A systems approach to consistency control and dry stock blend

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ABSTRACT *A process control strategy to blend pulp on a fiber weight basis was developed for the wet end of the paper machine. There are several problems with conventional consistency control that adversely affect this strategy. These difficulties include control loop interaction between furnish flow and consistency, variable process gain arising from changes in furnish flow and storage tank consistency, and variable process dead time also caused by changes in furnish flow. These problems can be solved with a new method for consistency control and a continuous self-tuning algorithm that uses only process data to adapt controller gain and reset. The benefits of using this system can include a reduction in furnish costs and blend variability, enhanced quality and machine runnability, and a more uniform sheet.*

KEYWORDS
Automatic control
Consistency
Mixing
Process control
Stock preparation

Good consistency control is critical in most pulp and papermaking processes, especially at the wet end of the paper machine, where furnishes are blended to produce good quality and uniformity at minimum cost. To achieve these benefits, it is necessary to minimize the variability of the furnish blend on a fiber weight basis (dry stock blend). Less variation in the blend allows the papermaker to lower the setpoint on the most costly furnish without loss in quality.

Traditional blend controls, however, consist of setting fiber stock ratios for each furnish on a volumetric basis (wet stock blend). This strategy relies on uniform consistencies from each furnish to maintain the desired constant dry stock blend. Ideally, if each furnish can be controlled at the same consistency, the wet and dry blends will be the same. However, as a result of process upsets and specific mill operating objectives, this control is not always possible. Consequently, to achieve a precise blend, it is necessary to develop a stable control strategy that addresses all the problems causing variable consistency.

There are certain problems in using supervisory equations for dry stock blend. These problems are solved by introducing a new control strategy for consistency and by developing a method for adaptive tuning. Such a system has been used successfully at Daishowa America's Port Angeles mill.

Supervisory control

Probably the most straightforward approach to implementing dry stock blend is to use a set of steady-state equations that determine wet blend setpoints as a function of dry blend setpoints and furnish consistencies.

$$WSP_i = [(DSP_i/C_i)/\sum_{j=1}^{n}(DSP_j/C_j)]100\% \quad (1)$$

where

WSP_i = the wet blend setpoint for furnish i, %
DSP_i = the dry blend setpoint for furnish i, %
C_i = the consistency of furnish i, %
n = the number of furnishes.

The derivation of these equations for these expressions is given in **Appendix A.** These equations can be used to provide blend controls, as shown in **Fig. 1**

However, this strategy cannot be implemented successfully using conventional consistency control. There are several inherent problems that can be analyzed and easily solved with a different control strategy for consistency.

Consistency control

The conventional approach to consistency control is shown in **Fig. 2A.** The most serious problems with this approach are (a) control loop interaction between furnish flow and consistency and (b) variable process gain arising from changes in furnish flow. These problems must be solved to achieve a stable dry stock blend. An analysis can be done by using both the overall balance and the fiber material balance to model the process.

$$F_I + F_D = F_F \quad (2)$$
$$F_I C_I + F_D C_D = F_F C_F \quad (3)$$

where

F_I, C_I = inventory flow and consistency (before dilution)

F_D, C_D = dilution flow and consistency
F_F, C_F = furnish flow and consistency (after dilution).

These equations can be combined to show the relationship between the controlled variable C_F and the manipulated variable F_D at steady state.

$$C_F = C_I + (F_D/F_F)(C_D - C_I) \quad (4)$$

This equation shows that a disturbance in furnish flow will affect consistency. Furthermore, a disturbance in consistency will affect furnish flow in accordance with Eq. 1 (dry blend). Moreover, these interactions may cause an instability that can only be corrected by proper control loop decoupling. A relative gain analysis shows that the interaction increases as the difference increases between inventory consistency in the storage tank and furnish consistency (setpoint). A consistency drop of 1% or more typically results in severe interaction.

The problem with variable process gain can also be shown using Eq. 4. Steady-state process gain is the amount of change in controlled variable per unit change in manipulated variable. This equation is obtained mathematically by differentiating Eq. 4:

$$\text{gain} = \partial C_F/\partial F_D = (C_D - C_I)/F_F \quad (5)$$

Since C_D is usually small compared to C_I, this expression becomes

$$\text{gain} = -C_I/F_F \quad (6)$$

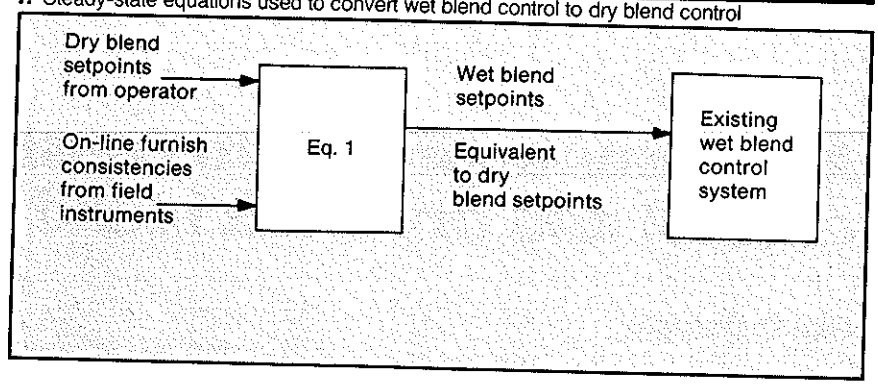
Therefore, both the process gain and consequently the control loop gain (Fig. 2A) vary inversely with furnish flow. This relationship can cause severe stability problems with a large turn-down in flow, which is common in some paper mills. An example of this problem is shown by the control response in **Fig. 3**. The consistency loop is well tuned, and it provides good control at higher furnish flows (1140 L/min). However, when the flow is reduced (55%), loop stability is completely lost.

Both of these problems can be solved by setting a ratio of dilution flow to furnish flow, as shown in Fig. 2B. By keeping this ratio constant, changes in furnish flow will not affect consistency. This control strategy also solves the problem of the inverse variation of process gain with furnish flow. Equation 4 can be differentiated with respect to the new manipulated variable (F_D/F_F) to determine the process gain:

$$\text{gain} = \partial C_F/(\partial F_D/F_F) = C_D - C_I \cong -C_I \quad (7)$$

The control strategy in Fig. 2B can provide an improvement over conventional consistency control. It also makes possible the successful implementation of a stable dry stock blend control, as shown in Fig. 1. However, there are still two problems with this consistency loop that can be corrected. They include (a) variable process dead time caused by changes in furnish flow and (b) variable process gain caused by changes in storage tank consistency (Eq. 7). Probably the easiest way to overcome these problems is to develop an adaptive tuner. **Appendix B** presents both the control theory and the adaptive equations.

1. Steady-state equations used to convert wet blend control to dry blend control



I. Gains and phase lags for consistency loop

Block from Fig. 8	Steady-state gain	Dynamic gain	Phase lag
PI consistency controller	G_C	$\sqrt{1 + \tan^2 \phi_C}$	38°
Ratio scaler	0.01	...	...
PI ratio control loop (flow)	1.0	1.0	360 (θ_P/T_L)
Process (dead time)	$-C_I$	1.0	360 (θ_P/T_L)
Consistency transmitter	$100/R_T$	1.0	...

Application results

The Daishowa America Port Angeles mill makes lightweight directory paper from refiner groundwood and purchased kraft. As part of an ongoing effort to reduce the use of chemical pulp, consistency and dry stock blend controls were implemented.

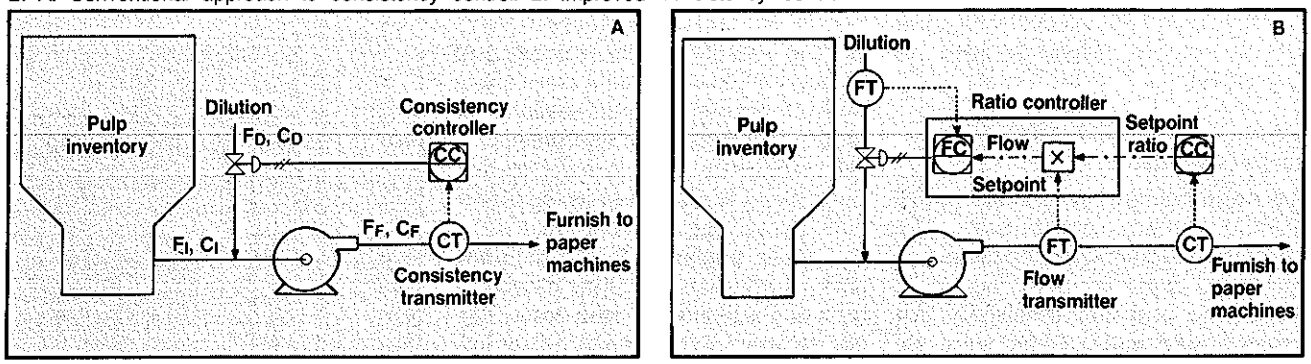
Results

Results were quite favorable, with the variability in kraft blend being reduced from ±2.5% to ±0.2%. This improvement has allowed the kraft setpoint to be lowered without sacrificing quality or machine runnability. The project is currently saving $1 million annually and will be paid back in less than 1.6 years after taxes.

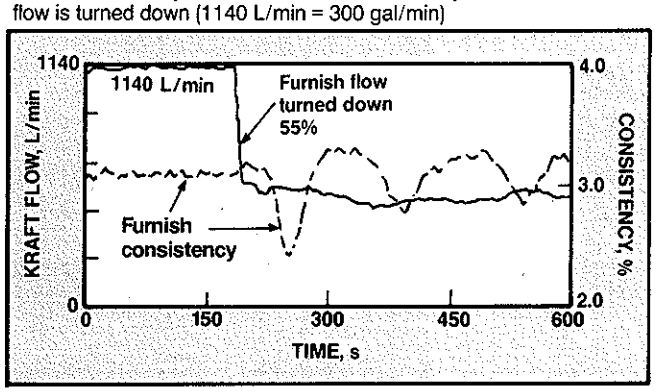
Configured on a Bailey Network 90, the controls perform well. There is virtually no control loop interaction between furnish flow and consistency. The adaptive algorithms for consistency control were tuned to provide a loop gain of 0.5 and a controller phase lag of 38°. These algorithms have not required additional tuning since startup. The adapted gain for a typical controller at Port Angeles varies from 0.11 to 0.14, while the adapted integral varies from 1.0 to 6.0 repeats/min.

The consistency response for a load change in furnish flow (1025-3300 L/min) resulting from a machine start-up is shown in **Fig. 4**. Large changes in load typically cause only small deviations from setpoint (0.20% or less), and recovery is usually less than 1 min. The consistency responses for a

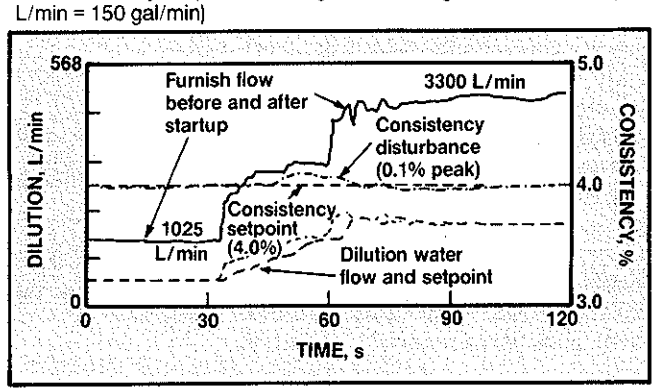
2. A: Conventional approach to consistency control. B: Improved consistency control



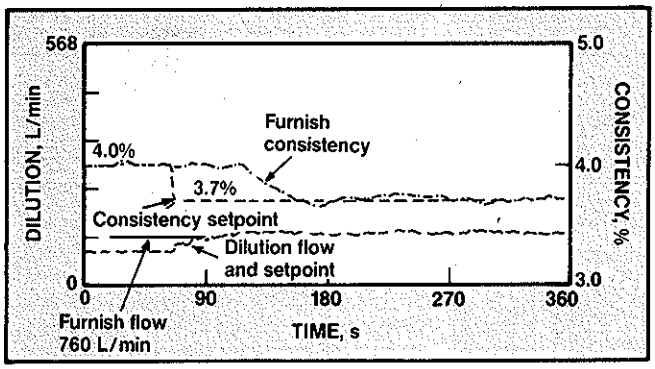
3. Loss of stability with conventional consistency control when furnish flow is turned down (1140 L/min = 300 gal/min)



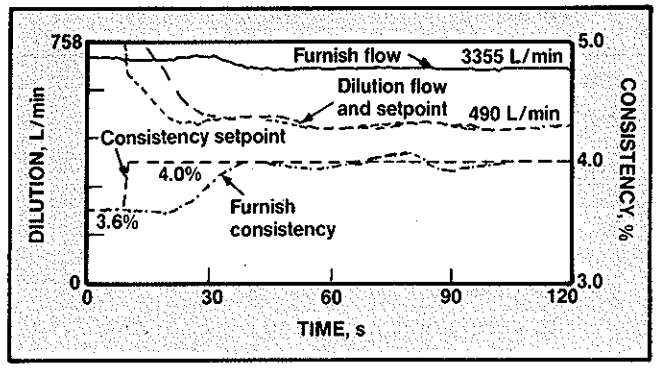
4. Consistency response for large load change in furnish flow (568 L/min = 150 gal/min)



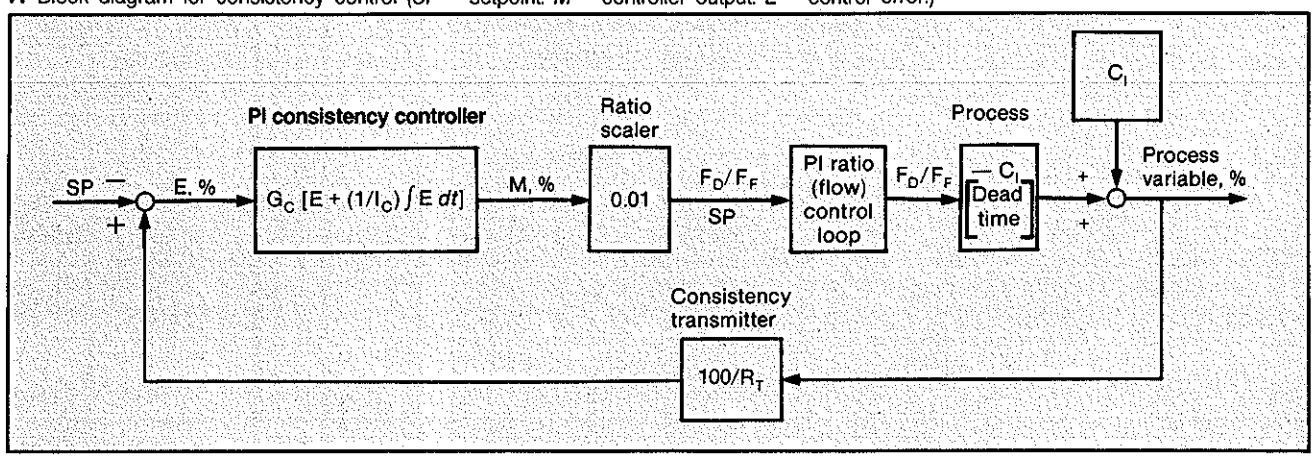
5. Response for consistency setpoint change at low furnish flow (568 L/min = 150 gal/min)



6. Response for consistency setpoint change at high furnish flow (758 L/min = 200 gal/min)



7. Block diagram for consistency control (*SP* = setpoint. *M* = controller output. *E* = control error.)



setpoint change at low and high furnish flows (760 and 3355 L/min) are shown in **Figs. 5 and 6**, respectively.

Other aspects contributing to the project's success

An evaluation was done on all paper mill consistency transmitters. The evaluation determined transmitter accuracy, linearity, drift, signal to noise ratio, and flow sensitivity. All unacceptable instruments were replaced.

Operations and maintenance training was emphasized to ensure a good understanding of the new controls. A process control simulator was developed to provide several months of training prior to startup. This effort smoothed the transition from simulation to online operation.

A commitment was made to maintain good consistency calibration on all transmitters. Even the best instruments currently available require daily attention. Without this commitment, peak performance of the system cannot be maintained.

Process control engineering and startup was done using internal mill resources. This ensured a more effective integration of mill needs with control technology and equipment.

In summary, good control of dry stock blend is a big step in the direction of providing a constant furnish to the paper machine. It can enhance paper quality and machine runnability while reducing furnish costs. The key to providing further blend improvements, however, must come from new technology for better and more reliable instruments for measuring consistency.

The author wishes to thank Joe H. Michalczik, Dick M. Sisson, the Instrument Dept., and other mill personnel who contributed to this project. In addition, the author acknowledges Mark A. Hannah for his suggested improvements to the organization of the original draft.

Received for review Jan. 4, 1988.

Accepted March 4, 1988.

Presented at the 1988 TAPPI Papermakers Conference.

Appendix A: supervisory equations

The equations needed for dry stock blend can be derived from the expressions that define the setpoints for steady-state wet blend (Eq. 8) and dry blend (Eq. 9) for each furnish. In addition, the wet and dry setpoints summed over all furnishes will equal 100%, as given by Eq. 10 and Eq. 11, respectively.

$$WSP_i = [F_i / \sum_{j=1}^{n} F_j]\,100\% \quad (8)$$

$$DSP_i = [F_i C_i / \sum_{j=1}^{n} (F_j C_j)]\,100\% \quad (9)$$

$$\sum_{j=1}^{n} WSP_j = 100\% \quad (10)$$

$$\sum_{j=1}^{n} DSP_j = 100\% \quad (11)$$

where

WSP_i = the wet blend setpoint for furnish i, %

DSP_i = the dry blend setpoint for furnish i, %

F_i = the flow rate of furnish i, L/min

C_i = the consistency of furnish i, %

n = the number of furnishes.

By algebraically combining these equations, the expressions used for dry stock blend (supervisory control, Eq. 1) are obtained.

Appendix B: adaptive tuning

Because consistency measurement is typically noisy and pulp dilution is a pure dead-time process, consistency control requires proportional plus integral (PI) action but not derivative. A good method for tuning PI controllers was proposed by Shinskey.[1] It involves setting the controller gain to achieve an overall loop gain of 0.5 (1/4 decay ratio) and setting the integral to obtain a specific, constant phase lag across the controller.

Simulations of dead time processes show that a phase lag of 36° to 41° is optimum. For a step change in load, this broad range of settings (and a loop gain of 0.5) will produce a response with near-minimum integral absolute error (IAE). In addition, changes in setpoint will also produce a good process response with this tuning.

Adaptive gain

To use this method for adaptive tuning, a loop analysis can be done using the block diagram in **Fig. 7**. The overall loop gain is the product of the steady-state and dynamic gains of all blocks. These are given in **Table I**. The controller gain is obtained by setting the product of these gains equal to the desired loop gain (as in $G_L = 0.5$) and solving for controller gain, G_C:

$$G_C = G_L R_T / [C_t (1 + \tan^2 \phi_c)^{1/2}] \quad (12)$$

where

R_T = consistency transmitter span, %

ϕ_c = controller phase lag, °.

Consequently, the controller gain is only a function of transmitter span and storage tank consistency. The span can be periodically determined using consistency calibration data. The storage tank consistency can be calculated using online instrument data and a rearranged Eq. 4 (assuming dilution consistency is negligible):

$$C_t = C_F / (1 - F_D / F_F) \quad (13)$$

[1] Shinskey, F. G., Process control systems, McGraw Hill, New York, 1979, p. 96.

In practice, the value obtained by Eq. 13 should be averaged, over 5 min for instance, before substitution into Eq. 12. This averaging helps eliminate errors arising from flow and consistency loop dynamics. In addition, it is practical to treat the overall loop gain, G_L, as a tunable parameter when using Eq. 12 for adaptive gain. This allows tuning (other than 0.5) during startup and at times when the consistency transmitter is not properly calibrated.

Adaptive integral

There are only three elements in the consistency loop (Fig. 7) that exhibit a significant phase lag caused by dynamic behavior. These include the PI consistency controller, the ratio (F_D/F_F), flow loop, and the process dead time. The phase lag for each is given in Table I.

The optimum integral tuning will produce about a 38° lag across the consistency controller at the loop's period of oscillation. The ratio control loop exhibits a lag that can be approximated by a constant dead time. This was observed in practice over a broad range of operating conditions (varying T_L) and was verified by simulation. Since control loop oscillations occur when the sum of all phase lags equal 180°, the loop period (T_L) can be determined using the following equation:

$$\phi_C + 360\theta_R/T_L + 360\theta_P/T_L = 180 \quad (14)$$

where

θ_P = process dead time, s
θ_R = effective dead time contributed by the ratio control loop, s
T_L = consistency loop period of oscillation, s.

Solving for T_L gives

$$T_L = 360(\theta_R+\theta_P)/(180-\phi_C) \quad (15)$$

The relationship between the lag of a PI controller and the integral tuning is given by

$$\tan\phi_C = T_L/(2\pi I_C) \quad (16)$$

where

I_C = the integral time per repeat, s.

Combining Eqs. 15 and 16 and solving for I_C gives

$$I_C = 180(\theta_R+\theta_P)/[\pi(180-\phi_C)\tan\phi_C] \quad (17)$$

Consequently, the integral setting is only a function of the desired phase lag of the controller, the process dead time, and the effective dead time contributed by the ratio flow loop. Although the optimum controller lag is 38°, it was retained as a variable in Eq. 17 so that it can be used as a tunable parameter for online applications.

The process dead time is the time required for furnish to flow from the dilution line to the consistency transmitter and thus is a function of flow rate. If the transport volume (V) between the dilution line and transmitter is known, the dead time can be computed online as follows:

$$\theta_P = V/F_F \quad (18)$$

The transport volume can be easily determined by stroking the dilution valve and clocking the dead time. This dead time multiplied by the furnish flow rate is the transport volume. In practice, this evaluation should be repeated at several different flow rates, averaging the results to obtain a good, accurate value.

The effective dead time from the ratio flow loop, θ_R, is constant over a broad range of T_L. Depending on the specific flow loop, θ_R can range from 3 s to 5 s, assuming the loop is well tuned. A more exact determination can be done by forcing the consistency loop to oscillate and timing the lag between setpoint peaks and flow peaks in the ratio loop.

The use of Eqs. 12 and 17 for adaptive tuning is specific in the consistency control strategy shown in Fig. 2B. The method used to derive these equations has several advantages over other approaches to self-tuning.

First, this method provides continuous tuning that corrects for changes in process dynamics and gain as they occur. Because the method is application specific, its performance is typically better than general-purpose algorithms. Application programming is relatively easy to do, and program execution requires little computer overhead.

Furthermore, little or no tuning is required to bring the system online once instruments have been calibrated. After startup, periodic bumping of the process is not required to make tuning changes.