Integration of paper machine operations

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The industry has no standards for control performance and does not fully appreciate the impact of control performance on sheet quality and customer satisfaction.

The demands for paper quality have never been higher than they are today. The trend of increasing customer demands for better paper quality is likely to continue, especially with regard to improved product performance. The newspaper publisher will continue to press for better pressroom runnability, print quality, and color register as the demands for high-quality color printing and advertisements continue to rise. The fine-paper user will continue to press for a curl-free, two-sided sheet with higher standards of printability and sheet surface, as xerographic, ink-jet, and laser printing technologies become more

How do these quality requirements translate into requirements for improved control of the paper machine? Today, the modern paper machine is controlled by an impressive array of distributed control systems, programmable logic controllers (PLCs), digital drive systems, computer-based gauging systems, and cross-direction (CD) control systems.

The suppliers of these various systems, however, come from different technical cultures and are likely to have widely ranging opinions regarding control objectives as they perceive them. Since these suppliers often compete for overlapping market segments, they do not always easily cooperate with each other.

In this environment, how thoroughly have good control engineering principles been applied to the control of the many interacting variables of the paper machine? How well is the average paper machine controlled?

Evolution of paper machine control systems

Twenty years ago, the paper machine was controlled by using single-loop analog controllers, relay logic, line shaft control, or possibly sectionalized analog dc drives. In a few cases, a dedicated packaged computer system was used for basis weight and moisture control.

The distributed control system

Today, the analog controller has been replaced by the distributed control system. The distributed control system evolved from the original idea of replacing analog controllers with digital distributed controls when the 8-bit microprocessor became available in the mid 1970s. Today, the distributed control system has surpassed the flexibility and computing power of some of the original minicomputer-based systems and in many cases is now based on powerful 32-bit processors.

Many current distributed control designs are powerful enough to implement unit process control of most pulp and paper processes. In most cases, they also have the computing power to implement various model-based control algorithms, including designs based on modern control theory. Distributed control systems are also able to implement the discrete logic and interlocks which traditionally have ben implemented in PLCs.

Unfortunately, many control designers using distributed control equipment simply emulate the original single-loop analog design without any regard for the interacting process dynamics or for the available computing power.[1] This is a human issue involving training and technology transfer problems. It is not a shortfall in technical capabilities.

The PLC

Like the distributed control system, the PLC evolved from the design concept of replacing relay logic with 8-bit digital systems. The ability to implement discrete logic using the familiar online "ladder" logic held immediate appeal for the electrical engineer and mill electrician. Like the distributed control system, the PLC of today has become much more powerful by also using 32-bit processors.

This increased power has led to fast scan times and an ability to process a heavy load of digital signals. Although the PLC has been able to process analog signals for some time, the migration of PLC users into the "analog" control world has been largely stifled by a technical culture oriented towards electrical interlocks rather than the control of process variability. Hence, the design pressures on PLC designers have not included the algorithmic and configuration requirements typical of process control.

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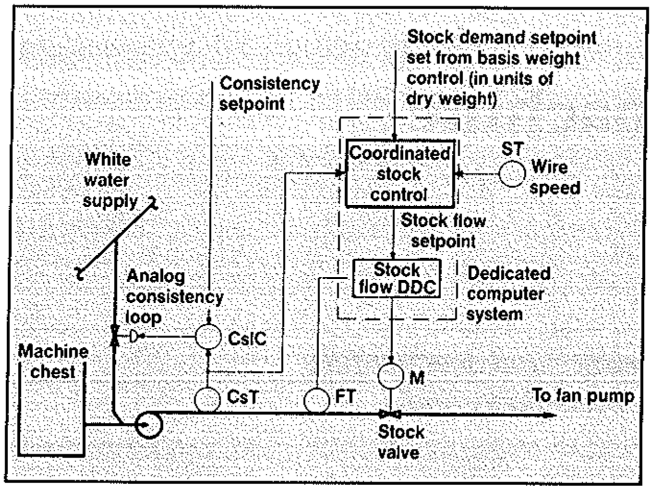
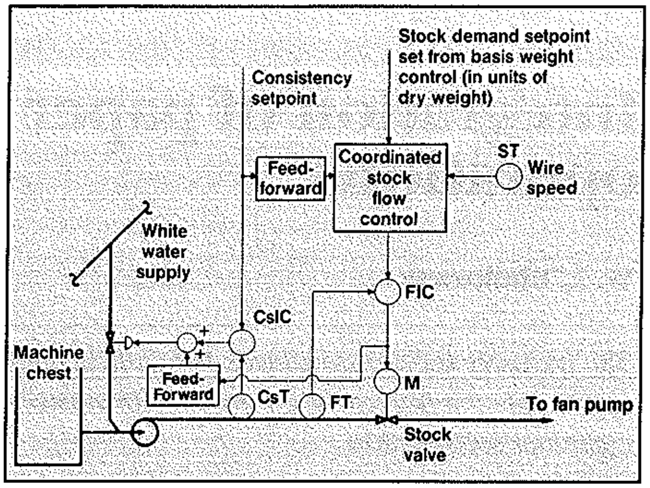
[1]Loewen, B., Pneumatic emulator syndrome (and how to avoid it), Control Systems '88, cosponsored by the Technical Section, CPPA, The Instrument Society of America Pulp and Paper Division, and the Swedish Association of Pulp and Paper Engineers.

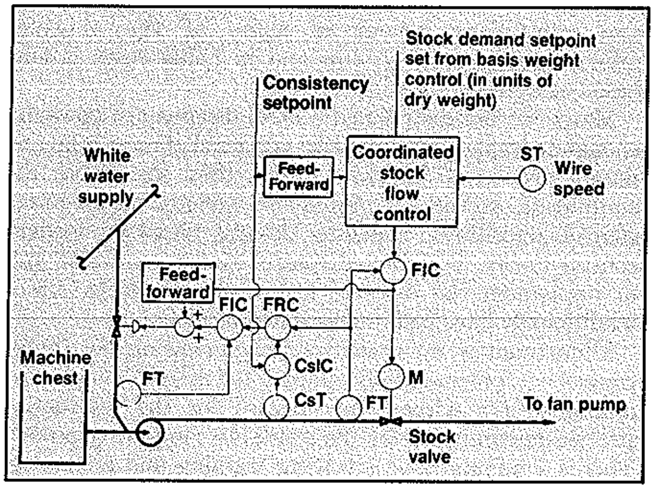
1. A typical stock control loop in which the analog signals often are scanned only once every 5 s



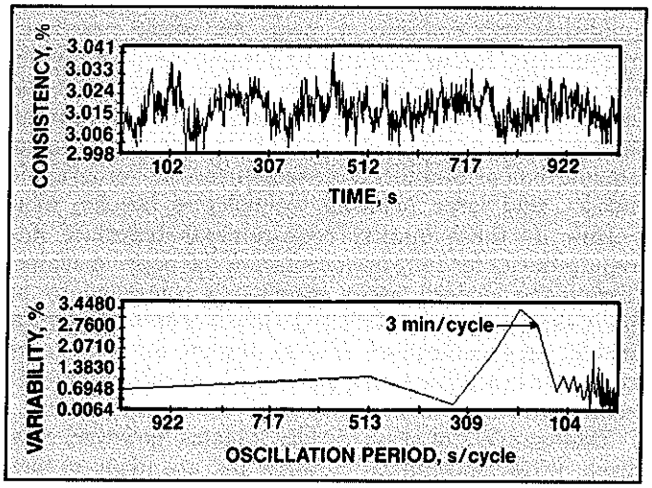
2. A coordinated stock flow system with measurements of consistency and flow rate



3. Coordinated stock flow and consistency control with compensation for white water pressure disturbances



4. Variability of thick stock consistency (Mean = 3.017 % consistency. 2σ = 0.014. Variability = 0.46%)

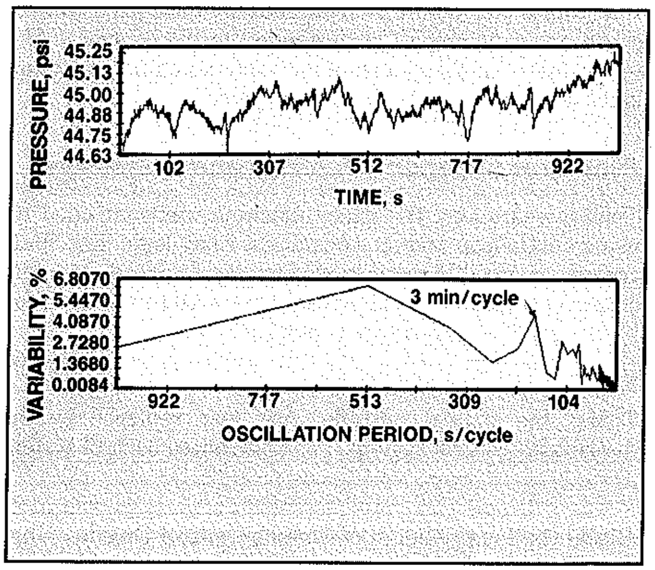


Within the paper machine control environment, the PLC will continue to start and stop motors where mill personnel feel comfortable with the PLC concept. In most cases the PLC is linked to the distributed system, whose console provides the operator interface. The responsiveness of the PLC to the distributed system interface is often a critical issue. In other mills, the start-stop and interlock functions are already being performed by the distributed system directly, without a PLC. The issue is often a jurisdictional one, pertaining to electrical and instrumentation departments. From the standpoint of making better paper, the use of the PLC is not usually an issue. However, discrete logic has a role to play in the area of automatic startups, grade changes, and shutdowns, where there are economic benefits to be gained.

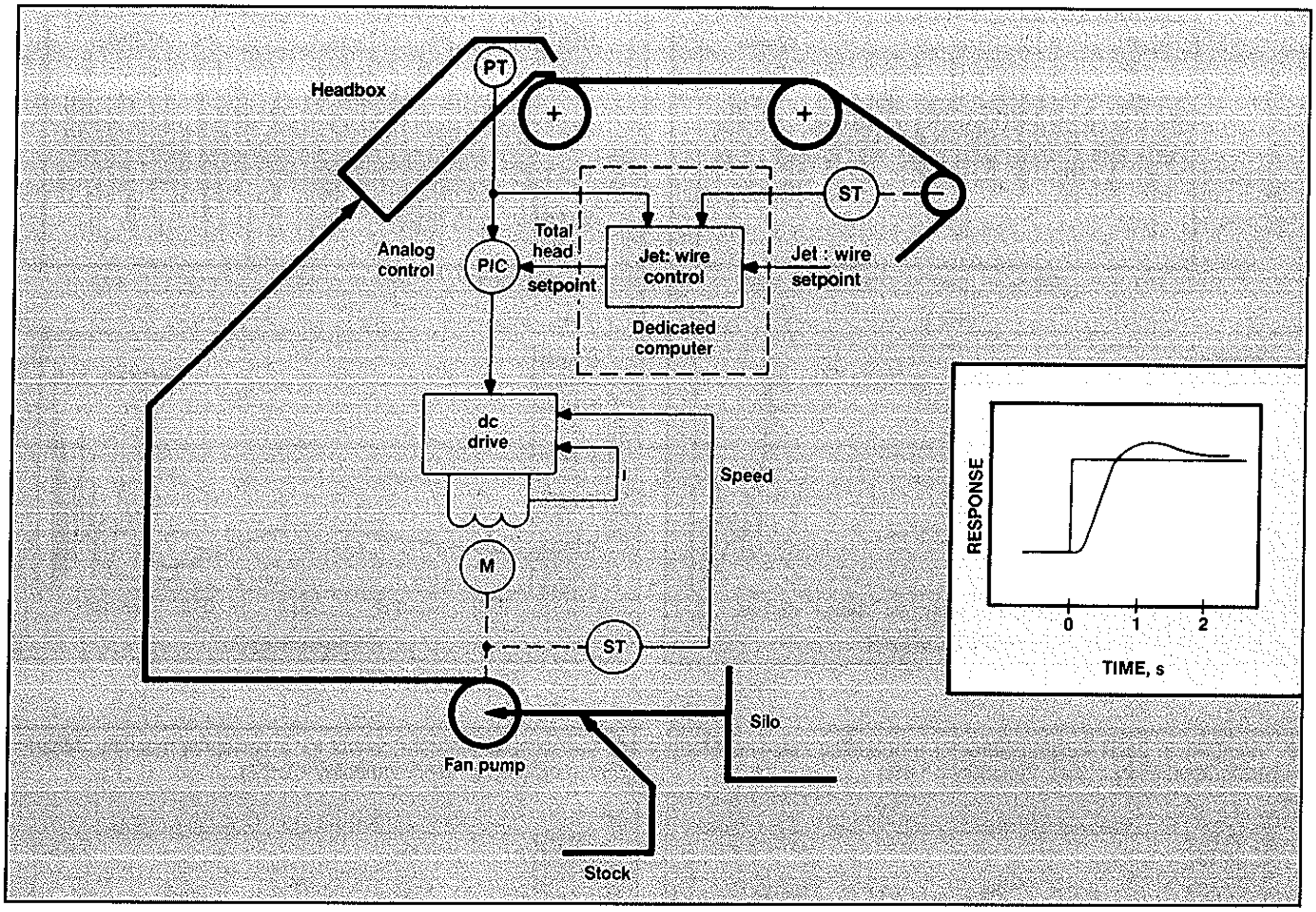
The digital drive

The digital drive system for variable-speed fan pumps and sectional drives also has evolved in a similar way—a simple replacement of analog technology with microprocessor-based technology. The ability to use virtually noise-free

5. Variability of white water header pressure (Mean = 44.9 psi. 2σ = 0.193. Variability = 0.43%)



6. Typical control for headbox total head, with dc drive step response shown in the inset



pulse tachometer signals directly for speed feedback has advanced the accuracy of speed regulation, tracking, and responsiveness. However, the nature of the speed control problem has not changed fundamentally and still includes:

- A load with rotational inertia
- An inner feedback loop for regulating the armature current
- An outer loop for regulating tachometer feedback.

The technical culture and approach to speed regulator tuning has not changed among the digital drive suppliers and is based directly on the original servomechanism theory. In contrast, the process control world has had to face the regulation problem from the standpoint of reducing random process variability. This approach has led to an evolution of modern stochastic control, which has had an impact on modern control engineering practices.

In this environment, the speed regulator would be seen as an amplifier of process disturbances with a period of 1–2 s/cycle. The digital drive designers could learn from process control experience in the area of regulation performance in a noisy environment. With the computing power of the digital drive and the use of simple gain scheduling concepts, it should be possible to improve the steady-state regulation performance while still maintaining aggressive tuning for major load upset recovery.

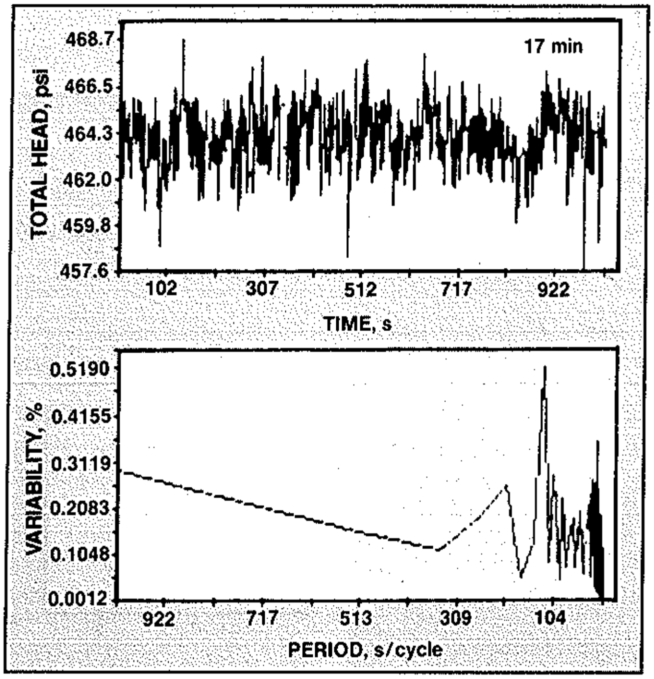
Basis weight and moisture control

Systems for basis weight and moisture control based on dedicated computers have their origins in the early beta gauge and original 16-bit minicomputer of the late 1960s. Technology for machine-direction (MD) control of basis weight, moisture, dryers, and the headbox evolved fully by 1975. Further development of the design has essentially been "frozen" in computer code since.

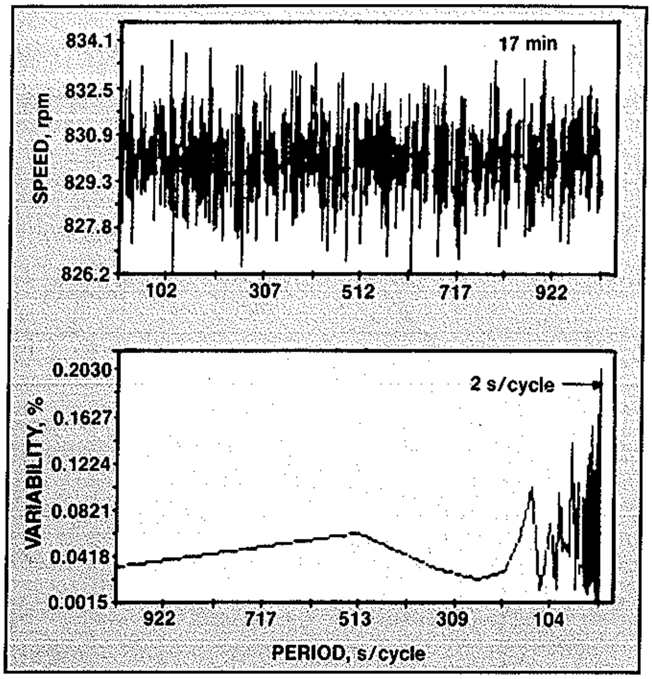
The design evolved before the distributed control system and reflects the comparatively low performance expectations of that time for analog-based consistency control, stock flow control, total head control, and steam pressure control. The major feedback loops for basis weight and moisture control tend to use conventional deadtime compensators such as the Smith Predictor and Dahlin algorithm. Also, attempts are being made to keep the model parameters at corrected values as machine speed and other operating variables change.

Control designers in the early 1970s made extensive use of deadbands and other nonlinear compensation methods, which today are thought to be of questionable value, often leading to limited cycles and increased variability. Virtually all major paper machines today have such systems, which are usually sold by one of several suppliers on a turnkey, guaranteed-results basis with usually a maintenance contract. This market segment is one of extreme competition and considerable secrecy regarding

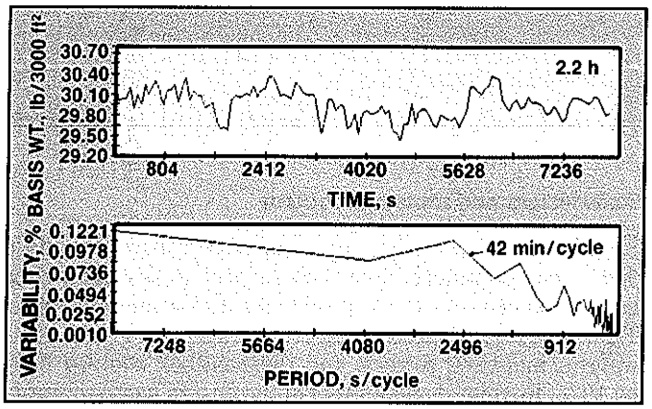
7. Variability in headbox total head



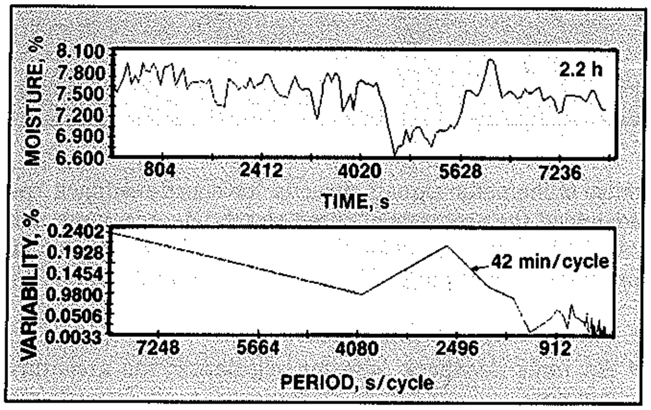
8. Variability in fan pump speed



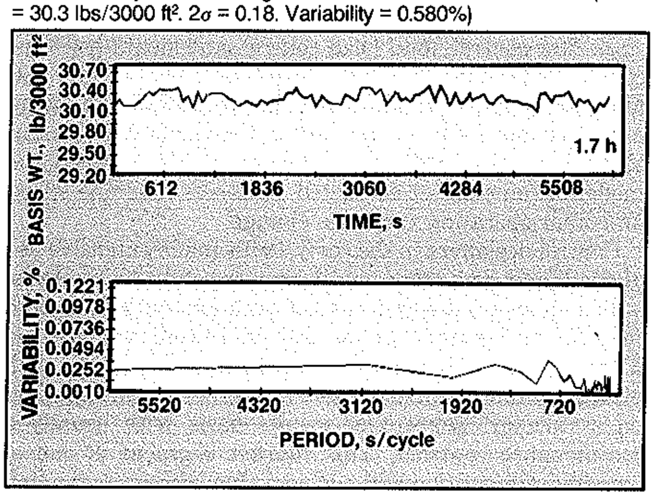
9. Variability in basis weight control for a newsprint machine (Mean = 29.9 lb/3000 ft², 2σ = 0.41. Variability = 1.4%)



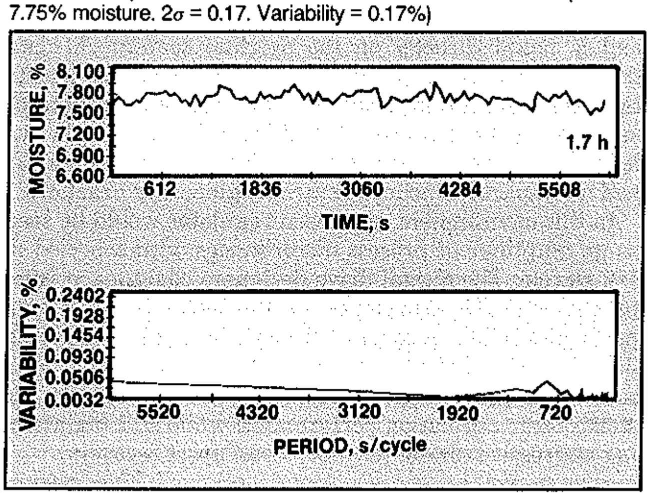
10. Variability in moisture control for a newsprint machine (Mean = 7.53% moisture. 2σ= 0.60. Variability = 0.6%)



11. Variability in basis weight control with controls on manual (Mean = 30.3 lbs/3000 ft². 2σ = 0.18. Variability = 0.580%)



12. Variability in moisture control with controls on manual (Mean = 7.75% moisture. 2σ = 0.17. Variability = 0.17%)



technology. Unlike the distributed control system technology, which is tending towards an open architecture hence allowing the user easy access to control configurations, these systems are closed for the typical mill user.

On an increasing scale, some of the suppliers of distributed control systems are competing for the MD paper machine control market, with each hoping to supply a "single window" on the process, whereby all process information, regardless of its source, is provided to the operator through operator consoles of one type. Of course, these suppliers must first gain access to scanning sensor information from the gauging supplier. Some suppliers of distributed control systems no doubt also plan to include CD control on their consoles. For the moment, however, the constraint that distributed CD control faces is the large quantity of profile data from the many on-machine scanners, requiring specialized handling, display, and even more specialized control. These requirements will severely tax data highway traffic and computing power.

The CD control system

CD control technology dates back to early prototype installations of basis weight and reel hardness in the early 1970s, but the major commercial push came in the early 1980s with basis weight, moisture, and caliper. During this period, a number of CD actuator suppliers came on the market with specialized actuators for caliper, moisture, and finally basis weight. Some of these were developed by the companies that manufacture gauges for determining basis weight and moisture profile. Others were developed by new companies specializing in CD actuators.

Today, several companies supply a set of CD actuator options and are prepared to implement CD control within their own control systems, taking sensor readings of basis weight, moisture, or caliper from the equipment of one of the suppliers of gauging systems. In this marketing environment, there is considerable competition, with the gauging and specialized CD suppliers often competing for the same CD control orders. On shared installations, relationships between gauging suppliers and CD control suppliers are sometimes strained. While recalcitrance in cooperating with a competitor is understandable, the paper manufacturer faces the hazard that commercial conflicts between the suppliers may interfere with their concentration on those aspects of control that affect paper quality—such as interactions between CD and MD control and the resolution of CD profiles.

Why are we falling short of the goal?

There are five different and separate control technologies that are often applied simultaneously to control a paper machine. These technologies are usually brought to bear by five different groups of people. Each group has a different vision of what its technology is to accomplish with the paper machine. The groups seldom communicate. In some cases, they are direct competitors, and their relationships are strained by commercial pressures.

On the other hand, the paper machine owner wants a high-quality sheet so that he can maintain his market share. He concentrates his technical efforts on papermaking problems. He usually has no people who understand control and prefers to leave control to the experts. He considers that each of his suppliers are experts and will solve their application problems to his satisfaction. He lives by the motto "I make paper—I don't play with computers." Unfortunately, he has chosen not to be able to understand the control-related reasons as to why he succeeded or failed as a producer of quality paper.

There are many reasons why we may be failing to achieve effective integrated control of the paper machine. Some of these can be classified as: historical, commercial, inadequate communications, inadequate application of known principles, and inadequate knowledge. A few examples will help us examine these issues.

Example 1: stock flow control

The typical control loop design

Figure 1 shows a typical stock flow control loop available in most current control systems. The basic thrust of the design is to control a motor-driven valve (usually an electric valve) to simultaneously achieve four objectives:

- Regulate stock flow
- Compensate for consistency upsets
- Compensate for speed changes
- Change the stock flow in response to basis weight feedback control.

The consistency controller is assumed to work independently.

This design dates back to the late 1960s and continues to be used in most paper machine control systems. There are minor differences between individual designs. All provide a stock demand setpoint calibrated in weight units (lb/ream or g/m^2). Some provide separate flow feedforward compensation for consistency and wire speed. Others combine consistency, flow, and speed as a pseudo-weight variable and control it directly. This difference has relatively minor impact dynamically.

A more serious issue is that in the late 1960s, some of the systems could only scan analog inputs once every 5 s. Unfortunately, it is fairly common to find many systems still scanning every 5 s today. The recommended sampling rate, based on good engineering practice, is a minimum of three times per time constant. Since the typical time constant for stock flow is about 2 s or less, the minimum practical sampling rate is about 0.5 s. The sampling rate of 5 s is hence 10 times slower than good design practice allows and 50 times slower than that of many modern distributed control systems.

Good design practice also requires that anti-aliasing analog filters be provided ahead of the analog-to-digital converter. When signals contain variability that is faster than the sampling rate, this can often cause a fictitious and slow or aliasing-type variability to be present in the sampled signal. The anti-aliasing filters prevent corruption of the digital signal caused by variability that is faster than the sampling rate. A consequence of the slow sampling and the omission of anti-aliasing analog filters is that excessive digital filtering is often used on the stock flow signal, producing an apparent stock flow time constant as great as 25 s, which is ten times slower than the true dynamics of stock flow.

It would be better to prefilter the flow signal with an analog filter of a relatively short time constant and then to scan and signal much faster. This approach would allow the stock flow loop to be tuned to have closed-loop dynamics with, say, a 10-s time constant. In turn, closed-loop time constants of some 1.5 min for feedback on basis weight control would be attainable without causing cycling and increased variability.

Good control engineering practice requires that the inner cascade loop be tuned 5-10 times faster than the outer loop to prevent the cascaded system from cycling. This rule is often broken by having excessively slow tuning of the stock flow loop but aggressive tuning of the feedback basis weight loop.

Figure 1 reveals another interesting feature. The digital system designer in 1970 had access to the stock consistency signal but not to the consistency analog loop. He did what he thought was the next best thing—compensate the stock flow control for consistency changes. The assumption was made that the quality of control provided by the analog consistency controller was not likely to be high and that he should therefore give it all the help that he could.

Unfortunately, this design ignores the basic dynamics of the stock line and dilution stream. When the stock valve is opened and the stock flow increases, the consistency will increase unless white water is added simultaneously in the right proportion. This effect may cause strong coupling between the stock consistency and the consistency-compensated stock flow loop, to the degree that cycling may mutually occur if both are tuned to be responsive. Both would then be compensating for the same consistency upsets simultaneously—and overcorrecting.

Improved designs

Figure 2 shows a better design, which requires fast scanning rates for implementation. All attempts have been made to achieve the best consistency control possible at all times. Design features include feedforward control to add white water just when the stock valve is opened, to prevent consistency upsets. Also, the consistency controller uses a deadtime compensator such as a Smith Predictor instead of PID, if the deadtime is appreciable (5 s or longer). Stock flow then only needs compensation for consistency setpoint changes.

To implement this design, there must be a provision to accurately position an electric valve. This positioning requires a digital output control with a timed contact closure, for duration increments of 0.1 s or finer to be effective. Historically, distributed control systems have lacked such a feature, although some now have it available. The motor-driven valve is not part of the technical culture of distributed control, which has concentrated on providing 4-20 mA outputs to modulating actuators.

A further improvement in stock flow and consistency control is shown in **Fig. 3**. In this design, changes in white water header pressure are recognized as a frequent source of consistency upsets. This design compensates for these upsets by controlling the white water flow in ratio to the stock flow. Consistency control adjusts the ratio setpoint. Furthermore, feedforward control action from the stock flow output compensates for the flow loop dynamics. White water pressure fluctuations are common and are a frequent source of consistency variability and coupling between consistency control loops.

Figure 4 shows a time series analysis of a control loop for thick stock consistency, while **Fig. 5** shows the same for the white water header pressure. In each case, data were automatically collected using a portable microcomputer. The top graph in each figure shows the traces for a period of just over 1000 s. The bottom traces show the power spectra for each signal. The power spectrum breaks down the variability in the signal by frequency content and plots that result by a period of oscillation in seconds.

There is significant variability at about 3 min/cycle on consistency, which is probably caused by the white water pressure cycle at the same frequency. This pressure cycle could in turn be caused by another consistency control loop feeding off the same white water header. The consistency variability in this case translates into about 0.5% of fiber flow. This percentage can be significant in a marketplace where 1% basis weight variability is acceptable but not excellent.

The feedback loop for basis weight control is limited by its process dynamics to controlling variability that is slower than about 10-20 min/cycle. On the other hand, the control systems for stock flow and consistency shown in Figs. 2 and 3 should be able to control variability that is slower than only 1-2 min/cycle. If the consistency loop is tuned to be much slower than that, a major opportunity is lost in that all of the variability with periods longer than 2 min/cycle and shorter than 20 min/cycle will end up in the sheet as nonuniform quality.

In practice, a typical analog controller tuning for consistency control may have a proportional band of about 150% and a reset time of 0.5 min. This tuning has a frequency cutoff at about 6 min/cycle, which is about three times slower than that possible in many well-designed consistency control installations. The reason for this situation is that the concepts of variability and the techniques of tuning regulators to minimize variability lie outside the technical culture and technical training of most instrumentation departments in the pulp and paper industry.

Example 2: headbox control

Figure 6 shows a typical control strategy for headbox total head for a hydraulic headbox using a variable-speed fan pump and dc drive system. The tuning specification for the fan pump usually requires a step response similar to that shown in the inset. This response is similar to that required for most drives. The response has a rise time of about 0.5 s and an overshoot of about 20%. This response is typically achieved by tuning the armature current feedback regulator to have a natural frequency of some 30 radians/s and the speed regulator to have a natural frequency of 3 radians/s, or approximately 0.5 Hz or a period of 2 s. As a result, fan pumps tend to have a damped oscillation with a period of 2 s, which in turn usually causes the headbox total head to be quite noisy. At 3000 ft/min, a 2-s cycle represents a distance of 100 ft in the machine direction.

Figure 7 shows time series plot of headbox total head, and **Fig. 8** shows the time series plot for fan pump speed. The data were collected from a hydraulic headbox during a period of slightly over 1000 s. For headbox total head, the variability on a 2-σ basis is 2.9 in. of water, with an average of 464 in., or 0.6%. The fan pump variability is 2.4 rpm on a 2-σ basis, with an average of 830 rpm. There is a predominant oscillation of 2 s/cycle.

The fan pump variability has induced most of the high-frequency variability in total head, although some of the 2-s variability has been attenuated. The high-frequency content of the total head makes it difficult to effectively tune the total head and jet:wire ratio control. It would be better if the electrical engineers tuned the fan pump dc drive to have a damping ratio of no more than 0.9 and hence no overshoot. Typical damping ratios currently specified are between 0.4 and 0.5, which gives a 15–20% overshoot on the step response and a frequency response peak of up to +3 db. It is this peak which tends to amplify high-frequency noise.

The reason for this situation is at least in part due to the fact that electric drive control concepts are well covered in the classical literature of servomechanism theory and date back to the 1940s. Tuning for 20% overshoot may be fine in a noise-free world in which step disturbances may normally be expected, but the paper machine is not a noise-free environment, as Figs. 7 and 8 show. Hence, the concepts of the stochastic control and regulator tuning to minimize the impact of random variability should apply. In this environment, tuning for 20% overshoot has no place. A more damped tuning of the fan pump speed would permit more aggressive regulation of total head and jet:wire ratio.

Example 3: basis weight and moisture control

Most people make the fundamental assumption that MD and CD basis weight and moisture controls naturally have no significant effect on one another. Another common assumption is that any kind of MD and CD control is better than none at all.

Figure 9 shows the variability in basis weight for a typical newsprint machine over a period of some 2 h, and **Fig. 10** shows moisture variability for the same data. All MD and CD controls are on automatic for this example. Each data point in the time graphs of both figures is a full-scan average.

There is considerable variability at about 2400 s, or 40 min/cycle, on both basis weight and moisture. Also, both variables show variability that is even slower. The overall variability for the run consists of a 2-σ variability in basis weight of of 0.41 lb/3000 ft^2 (0.61 g/m^2) or 1.4%. The moisture variability is 0.6%. These results are slightly over the industry capability of 1% for basis weight and 0.5% for moisture.

Figures 11 and**12** show a 1.7-h run shortly after the data of Figs. 9 and 10 were collected. Both MD and CD basis weight and moisture controls have all been turned off. The 2-σ values for MD basis weight and moisture have settled down to 0.18 lb/3000 ft^2 and 0.17%, respectively—reductions in variability of 60% in going to manual control from automatic control The corresponding CD 2-σ values increased slightly on manual, but the total 2-σ values were better on manual than on automatic. This sobering result should cause reflection.

The technical reasons for this two-fold increase in MD variability when in automatic control mode were:

- Excessive deadbands and other nonlinear compensation
- Poor MD deadtime model compensation parameters
- Inappropriate MD tuning, including excessively slow stock flow and steam pressure loops
- CD and MD coupling.

The technical problems can be corrected, given technical competence and cooperation. The human reasons, however, are much more complex, given that several people from various organizations were likely involved. A multisupplier situation may indeed complicate the resolution of such technical problems. However, the human problem is ultimately founded on a lack of technical expertise on the part of the pulp and paper industry in the control engineering discipline and a resulting lack of performance standards.

Conclusions

How well are we achieving fully integrated control of the paper machine, with as many as five control system suppliers working on the same machine at the same time? The examples of process variability came from recent control performance audits and represent only a fraction of the many that could have been used. In no way extraordinary, these examples could have come from a paper machine anywhere in the industry. In our industry, control performance results are not checked, and we are unaware of what could be possible. There are no standards for control performance, and we do not fully appreciate the impact of control performance on sheet quality and customer satisfaction.

The issue of control performance and quality is not a technological one but rather a human one. Old designs are still used today, with some engineers using out-of-date tuning concepts and others tuning loops without any training in loop tuning. The papermaker is often not aware that these minor control-related problems have a critical effect on the quality of his product. As paper customers continue to press for improved quality, issues like these will eventually be resolved. However, the human issues will require education, retraining, and time to resolve, and these requirements are the ultimate constraints in our ability to compete in the marketplace.

Received for review May 31, 1988.

Accepted June 14, 1988.

Presented at the 1988 Engineering Conference.