is to be minimised.
4. In general, there are four ways in which control requirements might be satisfied—

   (*a*) Elimination or reduction in the magnitude of the disturbance. Although it is obviously desirable to eliminate all sources of variation, it is seldom possible to do so. In many cases, when it might be technically feasible, the cost may be prohibitive. On the other hand, the possibility should always be investigated. For example, the provision of increased resistance in the stock approach flow system may appear unattractive at first, but may yet provide the most satisfactory means of obtaining adequate control, when the resistance of the screen in the approach flow line varies unpredictably.

   (*b*) Design of the system so that its variables are inherently slow to respond to disturbances. If control is to be improved in this way, it is essential that the disturbances fluctuate about a steady level. The principle is essentially that of the flywheel, which maintains steady motor speed in the face of rapidly fluctuating drive power. If the disturbances are slow drifts or infrequent changes from one steady level to another, then, although the system responds only slowly, their final effect will be significant. When the effective inertia of a system is increased, the time taken to settle after an operating change is also increased. The value of this form of control will thus depend on the form of the disturbances, as well as on the relative importance of fast settling after a change.

   (*c*) Design of the system so that it is inherently self-regulating. The system responds to disturbances in such a way that the system outputs tend to remain constant. The great advantages of self-regulation are that control is not dependent on ancillary equipment and there is no delay in reducing the effects of a disturbance. Yet self-compensation is seldom exact and a residual error will persist if the disturbance has the form of a change in average value.

(*d*) Design of additional instrumentation and controllers to enable external, automatic control. This is sometimes the only method considered for providing satisfactory control. External control suffers from a delay in measuring and reacting to a change that could mar performance. It does allow exact long-term compensation.

The best design may blend all four methods of control so that the advantages of each are realised. It is also necessary to allow for conflicting attributes. For example, the external control of a system is more prone to instability when the inertia is high and then controller settings become more critical.

5. Alternative designs are compared according to the criteria that may be evaluated by direct calculation or simulation.

Control of a flow box

WHEN the general principles outlined are applied to the problem of achieving satisfactory control of slice flow and stock level, the details of the design procedure are as follows.

The total head and stock level are required to remain close to their set values when the flow of stock to the box is subject to disturbance. Equilibrium is reached quickly after a change in slice flow or specified total head. It is possible that the requirements for close control of both total head and level may conflict. In this case, it is clear that changes in total head have an important effect on slice flow and jet velocity, whereas small changes in level are not critical. Therefore, when the requirements conflict, it will be preferable to maintain tight control of total head at the expense of stock level.

The range of operating values for total head and slice flow must be specified. Step disturbances in stock flow may be described by the step size and frequency of occurrence. Continously varying fluctuations may be characterised in terms of the magnitude of the components at various frequencies (the power spectrum).

The means of judging the response to step changes in stock flow or operating conditions is to compare the transient response of alternative systems. The best transient response will have fastest settling and least overshoot. The ability to control in the face of fluctuations in stock flow can be gauged from the two ratios—

$$\frac{\text{Percentage variation in slice flow}}{\text{Percentage variation in stock flow to the flow box}}\;;\;\frac{\text{Percentage variation in level}}{\text{Percentage variation in stock flow to the flow box}}$$

at various frequencies. The relative importance of these ratios at different frequencies will depend on the power spectrum of the disturbances. Overshadowing these criteria are the hydraulic and structural design requirements that must be satisfied and the need to minimise cost for a given performance.

Alternative means of satisfying the requirements may be listed in the four categories given earlier—

1. Minimising the sources of disturbance. This method has already been discussed.
2. Slow response to disturbances. Design choices that influence this aspect are—
   (*a*) Open/pressurised flow box.
   (*b*) Air pad volume.
   (*c*) Stock surface area.
3. Self-regulation. This category includes—
   (*a*) Characteristics of pressurising air supply and exhaust system.
   (*b*) Hornbostel hole.
   (*c*) Internal overflow.
4. External control. The alternatives available include—
   (*a*) Level control alone by adjustment of air supply.
   (*b*) Control of total head by adjustment of the air supply and level by adjustment of stock flow.
   (*c*) Vice versa.
   (*d*) Various controller settings.
   (*e*) Non-interacting control.

It has been possible to derive the equations governing the performance of a flow box and use these to assess the influence of the various design alternatives. The details of the analysis are given in Appendix 2.

Disturbance response

By evaluating the expressions given in Appendix 2, it has been possible to determine the ratios—

$$\frac{\text{Percentage variation in slice flow}}{\begin{array}{c}\text{Percentage variation in stock flow}\\ \text{to the flow box}\end{array}}\ ; \qquad \frac{\text{Percentage variation in level}}{\begin{array}{c}\text{Percentage variation in stock flow}\\ \text{to the flow box}\end{array}}$$

for different design choices at various frequencies. These frequency response ratios are used to compare alternatives and to gauge the relative importance of each choice.

Open flow box

The frequency responses for an open flow box (Fig. 1) are similar in form for both slice flow and level. There is no reduction of low frequency disturbances until the ratios fall steeply after the breakpoint at $\frac{30}{\pi} \cdot \frac{a}{A}$ c/min.

where A in^2/in is the stock open surface area per unit width,

$a = (Q_o/2H)$ in/s is the slice setting index relating,

Q_o in^3/in s is the slice flow per unit width and

H in is the total head.

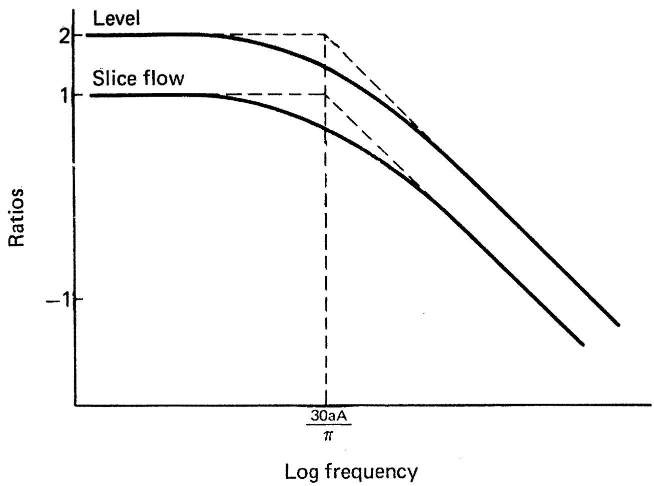

Fig. 1—Disturbance response ratios for and open flow box

For given operating conditions, a is fixed. The disturbance response is then determined by the stock surface area per unit width. As A is increased, the damping becomes significant at lower frequencies—that is, less rapid disturbances are smoothed.

Pressurised flow box

When the flow box is pressurised and the air supply and exhaust flow rates are independent of the flow box pressure, the frequency response is similar in form to that for an open box, but the breakpoint is at a frequency of—

$$\frac{30}{\pi} \cdot \frac{a}{A} \left(1 + \frac{PA}{V}\right) \text{ c/min,}$$

where P in is the absolute air pressure in the flow box and

V in^3/in is the air volume per unit width.

Since zero gauge pressure is 407 in absolute, (PA/V) is almost always considerably greater than unity and the breakpoint is at a much higher frequency than for an open box. The closed box is therefore much more sensitive to rapid disturbances.

In a practical flow box system, the air supply and exhaust flow rates are influenced by changes of flow box air pressure. A measure of this influence is the change in the net rate of the flow of air into the box, caused by a unit change of pressure in the box. In the mathematical analysis given in Appendix 2, this is the factor written as c. The units of c are inches absolute pressure times cubic inches per second change of air flow per inch width per inch change of pressure. The general form of the disturbance responses for slice flow and level is given in Fig. 2.

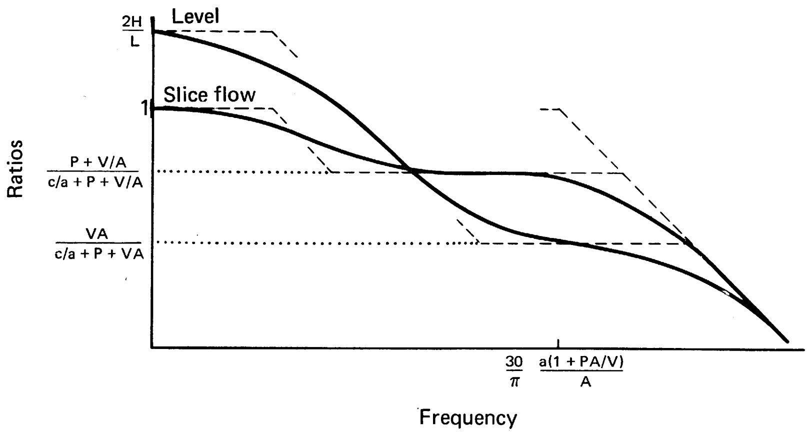

Fig. 2—Disturbance response ratios for pressurised flow box

The high frequency response is fixed by the same breakpoint at $\frac{30}{\pi}\cdot\frac{a}{A}\left(1+\frac{PA}{V}\right)$ c/min, but the mid-frequency ratios tend to $\frac{P+V/A}{c/a+P+V/A}$ for slice flow and $\frac{2H}{L}\,\frac{V/A}{c/a+P+V/A}$ for level. Again, there is no damping at low frequencies.

Dimensions and air system characteristics

THE effect of changes in the dimensions of a typical flow box are shown in the frequency response diagram on Fig. 3. These curves illustrate that the high frequency performance is determined almost entirely by the air pad

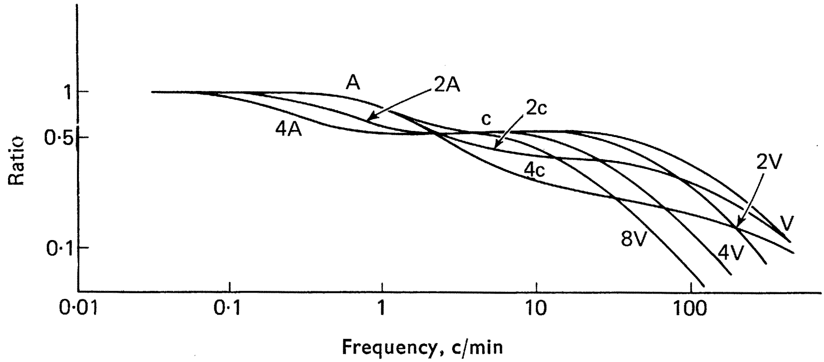

Fig. 3—Slice flow response ratios for various design choices

volume *V* and the frequency at which reduction in the effect of the disturbance first occurs depends on the stock surface area *A*.

The effect of increasing *c* (making the air system more sensitive to changes in flow box pressure) is to reduce the ratios in the middle frequency range. The *c* factor for a valve alone is directly proportional to the flow through it and inversely proportional to the pressure drop across it. Therefore, the *c* factor for an air system consisting of a constant volume blower and exhaust valve may be increased by increasing the equilibrium supply flow. A fan has a much flatter pressure/flow characteristic than a positive displacement pump, hence a greater *c* factor.

The fairly limited range of performance covered by quite major differences in these design choices can be gauged from the relatively small spread of the curves for alternative systems. The importance of the choices will depend primarily on the frequencies of the most troublesome disturbances. For example, it can be seen by reference to Fig. 3 that modification of the air system is the best method when the major disturbances are in the range 3–12 c/min.

Self-regulation of level

THE analysis of disturbance response confirms the observation that the basic flow box can damp high frequency disturbances, but provides no inherent control over slow changes. It is therefore necessary to incorporate further control. Level changes occur when the balance between stock flows to and from the box is upset so that level control may be exercised by inherent adjustment of the flow leaving the slice or overflowing within the box. Both of these forms of control have been considered in Appendix 2 and the frequency response diagrams for a typical flow box given in Fig. 4 and 5.

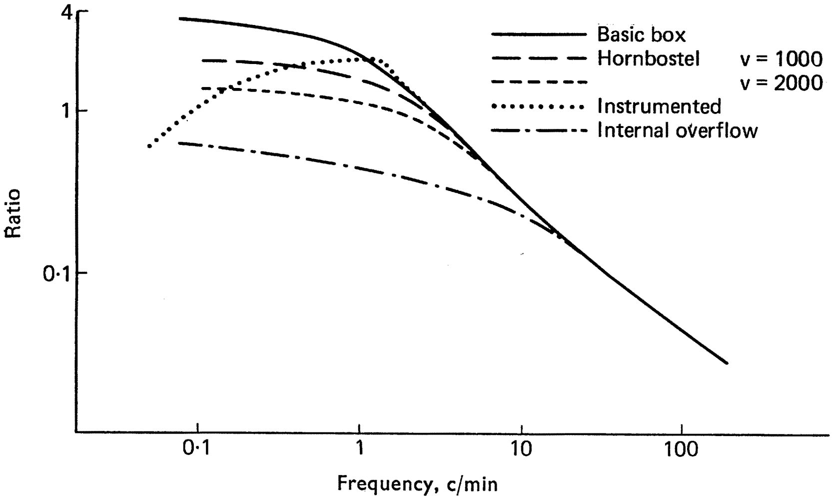

Fig. 4—Slice flow response ratios under various forms of level control

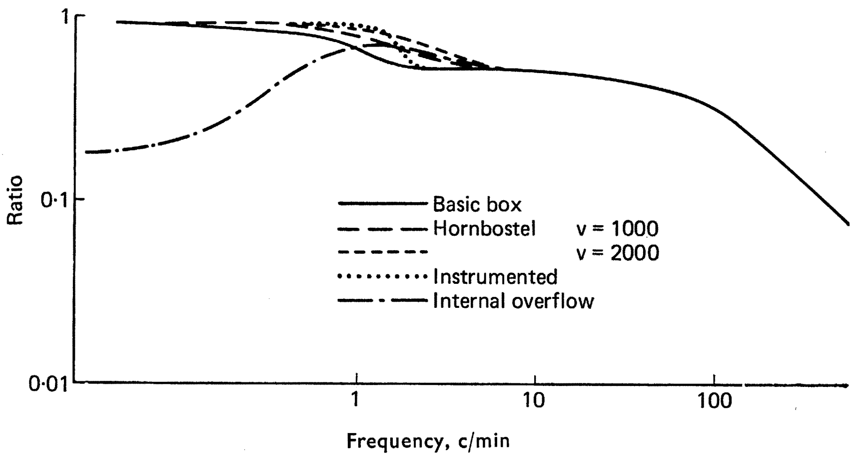

Fig. 5—Stock level response ratios under various forms of level control

The performance at high and intermediate frequencies for both systems is similar to the basic flow box, the differences between the various systems becoming apparent only at low frequencies.

The Hornbostel hole level controller inherently adjusts the air bleed, which in turn affects the air pad pressure and the flow from the slice. In this case, disturbances that upset the level are corrected by upsetting the flow from the slice. The conflict between the requirements for the control of slice flow and stock level that occurs for this controller is reflected in the performance curves. The gain setting (v), which maintains closest control of level, provides least reduction in disturbance of the slice flow and vice versa. The most satisfactory control will provide just sufficient low frequency attenuation to prevent the most rapid drifts from causing serious changes in level. Any further reduction is not required for adequate control of level and hampers control of slice flow. The Hornbostel hole has the advantage of simplicity, but suffers the disadvantage that the performance characteristics cannot be readily tailored to meet the requirements.

An alternative form of level control is obtained with an internal overflow to a surge chamber, in which the level is controlled by adjustment of the flow from the chamber. The low frequency performance of this system is superior for both slice flow and level. An advantage of this form of control is that the performance does not depend critically on the speed of response of the instrumented surge level controller.

External control

ALTERNATIVE forms of external control may be analysed by extending the mathematical analysis that was used to gauge the effect of flow box characteristics on control performance. An outline of this analysis is given in Appendix 3. Typical frequency response curves for various control configurations and controller settings are shown in Fig. 6.

These curves illustrate that the form of response in the high and middle frequency ranges is independent of the form of controller. The high frequency response is determined primarily by the air dome volume and the mid-frequency response by the amount of inherent regulation in the air supply and exhaust system. The curves also show that there are only minor differences between the performance of well-adjusted controllers of different forms.

When the flow box has no internal overflow, the stability of the level controller provides a major limitation in obtaining high attenuation of disturbances to stock flow. Besides the details of various design choices given in Appendix 3, a general conclusion is that control of slice flow can be improved by allowing poorer control of stock level. This is a case when the control requirements conflict and priority must be given to the more important one. Better external control will be possible also when the c value for the air system is high.

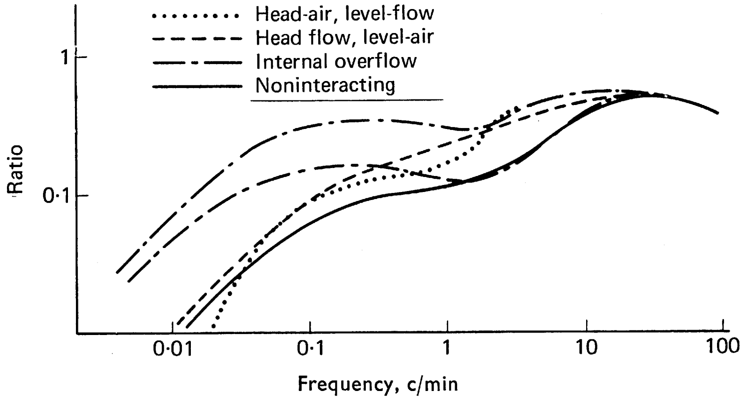

Fig. 6—Slice flow response ratios for alternative control systems

A flow box with internal overflow does not suffer from the difficulty of maintaining stable level control and may be quite readily set to give good control. Speed of response is improved by maintaining a high ratio of c/V.

By suitable connection of the controllers, the inherent interaction may be removed. The controllers may then be separately tuned to give good performance. The difficulty with such external control is that it will be sensitive to changes in operating conditions unless the controller settings are themselves altered when conditions change. On a machine where operating conditions vary little, this method would be attractive. Under computer control, it would be possible to provide automatic controller tuning and again non-interacting control would be advantageous.

Response to deliberate changes

Apart from being insensitive to disturbance, the flow from the slice and the level of stock in the flow box should settle quickly after a deliberate change in operating conditions. Deliberate changes may be made in the slice opening or the setting for total head. The resultant changes will depend on the dynamic response of the flow box, which can be calculated from the frequency response expression.[(2)]

Although the details of the calculation will not be given here, in each case, the initial part of the dynamic response depends on the high frequency performance, the time of settling is determined by the low frequency response and the amount of overshoot by the degree of stability of the system. The characteristics that were sought to obtain good frequency response will therefore also give satisfactory response to deliberate changes and there will be no need to compromise.

Conclusion

THE importance of considering control as a basic design requirement has been stressed. A general procedure for control design has been given and used as a basis for discussion of flow box design. The analysis of flow box control performance shows that factors to influence the structural and hydraulic performance are also important in determining the control performance. They are important not only because of their direct influence on the response of the flow box to disturbances and operating changes, but also because they determine the external controller settings that may be used.

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Appendix 1—Design of a flow box

1. Specification of requirements

(*a*) Inexpensive.
(*b*) Structurally robust.
(*c*) Slice jet free from undue flocculation or large-scale turbulence.
(*d*) Structural stability in the face of variations in temperature and pressure inside the box.
(*e*) etc.

2. Characterisation of the environment

(*a*) Range of expected flows.
(*b*) Range of total head.
(*c*) Range of temperature.
(*d*) Stock type.
(*e*) Stock freeness.
(*f*) etc.

3. Development of criteria

(*a*) Cost to be minimum.
(*b*) Maximum extent of flocculation to be tolerated.
(*c*) Turbulence to be less than a specified maximum.
(*d*) Maximum allowable variation in slice opening.
(*e*) etc.

4. *Synthesis*
   (*a*) Various materials.
   (*b*) Various methods of construction.
   (*c*) Inclusion or exclusion of an internal overflow.
   (*d*) Open or pressurised flow box.
   (*e*) Number and type of holey rolls.
   (*f*) Box dimensions.
   (*g*) etc.

5. *Analysis*
   (*a*) Cost estimates.
   (*b*) Pilot scale testing.
   (*c*) Comparisons of existing models.

Appendix 2—Flow box frequency response

The equations governing the behaviour of a pressurised flow box without internal overflow or external control are—

$$Q_o = C\sqrt{2gH} \qquad (1)$$

where Q_o is the slice flow per unit width,
C is the effective slice jet thickness,
H is the total head in the box.

$$A\frac{dL}{dt} = Q_1 - Q_n \qquad (2)$$

where A is the flow box stock surface area per unit width,
L is the stock level,
Q_1 is the flow into the box per unit with.

$$PV = M\frac{RT}{M_w} \qquad (3)$$

where P is the absolute pressure of the air pad,
V is the aid pad volume per unit width,
M is the mass of air in the pad per unit width,
R is the gas constant,
T is the absolute air temperature. (Since the air in the box is continually being replaced by air from the supply system, it is assumed that the air temperature remains constant in the face of changes in mass, pressure or volume.)
M_w is the molecular weight of air.

$$\frac{dM}{dt} = F_1 - F_2 \qquad (4)$$

where F_1 is the mass rate of air flow into the box per unit width,
F_2 is the mass rate of air flow out of the box per unit width.

$$H = L + P - P_0 \qquad (5)$$

where P_0 is the absolute pressure of the air outside the flow box.

Consider a small change q_1 in Q_1, which results in corresponding small changes h, l, q_0, p, etc. in H, L, Q_0, P, etc. Substituting these in each equation and making use of the fact that the changes are small,* the equations become—

$$q_0 = ah \qquad (6)$$

where $a = Q_0/2H$

then

$$A\frac{dl}{dt} = q_1 - q_0 \qquad (7)$$

$$pV - lAP = m\frac{RT}{M_w} \qquad (8)$$

The small changes in air flow to and from the box are caused by the small changes in the pressure differential across the supply and exhaust systems.

$$\frac{dm}{dt} = \frac{\partial F_1}{\partial P}p - \frac{\partial F_0}{\partial P}p \qquad (9)$$

$$= -kp$$

$$h = l + p \qquad (10)$$

Taking Laplace transforms and simplifying—

$$\frac{q_0/Q_0}{q_1/Q_1} = \frac{1+S\left(\dfrac{AP+V}{c}\right)}{1+S\left(\dfrac{A}{a}+\dfrac{AP+V}{c}\right)+S^2\left(\dfrac{A}{a}\dfrac{V}{c}\right)} \qquad (11)$$

$$\frac{l/L}{q_1/Q_1} = \frac{\dfrac{2H}{L}\left(1+S\dfrac{v}{c}\right)}{1+S\left(\dfrac{A}{a}+\dfrac{AP+V}{c}\right)+S^2\left(\dfrac{A}{V}\dfrac{V}{c}\right)} \qquad (12)$$

where $c = kRT/M_w$ is a measure of the change in the net rate of flow of air into the box caused by a unit change of pressure in the box.

The frequency response may be determined from a knowledge of the poles and zeros of these transfer functions.[3] The poles of the frequency responses are at—

$$a\frac{(c/a+P+V/A)}{2V}\left\{\pm 1\sqrt{1-\frac{4Vc/a}{A(c/a+P+V/A)^2}}\right\}$$

P is never less than 350 in,

c/a is never greater than 5 000 in,

V/A is never greater than 1 000 in.

In a typical case, c/a and V/A are much smaller.

* Simulation studies on an analog computer have verified that the approximations used are valid for changes of up to 20 per cent of the nominal values

Therefore $\dfrac{4Vc/a}{A(P+V/A+c/a)^2}$ is much less than unity and the poles are at—

$$\frac{a}{A}\cdot\frac{(c/a+P+V/A)}{V/A},\quad \frac{a}{A}\cdot\frac{c/a}{(c/a+P+V/A)}$$

An open box has $c\rightarrow\infty$ and the response function reduces to a single pole at (a/A). A box for which the air supply and exhaust flows are completely independent of flow box pressure has $c = 0$ and the response function reduces to a single pole at—

$$\left(1+\frac{AP}{V}\right)\frac{a}{A}$$

Returning to the general case, the transfer function for slice flow has a zero at—

$$\frac{c/a}{P+V/A}\cdot\frac{a}{A}$$

and poles at

$$\frac{c/a}{c/a+P+V/A}\cdot\frac{a}{A}$$

and

$$\frac{c/a+P+V/A}{V/A}\cdot\frac{a}{A}$$

The transfer function for level has a zero at $\dfrac{c/a}{V/A}\cdot\dfrac{a}{A}$ and poles at the same locations as for slice flow.

When a Hornbostel hole is fitted to a pressurised flow box, equation (*9*) becomes—

$$\frac{dm}{dt} = -kp+ul \qquad (13)$$

where u is the effective gain of the Hornbostel hole at the operating conditions for the system. The transfer functions are then modified so that the poles of the frequency response are at—

$$\frac{a}{A}\cdot\frac{(c/a+v/a)}{(c/a+P+V/A)}\quad\text{and}\quad\frac{a}{A}\cdot\frac{(c/a+P+V/A)}{V/A}$$

For slice flow, the zero is at $\dfrac{a}{A}\cdot\dfrac{(c/a+v/a)}{P+V/A}$ and for level at $\dfrac{a}{A}\cdot\dfrac{(c/a)}{V/A}$

where $v = \dfrac{uRT}{M_w}$.

When the flow box is designed with an internal overflow, the original equations (*1*)–(*5*) are modified only in that equation (*2*) becomes—

$$A\cdot\frac{dL}{dt} = Q_1-Q_0-Q_R \qquad (14)$$

where the overflow per unit width Q_R in^3/in s is given by—

$$Q_R = 11{\cdot}53\,(L-L_0)^{1.5} \qquad (15)$$

and the level in the overflow chamber is given by—

$$B\frac{dX}{dt} = Q_R - Q_S \quad . \quad . \quad . \quad . \quad . \qquad (16)$$

where X is the level in the overflow chamber,

B is the overflow chamber stock surface area per unit width and

Q_S the flow from the chamber is determined by the valve setting and the head difference between flow box and wire pit.

For small changes in flow box variables, the head difference between flow box and wire pit does not vary significantly and the valve setting is proportional to surge tank level so that the linearised equations become—

$$q_0 = ah \quad . \quad . \quad . \quad . \quad . \qquad (6)$$

$$A\frac{dl}{dt} = q_1 - q_0 - q_R \quad . \quad . \quad . \quad . \quad . \qquad (17)$$

$$q_R = rl \quad . \quad . \quad . \quad . \quad . \qquad (18)$$

$$\text{where } r = \frac{\partial Q_R}{\partial L} = 7{\cdot}65 Q_R^{\frac{1}{3}}$$

$$B\frac{dx}{dt} = q_R - Kx \quad . \quad . \quad . \quad . \quad . \qquad (19)$$

$$pV - (lA + xB) = \frac{mRT}{M_w} \quad . \quad . \quad . \quad . \quad . \qquad (20)$$

$$\frac{dm}{dt} = -kp \quad . \quad . \quad . \quad . \quad . \qquad (9)$$

$$h = l + p \quad . \quad . \quad . \quad . \quad . \quad . \qquad (10)$$

Allowance is made for the fact that the surge level controller cannot react immediately to a change in level by writing the transform equation—

$$\frac{K}{B} = \frac{G}{1+ST} \quad . \quad . \quad . \quad . \quad . \quad . \qquad (21)$$

where G is the gain of the controller, normalised by the overflow chamber stock surface area per unit width,

T is the equivalent time constant representing the dynamics of measurement and control action.

The resulting Laplace transform expressions are lengthy and have not been reproduced here.

When a measurement of stock level is used to position an air valve, the control amounts to an instrumented form of the Hornbostel system. In this case, the dynamics of the control loop will influence the frequency response. For a proportional plus reset controller that has a limited response at high frequencies—

$$v = \frac{Kc}{S} \cdot \frac{1+SR}{1+ST} \qquad (22)$$

where R is the reset time,

T is the equivalent time constant of the measurement and control units.

Again the frequency responses, which may be derived from the transform equations, are not given because of their length, but typical response curves, calculated from these expressions, are shown in Fig. 4 and 5.

Appendix 3—External control of total head and stock level

Total head by adjustment of air, level by adjustment of stock flow—system (a)

The transform equations derived in a similar manner to those given in Appendix 2 are—

$$q_0 = ah \qquad (23)$$

$$SAl = q_1 - q_0 - q_c \qquad (24)$$

$$q_c = yl \qquad (25)$$

$$pV - AP = -l\frac{cp}{S} - \frac{vh}{S} \qquad (26)$$

$$h = p + 1 \qquad (27)$$

where q_c is the correction made to the approach flow,

v is the transfer function of the total head controller,

y is the transfer function of the level controller.

If the level controller has proportional, integral and derivative terms—

$$y = \frac{y_o}{T} \frac{(S+1/R+S^2D)}{S(S+1/T)} \qquad (28)$$

where R is the reset time,

D is the rate time,

T is the time constant representing response delay,

y_0 is the controller gain

and the total head controller—

$$v = \frac{v_o}{W} \frac{(S+1/U)}{(S+1/W)} \qquad (29)$$

where U is the reset time,

W is the response lag time constant,

v_0 is the controller gain.

The frequency response expression can be derived from equations (*23*)–(*29*) and a typical curve given in Fig. 6. The influence of the controller settings and other flow box design variables on control performance can be studied by reference to the equivalent block diagram given in Fig. 7. The diagram emphasises that the system is a unity feedback system with the external controllers providing the minor loops around both level and total head. The most satisfactory attenuation of approach flow disturbances will result when the gain of the forward path is minimised and the response of each minor loop is made fast, yet well damped.

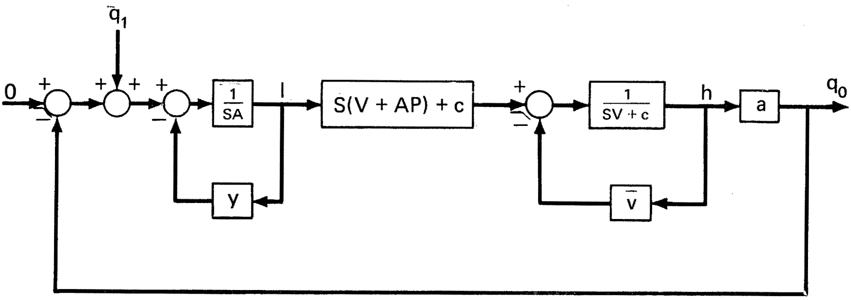

Fig. 7—Block diagram for external control system (*a*)

The forward path gain is $\frac{a}{A}(1+PA/V)$. The desirability of minimising this expression has already been discussed in connection with the choice of A and V. Root locus diagrams [4] have been used to determine how best to obtain fast, stable minor loops.

The level control loop is the least stable. Stability is most markedly improved by reducing the response lag T. Providing R is much greater than T, the actual value of the reset time has little influence on stability. The derivative term has a stabilising effect, which is particularly marked as D approaches T, but the major changes in system response, which correspond with minor changes in rate time when D is similar to T, make the control performance unacceptably sensitive to process changes. The other means of improving stability is to reduce the gain y_0.

Providing the ratio c/V is large, the stability of the total head loop is not such a problem and no derivative term is warranted.

Total head by adjustment of stock flow, level by adjustment of air—system (*b*)

The transform equations are similar to equations (*23*)–(*29*), except that equation (*25*) becomes—

$$q_c = vh \quad . \quad . \quad . \quad . \quad . \quad (25.1)$$

and equation (*26*) becomes—

$$pV - lAP = \frac{cp}{S} + \frac{yl}{S} \quad . \quad . \quad . \quad . \quad (26.1)$$

A typical frequency response is given in Fig. 6 and the block diagram in Fig. 8. In this case, the system is a set of nesting loops. The best performance will result when the gain of the forward path is minimised, the speed of response of each block is maximised without approaching instability and the gain of the feedback path is maximised.

The forward path is again $\frac{a}{A}(1+PA/V)$. The level control loop is again critical to stability. The stability is improved by increasing c, reducing the ratio $\frac{y_o}{T(V+AP)}$ and by judicious choice of the derivative rate time D. The speed of response will also be improved by reducing the response lag W and by raising the total head controller gain v_0.

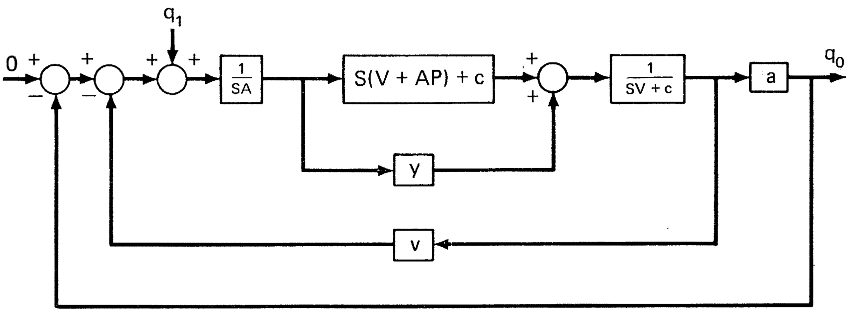

Fig. 8—Block diagram for external control system (*b*)

Internal overflow with total head control by adjustment of air—system (*c*)

When the instrumented level controller is replaced by internal overflow to a level controlled surge chamber, equations (*23*)–(*29*) are modified in that equation (*26*) becomes—

$$pV-(lA+xB)P = -\frac{cp}{S}-\frac{vh}{S} \quad . \quad . \quad . \quad . \quad . \quad (26.2)$$

equation (*28*) reduces to—

$$y = y_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (28.2)$$

and there is an additional equation—

$$SBx = q_c-\frac{K_o x}{1+ST} \quad . \quad . \quad . \quad . \quad . \quad . \quad (30)$$

A typical frequency response curve is given in Fig. 6 and the equivalent block diagram in Fig. 9. The forward path gain remains at $\frac{a}{A}(1+PA/V)$. The inherent level control loop has no stability problem. The total head control loop has exactly the same form as for system (*a*). The surge chamber level controller need not include an integral term, as offset in this level is of no consequence.

The stability of the surge chamber level loop will be improved by reducing K_o and by decreasing the response lag T. The general stability is also improved by reducing the ratio $\frac{Py_0}{V+AP}$ and increasing $\frac{c}{V+AP}$.

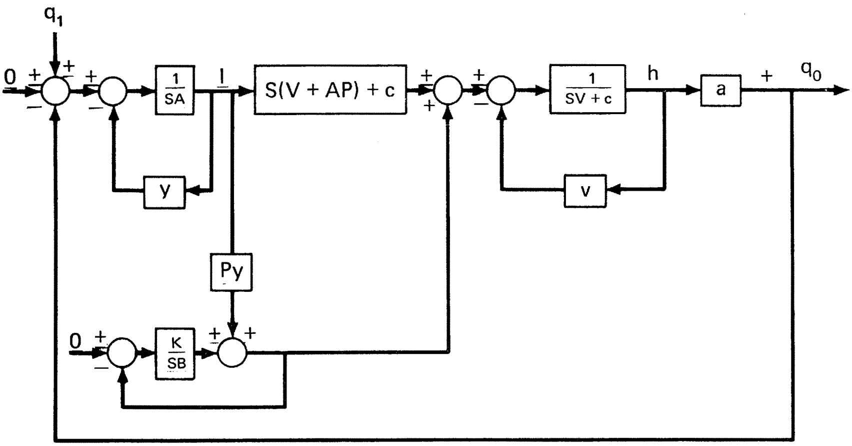

Fig. 9—Block diagram for external control system (*c*)

Non-interacting instrument control

The equivalent block diagram for the system with head controlled by adjustment of air flow and level controlled by adjustment of stock flow has been redrawn in

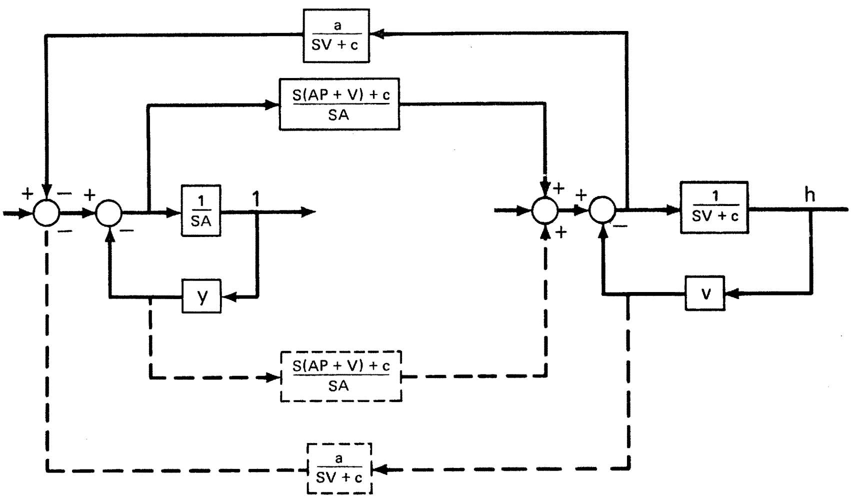

Fig. 10—Block diagram for non-interacting control

Fig. 10 to emphasise the manner in which the control loops interact. The interaction can be removed if the additional terms shown dotted are included in the controllers. Provided the additional blocks exactly reproduce the system interactions, the controllers will be entirely non-interacting. This will allow ease of tuning and higher performance from each loop. The difficulties with such a scheme are that the residual interaction caused by inexact replication of the interacting blocks will vary with operating conditions. Such a system is equivalent to a loop highly tuned for one set of operating conditions that may be quite unstable at another set. In a system employing computer control, the facility for automatically adjusting the controller settings with changes in operating conditions could be exploited.

Discussion

The Chairman You have covered an aspect of control that perhaps could be called precontrol, an aspect that is very frequently overlooked in thinking of process control. For someone with an existing installation on which consideration is being given for adding computer process control, perhaps there is not too much that can be changed very easily to improve the basic design for better control, but it is still worth the effort. With a new installation, preplanning the system design with control in mind is an area that can pay immense dividends later on. Many of the needs for sophisticated control can be minimised or even eliminated by careful design of the original system.

A Speaker Fig. 6 raises a query, since the amplitude ratio continues to increase with the frequency.

Dr B. W. Smith If you look closely at Fig. 6, the ratio is reducing towards the top of the range and that corresponds to the same performance in Fig. 3.

Let me take this opportunity to make a comment. The control performance on grade is as much an indication of how well the system behind the flow box has been designed and this makes it very difficult to compare installations. I have no figures to quote for a particular installation before and after a certain control was added to it. I think this is the only fair comparison.

For settling times, I can only quote simulation work that we have done in my company. We were able to obtain satisfactory settling after a set point change within 15–20 sec.

Dr I. B. Sanborn I would like to stress something you state in your paper about taking controllability into account when designing a system. One does not have to work long in the paper industry to recognise that our processes are unnecessarily slow and sluggish. Steps should be taken to avoid this whenever possible.

Discussion

Mr P. A. A. Talvio I have been involved in starting up several papermachines during the past 2–3 years. In every case, we have used a simple control system made with conventional analog controllers. The total head is controlled by changing the fan pump speed. The output of the PI controller can adjust the fan pump speed about 4 per cent. The base speed of the pump is set manually and the controller can change it ± 2 per cent. This is quite sufficient for good control and prevents the big upsets.

The results have been extremely good. The total head record is a thick straight line. The fast variations (like noise) cannot be controlled. The amplitude of noise varies from instance to instance, but it is normally 5–10 mm water gauge when the set head is 2–5 mm water gauge.

Most new machines have a stock de-aerator installed, which makes the head box control significantly easier. It absorbs the wide range of disturbance frequencies. Only long-term variations like drift and very high frequency variations are left.

I consider the complexity of head box control to be greatly exaggerated. I see no real need for advanced decoupling arrangements. I cannot even see that there is any problem in head box response when changing papermachine speed. There are other much slower factors that limit the rate of speed changes.

Dr D. B. Brewster I would like to ask two questions. Dr Smith's Fig. 3 shows the importance of the factor c for disturbance reduction by the head box and he mentioned the importance of selecting the proper air supply characteristics. Is there not an analogous effect on the stock supply side, which may be a problem for machines making a wide range of grades?

Secondly, there are devices such as head box compressor separators and vacuum separators in the cleaner system that closely resemble head boxes. These are frequently disturbance sources for the head box. Would they not benefit from the same analysis?

Dr Smith You are referring to the c values I used in specifying the interaction of the flow box pressure on the air supply. It is quite true that these will vary with operating point: in fact, a number of factors in the model vary with operating point. These cause the need for identification at each operating point mentioned by Dr Sanborn.

The instabilities further back in the system certainly have an effect and we should use equipment earlier in the system to remove some of these instabilities whenever we can.

The Chairman It might be helpful to some people if we define what identification is. It is the technique used for on-line calculation of the unknown constants in the transfer equations and it is done by making a deliberate change in one of the main variables and measuring the changes in others. The computer then calculates the constants from the measured changes.

Mr B. W. Wells (written comment) Although a knowledge of the effect of flow box dimensions in the form of a disturbance ratio versus frequency is useful, surely its practical use is mainly limited to the ease of replacing a flow box on an existing machine, where the frequency spectrum of the stock flow disturbances can be determined with a good degree of confidence?